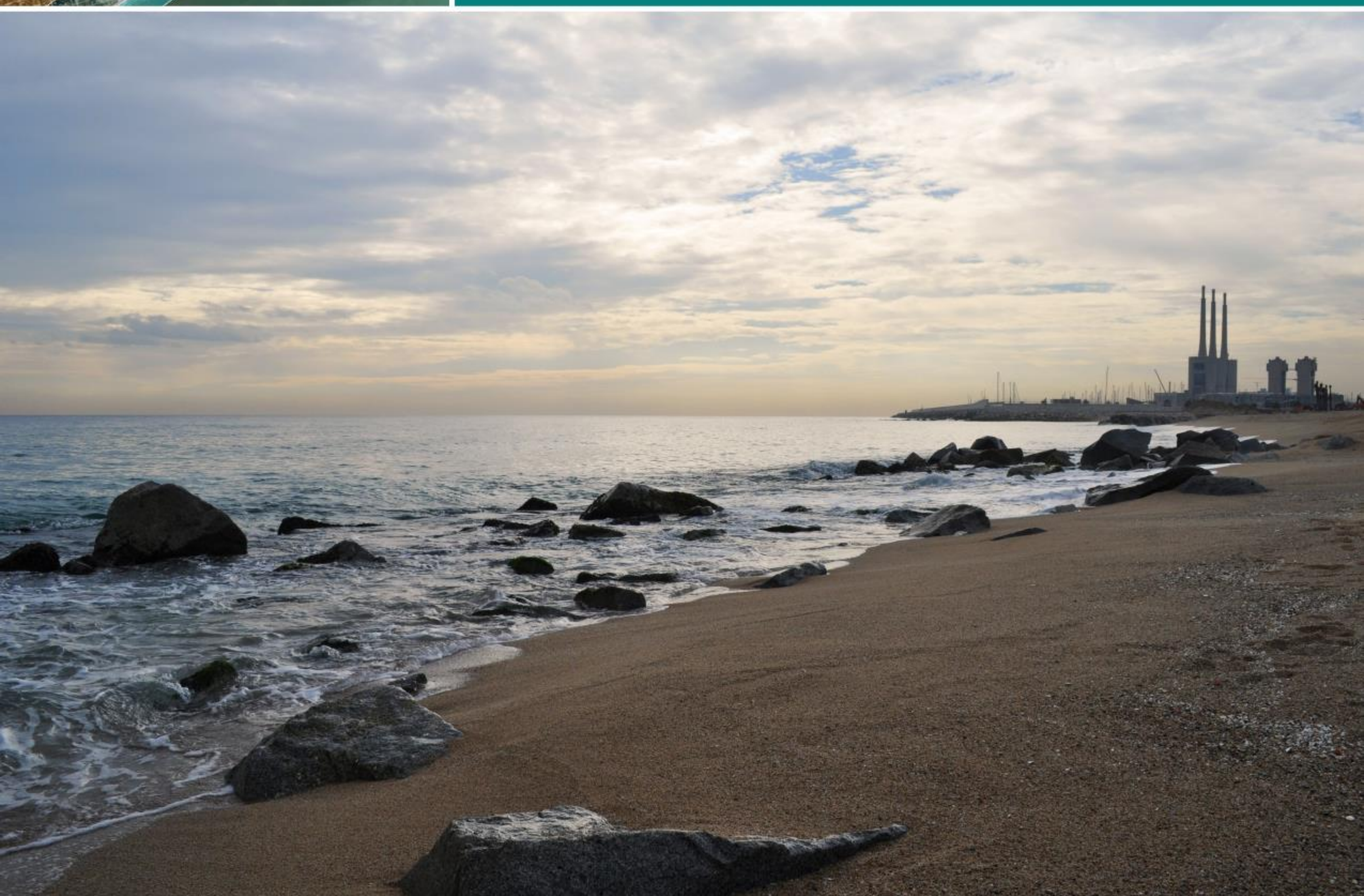
U.S. DEPARTMENT OF ENERGY

Climate Change and the Electricity Sector:

Guide for Assessing Vulnerabilities and Developing Resilience Solutions to Sea Level Rise

July 2016



Cover Photo Credits

Top: Satellite image of Hurricane Sandy (NASA 2016); Coastal area near Louisiana Highway 1 (NOAA 2012)
Middle: Federal Emergency Management Agency Flood Map for portion of Galveston, TX (DHS 2016)
Bottom: Power plant along coastline (Adobe Stock 2016)

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U.S. Department of Energy

Office of Energy Policy and Systems Analysis

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Preface

This report is one of numerous initiatives launched to support and facilitate energy sector climate preparedness and resilience at national, regional, and local levels. The U.S. Department of Energy's vision is a U.S. energy system that is reliable and resilient in the face of all climate hazards, supports U.S. economic competitiveness, and minimizes impacts on the environment. The U.S. Department of Energy is committed to ensuring the climate resiliency of U.S. energy infrastructure and systems through innovative technology development and deployment, enabling policy frameworks, robust analytical modeling, and assessment capabilities to address energy issues of national and regional importance.

Specific questions may be directed to Craig Zamuda, U.S. Department of Energy, Office of Energy Policy and Systems Analysis (SeaLevelRiseGuide@hq.doe.gov).

Executive Summary

Much of the energy infrastructure in the United States is located near the coasts, where it may be exposed to weather and climate-related hazards such as flooding at high tides and storm surge associated with intense storms as well as permanent inundation from sea level rise (SLR) (USGCRP 2014; DOE 2015a; DOE 2015b). Global sea level is projected to continue to rise (more rapidly than historical trends under most scenarios) and storm events will likely become more intense for many parts of the United States over the coming century (USGCRP 2014). DOE is committed to ensuring climate resilience of the U.S. energy infrastructure and systems to all climate hazards, including those related to SLR and storm surge. Resilience is defined as the ability to prepare for and adapt to changing conditions and to withstand and recover rapidly from disruptions (White House 2013).

The *Partnership for Energy Sector Climate Resilience*[1] is an initiative to enhance U.S. energy security by improving the resilience of energy infrastructure to extreme weather and climate change impacts. Under this partnership, owners and operators of energy assets will develop and pursue cost-effective strategies for a more climate-resilient U.S. energy infrastructure.

Electricity asset owners can assess challenges and opportunities brought about by changing climate hazards to improve resilience of existing and planned electricity infrastructure and service.

Document Purpose and Scope

This report was prepared to provide guidance for analyzing climate resilience challenges and opportunities in the power sector. The document is intended to be relevant to public and private sector stakeholders—particularly, the electricity sector—who are interested in evaluating how climate change hazards may impact the ability to provide service and implement measures to enhance resilience to climate change. The reference is limited to coastal climate hazards of flooding and permanent inundation due to SLR, as well as flooding from storm surge associated with extreme storm events. The document includes examples of climate resilience challenges and opportunities related to generation, transmission, and distribution assets, recognizing that the affected sectors may have different responsibilities for different types of assets or portions of the overall electricity system. This report provides principles that are meant to apply broadly to key aspects of any climate resilience analysis rather than instructions for a specific analysis. It also includes general reference on how to estimate the costs and benefits of resilience measures but does not serve as a manual for calculating economic benefits of resilience measures.

[1] U.S. Department of Energy, Partnership for Energy Sector Climate Resilience, http://energy.gov/epsa/partnership-energy-sector-climate-resilience. Accessed April 2016.

A General Approach for Assessment

An electricity asset owner can assess climate change–related resilience by determining the exposure and vulnerability of electricity assets, as well as the economic losses by analyzing direct and indirect costs. Resilience measures, including their benefits, can then be identified and prioritized. The process should be conducted with a specific application or decision context in mind so that the results can inform action. The assessment may also be iterative, allowing for updated results as new decision-relevant information becomes available. This report introduces a general methodological framework for this process, with the key steps shown in Figure 1.

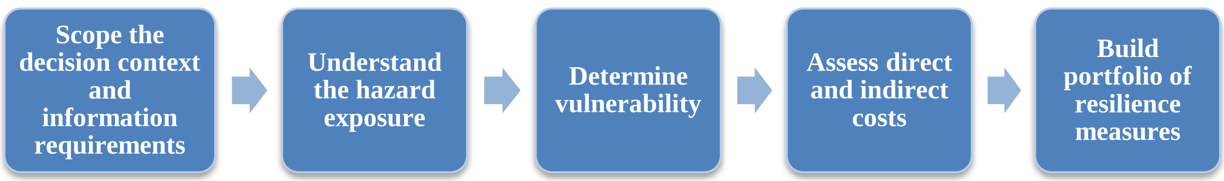


Figure 1. A general approach for assessing the current and future hazard, vulnerability, and associated direct and indirect costs from SLR and storm surge hazards, and the identification and prioritization of resilience measures.

Scope the Decision Context and Information Requirements

Stakeholders, both internal and external (as appropriate), should be engaged at the outset of a climate resilience assessment. For electricity asset owners, this engagement may take many forms and should be designed to improve transparency and buy-in from interested parties. If the assessment is part of a formal regulatory process, such procedures may already be well defined and the material presented here should serve to reinforce them. In addition, an assessment should be guided by the specific decision that the results are meant to inform.

Key considerations for scoping the decision context and information requirements include:

1. At the outset of an assessment, engage relevant stakeholder groups to help inform desired assessment outcomes. Seek collaborative relationships with external entities that can help translate and co-develop climate information needed for decision-making.

2. Identify opportunities to integrate results of climate resilience analysis into business practices and align the level of detail in climate information with the level of detail necessary to take action; identify the necessary amount of information needed to adequately inform the action.

Understand the Hazard Exposure

Sea level rise can lead to short-term nuisance flooding (i.e., flooding that occurs periodically due to high tides, for example, and causes a public inconvenience) and permanent inundation. Information about potential future global SLR—often presented through scenarios and which takes into consideration particular conditions that can affect how SLR manifests locally—can help utilities understand the potential exposure of electricity assets to these hazards. In addition, information on storm surge associated with extreme storms, including the potential for more intense or frequent storms and the amplification of storm surge due to SLR, is important for understanding exposure in a changing climate.

Key considerations for understanding the exposure of electricity assets to sea level rise and storm surge hazards include:

1. Identify areas where nuisance flooding is already problematic and consider the implications associated with an increase in exposure to flooding.

2. Consider any changes in the natural environment due to coastal erosion and barrier island migration that might affect exposure to SLR and storm surge. Obtain locally specific information about these potential changes from coastal scientists.

3. Select the global SLR scenarios most appropriate for the analysis and decision-making context, including the aversion to risk and time horizon.

4. Use nearby tide gage stations to identify how local sea level has changed relative to global sea level. Use this information to generate a rough estimate of the local correction that should be applied to the global scenarios to determine the amount and timing of local SLR for a given scenario. The inherent uncertainty in estimating future global SLR should not preclude action.

5. Identify past storms that had damaging coastal flooding associated with storm surge and the infrastructure that was exposed; future planning should determine whether storm surge is an issue or could become one within the planning timeline, as storm events are projected to increase in intensity for many regions.

Determine Vulnerability and Assess Direct and Indirect Costs

Impacts caused by the exposure of vulnerable assets to SLR and storm surge can incur a variety of costs that utilities will need to consider. After gathering information and completing analyses to understand the threat from SLR and storm surge as it relates to the decision context, utilities should determine the associated vulnerability and costs. Direct costs resulting from damages due to SLR and storm surge include cost of repair or restoration, cost of replacement, and cost of relocation. The electric power system is highly interconnected with other sectors, and climate change impacts may have far-reaching implications. Extended outages can impair a number of sectors, including communications, healthcare facilities, emergency management, and transportation systems (DHS 2013). Indirect costs include cost to customers from loss of service, broader societal costs (e.g., lost economic productivity, job loss) from loss of service, and cost of damages to interlinking infrastructures (e.g., oil and gas infrastructure connected to electric power sector). The electricity system is also connected across regions, such that loss of power or generation capacity in one area can cascade to a widespread outage.

Key considerations for assessing the vulnerability and costs of sea level rise and storm surge events include:

1. Combine public and proprietary sources of existing and projected asset location data with geospatial information on potential SLR and storm surge threats to determine which assets are potentially exposed. Ensure accuracy of databases, as asset inventories change over time.

2. Many different components within generation, transmission, and distribution assets may be vulnerable to increased nuisance flooding and permanent inundation due to SLR.

Asset vulnerabilities may be generalized for screening-level analyses, but for detailed assessments, utilities will need to consider specific design and site characteristics for individual assets.

3. A variety of sources, including expert opinion, design standards, and post-event reports, can be used to understand vulnerability of assets to particular climate-related threats. Estimate the potential impact quantitatively or qualitatively by combining the vulnerability information for exposed assets with SLR and storm surge scenarios, depending on decision requirements.

4. Interdependencies within the power system may contribute to vulnerability. It may be important to model future scenarios of network configuration to address potential SLR and storm surge vulnerability to planned investments.

5. Use the analysis of exposed assets to focus cost estimates. Direct costs due to impacts from SLR and storm surge threats will be context specific, and incorporating available asset vulnerability information, local relocation costs, and information on timing and frequency of events will improve accuracy when detailed estimates are required.

6. Determine the indirect costs from SLR and storm surge threats using methods that capture key aspects of the effect of outages on other sectors, such as value of lost load (VOLL).

7. Engage internal and external stakeholders in prioritizing actions based on potential costs to ensure meaningful metrics are used and that they can inform the selection of resilience measures needed to address costs and meet stakeholder expectations.

Build a Portfolio of Resilience Measures

Faced with the potential impacts from SLR and storm surge, electric utilities can choose from a range of resilience measures, including those related to hardening existing assets; new construction and relocation; policy, planning, and operations; smart grid and microgrid; distributed generation and demand response programs; ecosystem-based measures; and risk transfer to help ensure electricity service. A portfolio of resilience measures can help to address the vulnerabilities and avoid the potential direct and indirect costs from SLR and storm surge hazards.

Based on the identified vulnerabilities and the decision context, utilities can build a portfolio of measures by first identifying a full set of possible resilience measures. This list of possible measures should then be screened for applicability based on a variety of criteria (e.g., the decision context, political or technological feasibility, and flexibility), thereby reducing the number of measures to be further investigated. Information on costs and benefits should be analyzed for the measures that pass the screening. The selected measures can be evaluated in more detail based on multiple criteria, including the cost and benefit information. Finally, an asset owner can adjust the portfolio of measures to ensure consideration of the timing of related investments, synergies between measures, concerns over breadth of approaches and coverage, marginal benefits of related investment, and other decision-relevant priorities.

Key considerations for building a portfolio of resilience measures include:

1. There are many types of resilience measures that can address different aspects of vulnerability and that can be applied to different spatial or temporal scales. Utilities should use available resources, stakeholder input, and in-house expertise to identify as many potential resilience measures as possible. This list of measures will provide a foundation for building the portfolio of measures appropriate for the decision context and goals.

2. Screen potential resilience measures to help ensure that measures considered basic criteria related to the political and technological feasibility of each measure, effectiveness, flexibility, and other screening criteria deemed appropriate by stakeholders.

3. The cost and benefits of resilience measures may vary significantly. While there are potential low-cost resilience measures, some will require significant investments, which may be supported through transparent processes for assessing benefits and considering a portfolio of measures.

4. Resilience measures may have important co-benefits that should be included in an assessment of benefits. In some cases, economic metrics may be available, but more often the value of co-benefits to public health, ecosystem conservation, national security, or other sectors or aspects of society can be assessed qualitatively or with non-economic measures. Utilities may need to engage outside expertise for assistance in appropriately assessing co-benefits as part of more detailed analyses.

5. A variety of metrics exists for system reliability, which could be informative to assessing some aspects of the benefits of resilience measures. However, existing reliability metrics do not apply to assessing long-duration outages (i.e., days to weeks), Metrics that can be used to assess the system benefits from resilience measures to long-term gradual change, such as SLR, are not well developed, but utilities should at least consider the potential qualitative benefits of measures to address SLR hazards.

6. Use multiple criteria to inform the choice of a portfolio of resilience measures. While benefit-cost analysis will be important to many decision processes, it is important to consider other metrics alongside the benefit-cost analysis information.

7. There are potential limitations to capturing the full range of resilience benefits in a benefit costs analysis. Consideration of incremental costs related to resilience, incorporation of uncertainty of future conditions (including timing and amount of SLR) and flow of benefits will be necessary. Methods have been proposed to address some of these considerations, but the application of economic analysis to resilience measures remains an active area of research.

8. After evaluating individual resilience measures, consider how a portfolio of measures will meet decision goals. Adjust the final portfolio to take advantage of opportunities related to timing of investments, synergies between measures, concerns over breadth of approaches and coverage, or other decision-relevant priorities.

Conclusion

An assessment of vulnerabilities to SLR and storm surge should inform the design of a portfolio of resilience measures that can be implemented to help build resilience in the electricity sector. In addition, asset owners will need to assess vulnerabilities to other climate-related hazards (e.g., wildfires, heat waves, and drought) to identify a complete portfolio of actions that can be integrated with other actions designed to address non-climate hazards, such as cybersecurity and physical threats, not addressed in this document.

The electricity industry is undergoing significant change that could affect the vulnerability and resilience of electricity assets and service in the future. This report identifies key considerations for electricity assets, with an emphasis on utilities and the regulatory and market environment in which they operate today. Several aspects of resilience assessment can be further developed in the future to help asset owners build resilience in this dynamic environment, such as evaluation of the impact on resilience of increasing reliance on assets owned by outside entities, the evolving interdependencies across the electricity sector and with other sectors, and the opportunities for development and integration of demand response; microgrids, distributed generation and energy storage technologies; and consumer behavior programs into a portfolio of resilience measures. Resilience planning will also need to address those segments of society, particularly vulnerable populations that may be disproportionately affected due to less capacity to prepare for, respond to, and recover from climate-related hazards and effects. This report provides a foundation for moving forward on climate resilience in the electricity sector, and may be updated as new information on climate hazards and implementation of resilience measures becomes available.

Table of Contents

List of Figures

List of Tables

1 Introduction

Much of the energy infrastructure in the United States is located near the coast, where it may be exposed to climate-related hazards, such as permanent inundation from sea level rise (SLR), increases in flooding at high tides (i.e., nuisance flooding), and flooding from more frequent or intense storms and storm surge (USGCRP 2014; DOE 2015a; DOE 2015b). Over this century, there could be significant increases in exposure of electricity assets in coastal areas (where populations are growing rapidly). Global sea level is projected to continue to rise (more rapidly under most scenarios) and storm events will likely become more intense over the coming century (USGCRP 2014).

The electric power system is highly interconnected with other sectors, and climate change impacts may have far-reaching implications. Extended outages can impair a number of sectors, including communications, healthcare facilities, emergency management, and transportation systems (DHS 2013). For example, electrical power is required to operate light-rail transportation systems; regardless of how resilient the light-rail infrastructure system might be, recovery of service following flooding due to an extreme storm surge event depends on the restoration of electrical power (NIST 2015). Superstorm Sandy crippled much of New Jersey's energy infrastructure when it swept through the state in 2013 (DOE 2013c). Many of the state's residents could not get to work because the operations center for New Jersey Transit (NJ Transit) flooded, damaging backup power systems, emergency generation, and the computer system that controls train operations (City of Hoboken 2013; DOE 2013b; NJ Transit 2014).[2] The electricity system is also connected across regions, such that loss of power in one area can cascade to a widespread outage, as was the case in the Northeast blackout in 2003 (NIST 2015). In addition, a utility may depend upon electricity generated by other asset owners. Thus, a utility may need to understand not only the vulnerabilities to its own assets, but that of others on which it relies.

Resilience is defined as the ability to prepare for and adapt to changing conditions and to withstand and recover rapidly from disruptions (White House 2013). An electricity asset owner can assess climate change–related resilience challenges and opportunities brought about by SLR and storm surge hazards by determining the exposure of assets to SLR and storm surge hazards; the vulnerability of electricity assets to storm events based on sensitivity and recoverability measures; and the economic losses determined by analyzing direct and indirect costs. Resilience measures, including their benefits, can then be identified and prioritized to help ensure continuity of electricity service, including measures related to hardening existing assets; new construction and relocation; policy, planning, and operations; smart grid and microgrid; distributed generation; demand management; ecosystem-based measures; and risk transfer. The process should be done with a specific application or decision context in mind so that the results can inform action. The assessment may also be iterative, allowing for updated results as new decision-relevant information becomes available. Figure 2provides a general approach for the assessment process.

[2] DOE and Sandia National Laboratories are collaborating with the New Jersey Board of Public Utilities, City of Hoboken, and Public Service Electric and Gas to develop and implement a plan as part of Hurricane Sandy recovery efforts for the first-ever transit system microgrid that is capable of keeping the power on and trains running when the electric grid goes down.

Figure 2. A general approach for assessing the current and future hazard, vulnerability, and associated direct and indirect costs from SLR and storm surge hazards, and the identification and prioritization of resilience measures.

1.1 Document Purpose and Scope

This document was prepared to provide general reference for analyzing climate resilience challenges and opportunities in the power sector. The document is intended to be relevant to public and private sector stakeholders—particularly, the electricity sector industry—who are interested in evaluating how climate change hazards may impact the ability to provide service and implement measures to enhance climate resilience. The reference is limited to coastal climate hazards of nuisance flooding and permanent inundation due to SLR, as well as flooding from storm surge associated with extreme storm events. The document includes examples of climate resilience challenges and opportunities related to generation, transmission, and distribution assets, recognizing that the affected sectors may have different responsibilities for different types of assets or portions of the overall electricity system.

The remainder of the document is organized into sections to convey a logical progression of analyses that align with the components of the process shown in Figure 2. Section 2 emphasizes engaging stakeholders early in the process, the role of outside experts, and the importance of aligning the analysis detail with the decision context for useful results. Section 3 provides background on SLR and storm surge hazards and provides guidance regarding the use of climate information to inform the assessment. Section 4 discusses differential vulnerability of asset types and the potential direct and indirect costs associated with hazard impacts. Section 5 delves into resilience measures, including their benefits and considerations for creating an effective portfolio of measures. Section 6 steps back to provide some considerations of the challenges if analyses need to be scaled over very large areas (e.g., the entire Atlantic Coast).

When considering resilience investments in response to climate change, different decisions will need to be supported by varying levels of qualitative or quantitative analysis. This document provides principles that are meant to apply broadly to key aspects of any climate resilience analysis rather than instructions for a specific level of analysis. The document also provides general reference on how to estimate the costs and benefits of resilience measures but does not serve as a manual for calculating economic benefits of resilience measures. The focus on resilience includes measures that can improve utilities' ability to prepare and adapt to long-term gradual change, as well as measures that may improve their ability to recover rapidly from short-term disruptions. While some of the measures may improve electricity service reliability, this document does not directly cover how utilities could use resilience measures to meet required reliability targets.

This document considers both individual assets as well as the broader power system and its interconnections, recognizing that a utility will need to assess not only the vulnerabilities for the specific assets that it owns and operates, but also assets that it does not own but relies upon (e.g., electricity from independent power producers and merchant generators) or that are outside the direct control of the utility. For example, this may include distributed assets (e.g., PV solar systems) or the supply chain. In addition, the document considers the interconnections among the electricity sector and other sectors, especially in assessment of indirect costs. The document does not address other factors that might affect asset owner risks, such as the regulatory environment, economic environment, or cybersecurity and physical threats. Finally, while this report focuses on impacts caused by SLR and ocean water flooding associated with storms, aspects of the approach presented here may be applicable to addressing a wider range of climate hazards.[3]

2 Scope the Decision Context and Information Requirements

This section explores issues related to scoping the decision context with stakeholder engagement and aligning the context with the appropriate information detail. Stakeholders, both internal and external (as appropriate), should be engaged at the outset of a climate resilience assessment. For electricity asset owners, this engagement may take many forms and should be designed to improve transparency and buy-in from interested parties. If the assessment is part of a formal regulatory process, such procedures may already be well defined and the material presented here should serve to reinforce them. In addition, an assessment should be guided by the specific decision that the results are meant to inform.

[3] For example, electricity utility services and assets may be significantly exposed to climate-related hazards such as increasing atmospheric temperatures, changes in precipitation patterns and runoff, and changes in wind and wave regimes (DOE 2015a; DOE 2013a; Burkett 2011). In addition, the reference information provided here may be relevant input for a general model for evaluation of climate change resilience in the broader energy sector, building on other proposed frameworks (e.g., Economics of Climate Adaptation Working Group 2009; Watson et al. 2014), and following the example of other models for helping organizations evaluate, prioritize, and improve the capabilities for addressing other significant risks, such as cybersecurity (DOE 2014a).

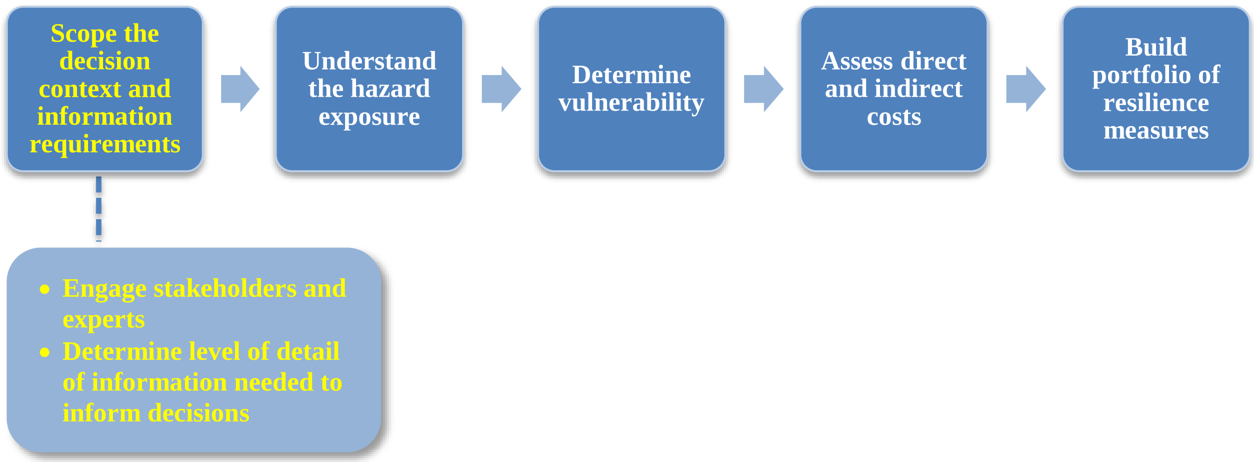


Figure 3. Key aspects of scoping the decision context and information requirements of an assessment.

2.1 Engage Stakeholders and Experts

Utilities have a wide range of important stakeholders and can draw on experience with stakeholder engagement to improve the design and outcomes of an assessment. Different types of engagement—including workshops, webinars, special conference sessions, or other appropriate meeting types—can be used to raise awareness, solicit input, vet results, and improve outcomes from the assessment process. Some existing processes, such as Integrated Resource Planning (see Table 1) or pre-existing asset-owner stakeholder groups, may provide opportunities to integrate topics related to climate resilience.

When undertaking an analysis of how future climate may affect an electricity service and assets, it can be useful to partner with experts who can assist in developing and/or translating the climate information into tailored projections useful to decision-making. For examples, Consolidated Edison of New York has engaged a stakeholder body, the Storm Hardening and Resiliency Collaborative, and has a relationship with Columbia University Center for Climate Systems Research to provide climate information (Con Edison 2014). Climate data, including changes in sea level, are publicly available. However, many communities have already reviewed various sets of projections and determined the optimum data to use in their planning. To ensure consistency with other findings in the community and avoid repeating past efforts, it can be helpful to engage collaborative stakeholders (e.g., representatives from the state or county level, academics, local industry, and planning organizations).

Regional climate collaboratives can assist utilities interested in resilience and provide effective mechanisms for engagement across sectors within specific regions. They have the potential to generate more robust resilience actions and better investment decisions and also be sources of additional funding streams (by helping to identify potential co-benefits beyond the electric system itself). These forums can reinforce the idea of the interconnectedness of the energy sector with the communities it serves.).[4]

2.2 Determine Level of Detail to Inform Decisions

It is important at the onset of an assessment to determine what level of decision-making the assessment will inform. Electricity asset–owner decisions and activities can apply to a range of geographic and time scales that must be informed by data that vary in level of detail and certainty. The decision needs may be driven by regulatory requirements, stakeholder preference, risk tolerance, utility policies, or other context considerations. Utilities or other electricity sector participants commonly engage in a variety of decision-making processes or activities. Table 1 provides an overview of examples of common planning activities, as well as the associated non-climate data requirements.

Table 1. Examples of Common Planning Activities in the Electricity Sector and Non-Climate Data Requirements.

Activity	Timeframe	Description of Planning Activity	Non-Climate Data Requirements
Weather-based Planning	1–2 weeks	Conduct GIS analysis to identify potentially exposed coastal assets.	Location of energy assets, vulnerability data of such assets, simulation modeling of weather events.
Resource Adequacy Planning	1–10 years into future	Ensure adequate reserve margin is available to serve the peak load demand. Typically, Monte Carlo–based analysis is used to account for generation unit outages and load forecast uncertainty.	Generation resources (megawatts [MWs], outage rates), load forecast (on a zonal basis), transmission interface capacity between zones.
Integrated Resource Planning	5–10 years into future	Conduct scenario-based analysis optimization algorithms to develop a portfolio of generation and other resources to serve the projected load demand that meets the strategic objectives and planning criteria (e.g., diversity, sustainability) at least cost.	Generation resources (MWs, locations), transmission interfaces and capacities, system demand projections, policy mandates (renewable RPS, Clean Power Plan) and other projected costs (costs and performance characteristics of resource options).

[4] An example of a collaborative is the Institute for Sustainable Communities, which hosts a forum for collaboratives around the country (Institute for Sustainable Communities, Resilient Regions Initiative, http://www.iscvt.org/program/resilient-regions-initiative/; Accessed April 2016).

Activity	Timeframe	Description of Planning Activity	Non-Climate Data Requirements
Load Forecasting[5]	1–10 years into future	Develop scenario-based projections of future demand levels based on historic demand, forecasted weather conditions, and economic indicators and other drivers, typically using a modeling platform such as regression analysis or bottom up methods.	Historic demand data collected from load serving entities, climate/weather correlation to system demand, forecast of economic indicators such as gross domestic product (GDP), population growth, industrial growth and employment opportunities.
Long-term Transmission Planning	1–10 years into future	Conduct power flow assessment (steady state, N-1 and N-1-1), and production cost modeling studies to identify reliability and congestion issues. Identify and develop appropriate mitigation solutions that resolve the violations and improve market efficiency.	Transmission system topology, contingency criteria (N-1 and N-1-1), load demand at individual nodes, generation resources (MWs, locations, and interconnection to bulk grid), emergency operating procedures, unit commitment and dispatch rules.

Climate change considerations can be integrated into these institutionalized planning and decision-making processes. The results of an assessment of the climate resilience challenges and opportunities for an asset owner may be important as a stand-alone product. However, an assessment (or parts of an exposure, vulnerability, cost, or climate resilience measure analysis) may also be informative to specific decisions an asset owner makes as part of its normal business practices. The level of detail in information used to assess the resilience challenges and opportunities for electric utilities should be aligned with the decision requirements to help ensure efficient use of resources.

The data and analysis techniques available to inform an assessment span a spectrum (see Figure 4). At one end, there is information that can inform a rapid, screening-level assessment drawing on public data, expert opinion, and limited modeling. For example, if a utility aims to mainstream SLR considerations into resource adequacy planning, rapid screening of assets potentially exposed to increases in nuisance flooding or permanent inundation due to SLR can be used to inform assessment of potential for increases in generating unit forced outage rates and resulting impacts on reliability and planning reserve margins. Results from high-resolution coastal process modeling that include erosion and barrier island dynamics may be unnecessary to inform these planning decisions in areas along the Atlantic Coast of the United States. For detailed analyses, such as those needed to inform engineering design, high-resolution data (e.g., proprietary utility data) and extensive modeling will be needed. Figure 4 provides a simplified set of information requirements an asset owner can consider, depending on the type of assessment needed to meet its decision requirements.

[5] Load forecasting occurs over many timeframes, with 1–10 years being one example.

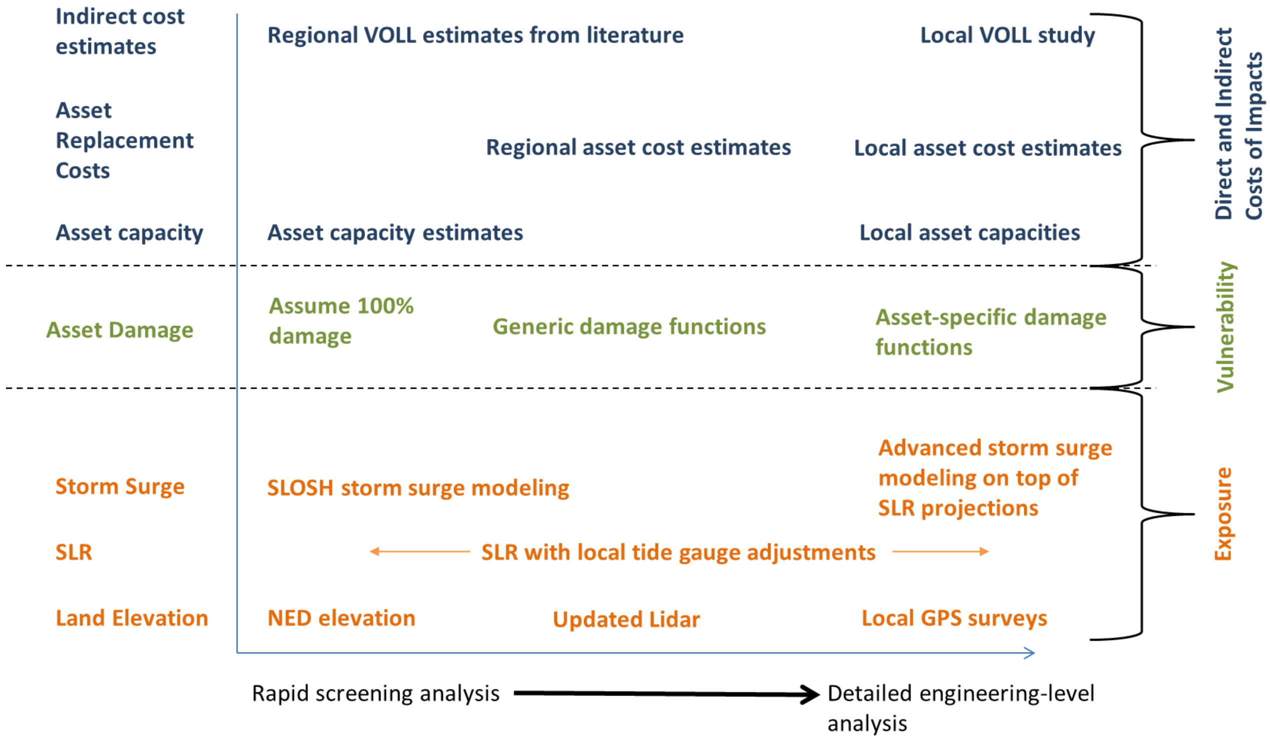


Figure 4. Examples of information needs for resilience assessment of different levels of detail. The vertical axis includes information categories necessary for key aspects of a climate resilience assessment: the exposure (orange), vulnerability (green), and costs of impacts (blue). Information examples increase in detail from left to right. VOLL is value of lost load and NED is national elevational dataset.

Key Considerations for Scoping the Decision Context and Information Requirements

At the outset of an assessment, engage relevant stakeholder groups to help inform desired assessment outcomes. Seek collaborative relationships with external entities that can help translate and co-develop climate information needed for decision-making.

Identify opportunities to integrate results of climate resilience analysis into business practices and align the level of detail in climate information with the level of detail necessary to take action; identify the necessary amount of information needed to adequately inform the action.

3 Understand the Exposure of Electricity Assets to Sea Level Rise and Storm Surge Hazards

Sea level rise can lead to permanent inundation and short-term nuisance flooding (i.e., flooding that occurs periodically due to high tides, for example, and causes a public inconvenience). Information about potential future global SLR (often presented through scenarios), which takes into consideration local conditions that can affect how SLR manifests locally, can help utilities understand the potential exposure of electricity assets to these hazards. In addition, information on storm surge associated with extreme storms, including the potential for more intense or frequent storms and the amplification of storm surge due to SLR, is important for understanding exposure in a changing climate. This section provides background on these hazards and guidance for understanding sources of information that can be utilized in an assessment.

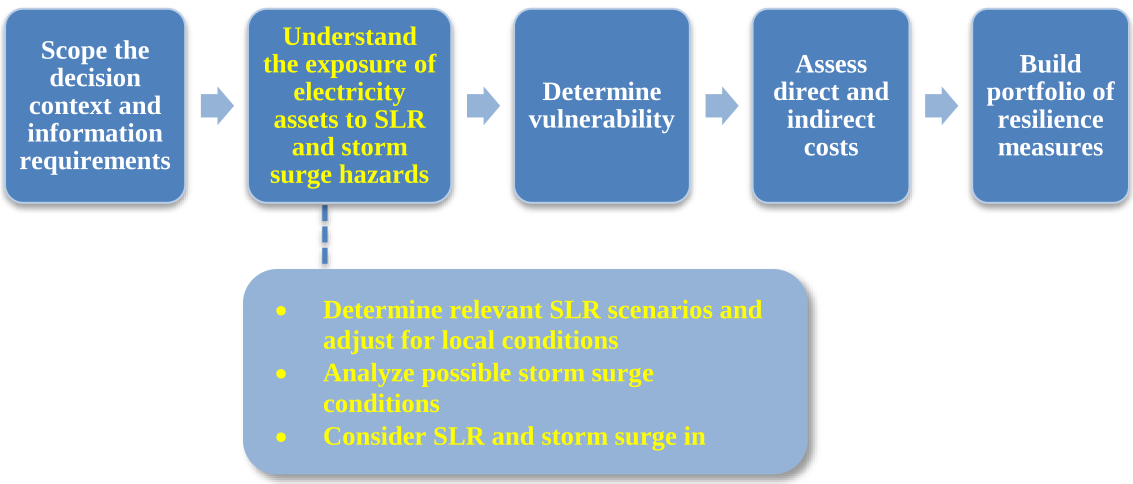


Figure 5. An overview of the approach to quantifying the threat from SLR and storm surge to electricity assets.

3.1 Understand Exposure to Sea Level Rise Hazards

Many coastal locations are currently affected by nuisance flooding. Nuisance flooding—coastal flooding that occurs during tidal conditions not associated with coastal storms or heavy rainfall—can cause road closures, overwhelm storm drains, and deteriorate infrastructure (NOAA 2014c). Gradual local SLR, particularly if combined with the loss of natural coastal barriers, may increase the frequency and/or the affected area for nuisance or continuous flooding, introducing new and potentially significant risks to electricity service and assets (NOAA 2014c). In some locations, "king tides" (the highest predicted high tide of the year at a coastal location) may provide a preview of conditions that will occur more frequently in the future.[6]

[6] USEPA, King Tides and Climate Change, http://www.epa.gov/cre/king-tides-and-climate-change. Accessed April 2016.

Since the 1960s, this form of flooding has increased along all U.S. coastlines from 300 to 925 percent, with rapid acceleration occurring along the East and Gulf coasts (NOAA 2014a; NOAA 2014c; see Figure 6). For example, nuisance flooding occurs regularly during high tide in Charleston, South Carolina, and Olympia in South Puget Sound (USGCRP 2014). The National Oceanic and Atmospheric Administration (NOAA) provides a website to view maps of local coastal nuisance flooding.[7]

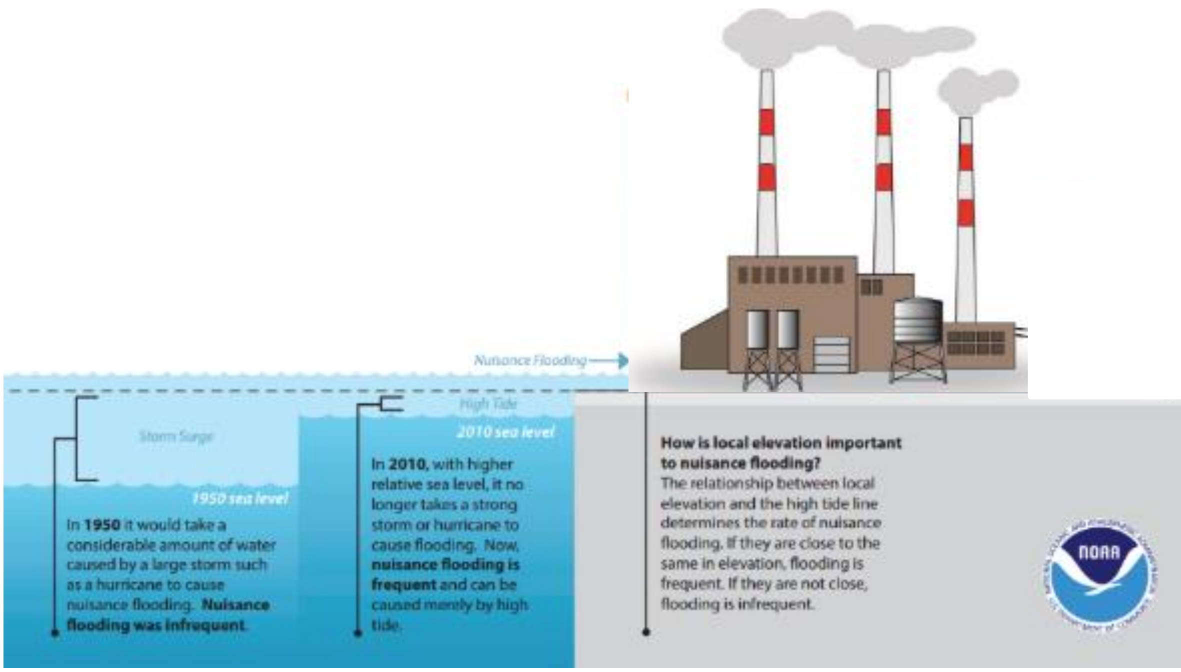


Figure 6. Nuisance flood events are significantly increasing around the United States (adapted from NOAA 2015).

Figure 7 illustrates how a long-term future increase in global sea level (due to factors such as ocean warming and melting land ice) may amplify the impacts of short-term variability due to storms and their wave run-up, tides, and phenomena such as the El Niño–Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). Thus, SLR will exacerbate the occurrence of nuisance flooding as well as the highly destructive flooding associated with the surge from major coastal storms. Another way that climate change may increase the frequency and magnitude of flooding from major storms is through a tendency for the strongest storms to have higher maximum wind speeds, which can lead to higher surges (USGCRP 2014). Thus, even in the absence of SLR, the frequency and intensity of the strongest storms may increase as a result of climate change. As discussed in the next section, estimates of future conditions suggest that certain areas in the United States may experience both an increase in sea level and an increase in the maximum wind speed from major coastal storms.

[7] Digital Coast Office for Coastal Management, Sea Level Rise Viewer, http://coast.noaa.gov/digitalcoast/tools/slr. Accessed April 2016.

The types of storms that may affect coastal energy assets through storm surge include hurricanes, tropical storms, and nor'easters.[8] There are many local factors, such as the slope of the coastline, which can affect the degree of surge. In some coastal locations, the topography can serve to funnel storm surge and thereby magnify it locally. During a hurricane, the storm surge can be the costliest hazard to life and property along the coastline (NOAA 2014b), in comparison to direct wind damage and other factors. When Superstorm Sandy inundated the New York Harbor with about 14 feet (4.27 meters) of water above the average high tide, it crippled the energy sector, leaving more than 8 million customers without power in 20 affected states and the District of Columbia (DOE 2013c).

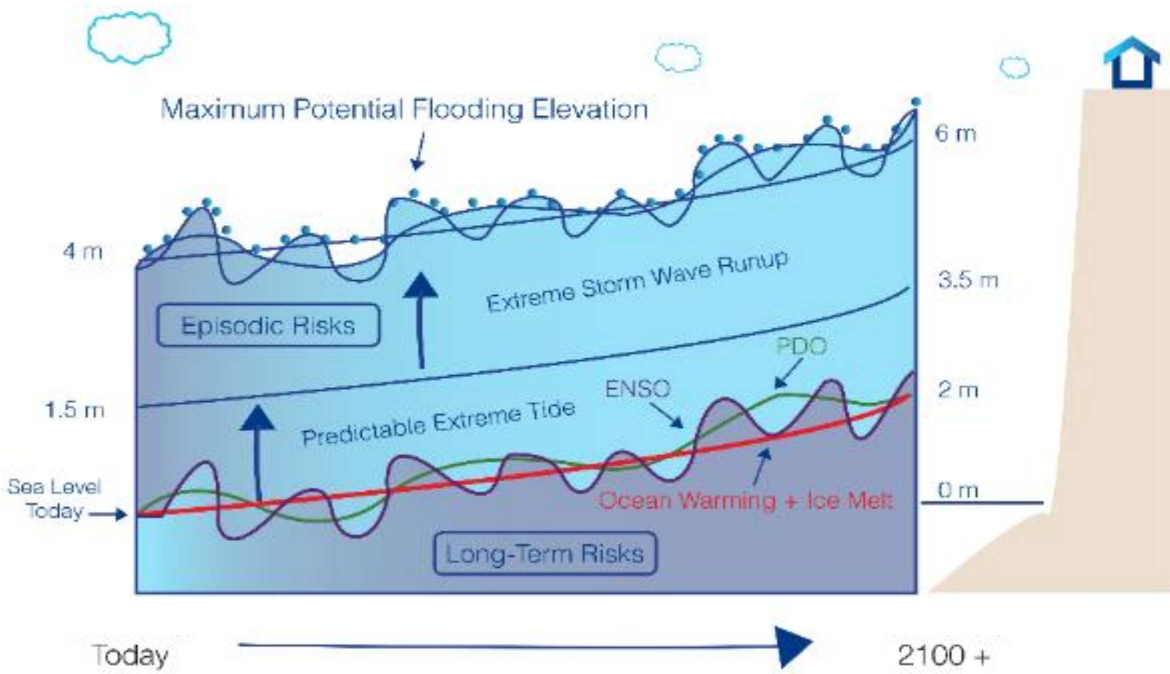


Figure 7. Inundation of coastal energy assets can occur from combinations of SLR, climate variability, tides, and wave run-up. ENSO refers to the El Niño Southern Oscillation and PDO refers to the Pacific Decadal Oscillation, both of which affect sea levels on different time scales (adapted from Grifman et al. 2014).

Since the 1970s, shoreline erosion associated with SLR and storm surge has been particularly problematic for half of the coastal area in Mississippi and Texas and 90 percent of the coastal area in Louisiana (USEPA 2009).[9] Barrier islands can make a big difference in protecting the coastline against coastal flooding by acting as a "natural" seawall and absorbing a large amount of wave energy. Presence of coastal wetlands, coastal forests, coral reefs, and sand dunes also play a critical role in protecting coastal infrastructure against SLR and storm surge. Identifying local natural protection and discussing potential changes in the landscape with coastal

[8] These storms may also impact energy assets through inland flooding, high winds, and lightning, but since the focus of this analysis is on impacts due to SLR and storm surge, they are not discussed here.

[9] The shoreline erosion in Louisiana is also affected by human alterations and loss of sediment supply (USEPA 2009).

stakeholders and planners will help identify if and how exposure to coastal flooding may change in the near future. Quantitative analyses of these important features may be required for detailed analysis.[10]

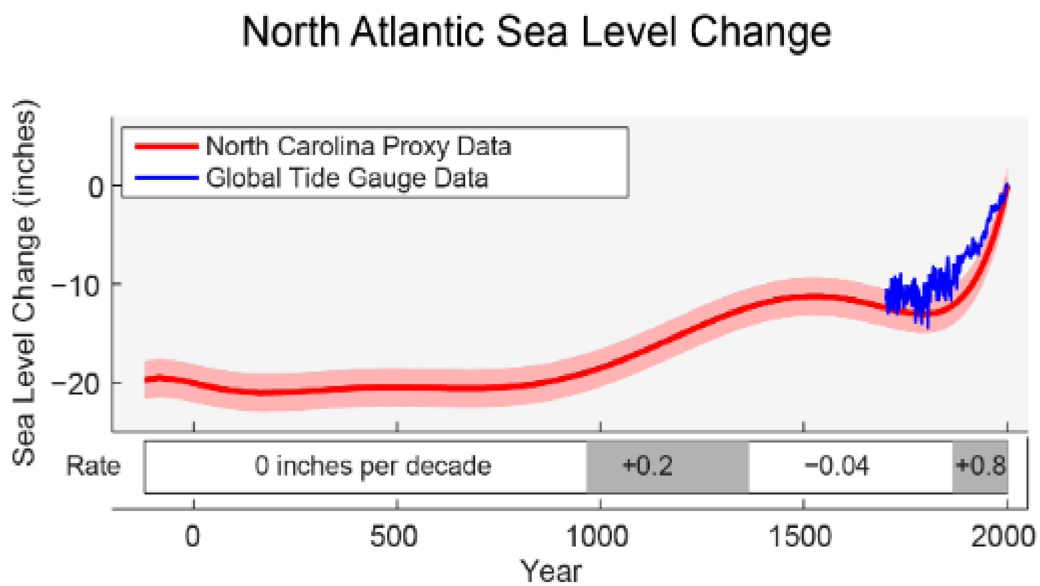


Figure 8. Sea level change in the North Atlantic Ocean relative to the year 2000 based on data collected from North Carolina (red line, pink band shows the uncertainty range) compared with a reconstruction of global SLR based on tide gauge data from 1750 to present (blue line) (Melillo et al. 2014, from NASA Jet Propulsion Laboratory).

During the 20th century, global sea level rose at a rate of approximately 0.8 inches/decade (USGCRP 2014; see Figure 8). Since the early 1990s, sea level has risen at a rate of about 0.12 inches/year (IPCC 2013). This has been attributed to higher temperatures that cause sea level to rise due to both thermal expansion of water (i.e., sea water expands as it warms) and an increased volume of ocean water from melting mountain glaciers, ice caps, snow cover, and ice sheets (IPCC 2013).

Projections of future sea level suggest a continued and even accelerated rise over the coming century for much of the United States. However, there is significant uncertainty associated with estimating changes in sea level both globally and locally (IPCC 2013). Sources of uncertainty regarding future sea level include:

- *Global uncertainty*: The choices that society makes and the development of technology will dictate greenhouse gas emissions (e.g., carbon dioxide) and other factors that drive global climate change. There is uncertainty associated with how much warming will occur with a particular increase in atmospheric greenhouse gas levels and how that warming will affect global sea levels, especially later this century. Current estimates of

[10] See Coastal Protection and Restoration Authority (http://www.coastalmasterplan.louisiana.gov/) for examples. Accessed April 2016.

global average SLR by 2100 are between roughly 1 and 6 feet (0.2 meters to 2.0 meters) (USGCRP 2014; see Figure 9).[11]

- *Local uncertainty*: Differences between global versus local SLR are often due to vertical uplift or subsidence along the coastline. Erosion and deposition of sediment, as well as changes in wind patterns and ocean circulation (i.e., currents, like the Gulf Stream) can also affect local sea level. Relative SLR refers to the change experienced in a location due to changes in sea level and vertical land movement. The relative SLR in a location that is experiencing subsidence, like coastal Louisiana, the California coast south of Cape Mendocino (NRC 2012), and Virginia, will be greater than the local SLR alone. The cumulative local effect of all of these factors is not generally well quantified for future timeframes. However, a number of studies for various locations around the United States have considered these factors and should be at least qualitatively considered for analyses where they are relevant (e.g., DOE 2014b).

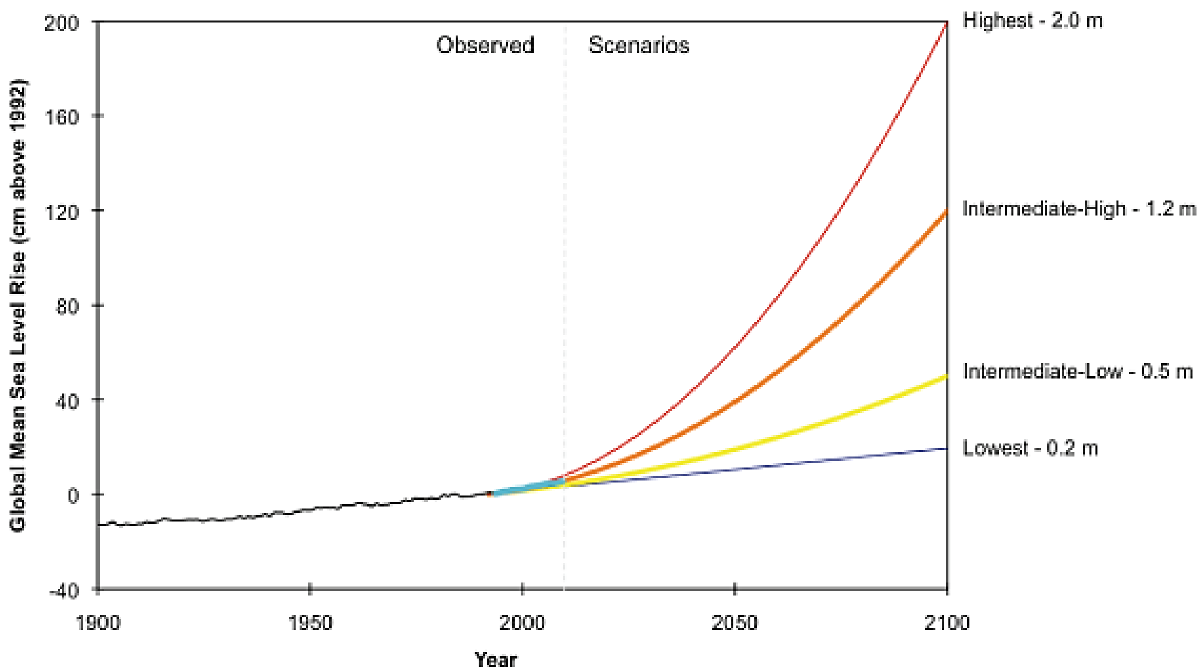


Figure 9. Global mean SLR scenarios (Parris et al. 2012).

Under most scenarios, the rate of global SLR is not projected to be constant over the coming century (see Figure 9). A NOAA technical report in support of the third National Climate Assessment (Parris et al. 2012) identifies a set of global SLR scenarios for a number of plausible futures. The high scenario estimates more than 6 feet (1.83 meters) of global SLR by the end of century. The intermediate-high is an average of the high end of ranges of several semi-empirical published methodologies that have been used to project global SLR. The intermediate-low is based on the projection of SLR from the IPCC Fourth Assessment Report at the 95 percent confidence interval. The lowest is simply an extrapolation of the current trend in SLR and is

[11] Compared to the year 2000.

generally considered to be an unlikely future, since global greenhouse gas concentrations continue to increase. None of these scenarios should be used in isolation and the report does not assign probability to any of the individual scenarios (Parris et al. 2012).

The choice of the global SLR scenarios to use in utility-level planning should be driven, in part, by how risk averse planners are for a particular decision (Hinkel et al. 2015). Risk-averse decision-making that involves long-lived infrastructure (e.g., power plants) may consider the impacts associated with the "highest" scenario (representing the current worst plausible case). If the performance life of the investment is only a few years to a decade, a change in average sea level may not be significant enough to impact resilience. In such cases, a careful examination of historical and current exposure of that location to flooding may be more important than the selection of a particular set of future scenarios that extend over decades. If the analysis is to inform general planning, then considering the minimum and maximum range over time will provide some sense of plausible futures. For very high-level decisions, a generalized trend based on the scenarios may be enough (e.g., coastal flooding is projected to increase). Except for analysis and decisions based on near-term conditions, it is strongly recommended not to rely solely on one scenario.

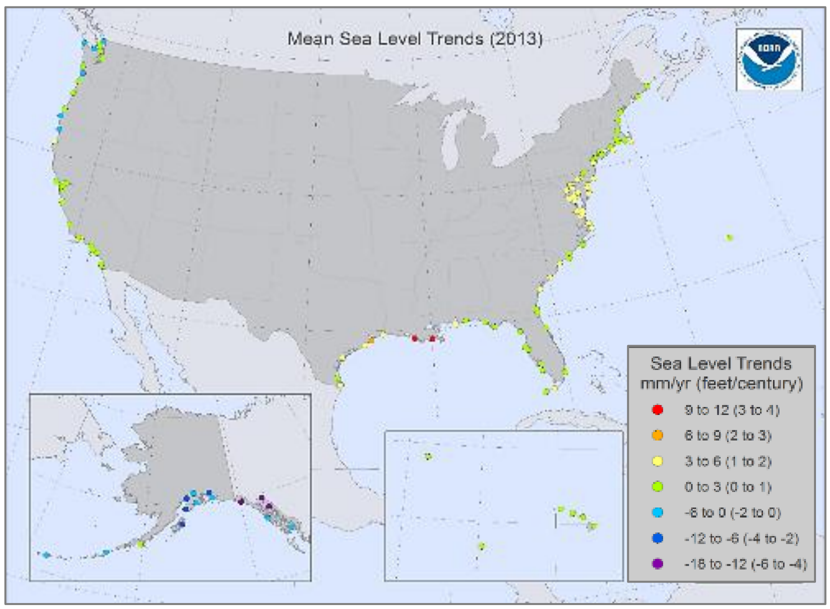


Figure 10. Sea level trends for the United States (NOAA 2013).

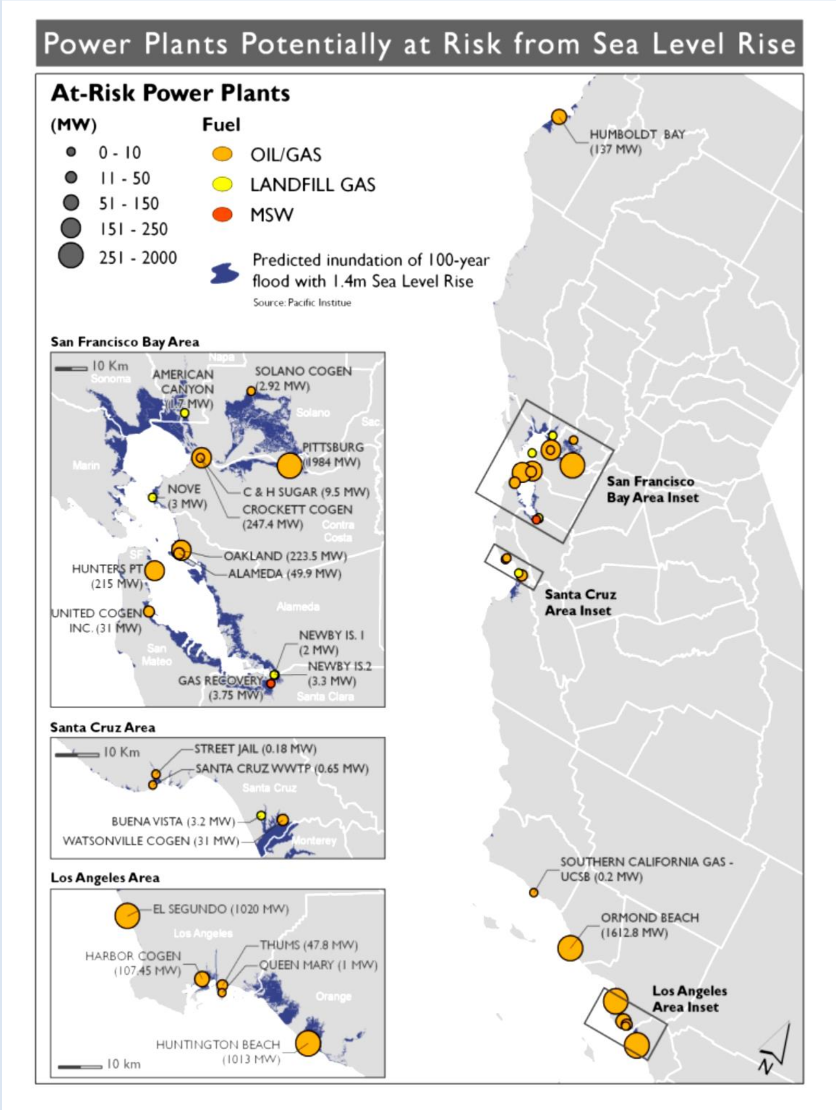
Within the United States and as shown in Figure 10, direct measurements of relative sea levels indicate average rates of increase from 1 to 2 feet per century along most of the Atlantic and Gulf coasts, and 3 to 4 feet per century along the Louisiana coast (the faster pace being due to relatively rapid land subsidence). Relative sea level is falling (due to land uplift) at the rate of a few inches per decade in parts of Alaska.[12] Sea levels are rising along most of the California coast and falling slightly at some sites further north, along the coasts of Oregon and Washington State (NOAA 2013).

[12] These trends are developed using data of at least 30 years collected at tide gage stations of the National Water Level Observation Network.

Sea Level Rise along the West Coast

The variation in SLR along the coasts of California, Oregon, and Washington depends on the global mean sea level rise and regional factors, such as ocean and atmospheric circulation patterns in the northern Pacific Ocean, the gravitational and deformational effects of land ice mass changes, and tectonics along the coast. The magnitude of projected SLR during this century could pose an increasing threat to energy infrastructure on the coast, including power plants, transmission and distribution lines. See power plants potentially at risk to a 100-year flood with a 1.4-meter SLR in the figure below (source: Sathaye et. al 2012, citing the Pacific Institute).

Infrastructure damage along the west coast is largely caused by storms—particularly the confluence of large waves, storm surges, and high tides during a strong El Niño. These events can produce water levels that exceed mean sea levels projected for 2100, and highlight the need to understand the potential effects of SLR in combination with extreme storms on infrastructure exposure and vulnerabilities (NRC 2012).



A comparison of local SLR against global average SLR over the same time period can indicate whether the local change is greater than, similar to, or less than the global rise. This information is critical when considering future local SLR (e.g., will it occur at a faster or slower rate than the global projections).

NOAA's Tides and Current website[13] provides data for local tide gage locations that may be useful in understanding how sea level has changed in a particular location. This site provides access to tide gage data that can be downloaded or viewed, including charts of local change in the mean sea level.

A relatively simple way to adjust the global scenarios of future SLR for local factors is to add the historical difference in SLR trend between the local tide gage and the observed global average to the global scenario (DOE 2014b). For example, if a global scenario indicates an increase of 10 inches by 2050 (relative to 2000) and the local gage data indicate a trend of 0.12 inches/year over the 20th century (compared to a global 20th-century average of 0.08 inches/year), a reasonable local estimate for 2050 for that scenario and location would be a 12.0 inch increase, relative to 2000.[14] There are a number of methodologies available for this translation, including the USACE SLR calculator (see Figure 11).[15] This approach assumes no changes in ocean circulation, wind patterns, erosion, and any other local factors that affected local sea level in the past. Some of those other factors may be accounted for through considerably complex calculations, which may be desirable to undertake, particularly for long-lived, expensive infrastructure decisions.

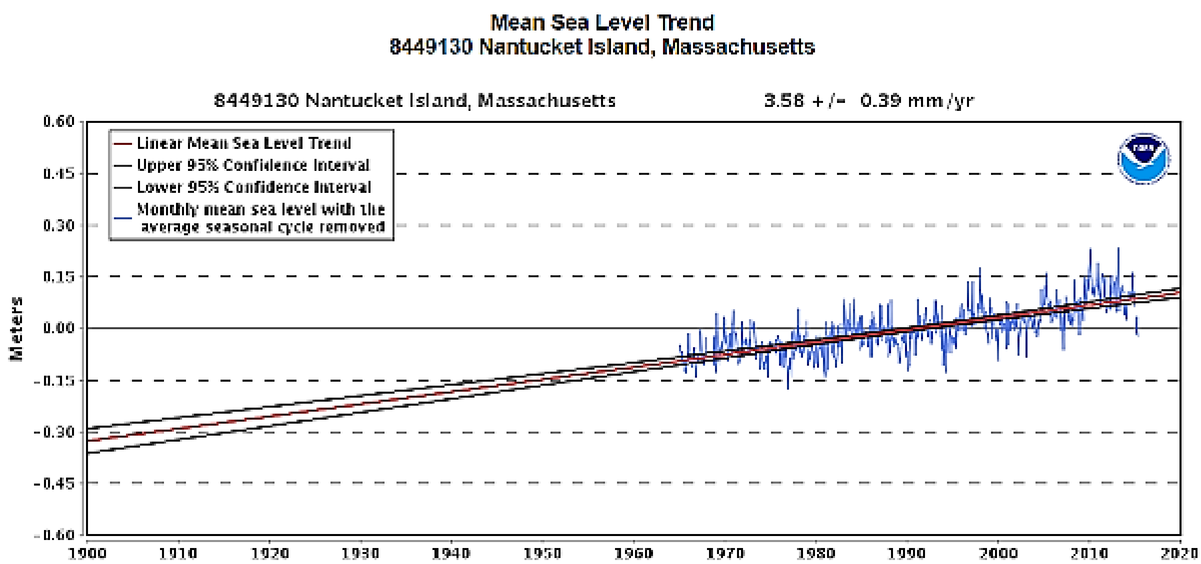


Figure 11. Example of mean sea level trend for a tide station provided by NOAA Tides and Currents website.

[13] NOAA, Tides and Currents, http://tidesandcurrents.noaa.gov/sltrends/sltrends.html. Accessed April 2016.
[14] This is calculated as: 10" + [(0.12"/year – 0.08"/year) x 50 years].
[15] Responses to Climate Change Program, Climate Change Adaptation: Comprehensive Evaluation of Projects with Respect to Sea-Level Change, http://www.corpsclimate.us/ccaceslcurves.cfm. Accessed April 2016.

Once the local height of inundation is estimated, NOAA's SLR viewer[16] can be used to get a sense of the area that will be inundated at that level (see Figure 12). It provides local inundation maps from 0 to 6 feet of SLR (at 1-foot increments) for much of the U.S. coastline. This can be an effective and fast tool to consider what infrastructure may be inundated at a future time due to local SLR. These NOAA data are included in an online DOE resource that provides information on the exposure of large energy assets to SLR projections based on locally adjusted NCA scenarios for nine metropolitan statistical areas around the country (see box in Section 3.3 for additional details).[17]

Some of the initial manifestations of impacts of SLR on energy infrastructure may be through temporary, nuisance flooding during extreme high tides. Therefore, a next step in estimating exposure to marine flooding can be to overlay the full tidal range on top of the aforementioned SLR analysis.

Figure 12. The NOAA SLR viewer provides information on SLR of 0 to 6 feet for all parts of the U.S. coastline.

3.2 Understand Exposure to Storm Surge Hazards

Recent studies suggest that tropical cyclones (i.e., tropical storms and hurricanes) have tended to become stronger since the 1970s, although there is no clear trend in the change in frequency of these events (IPCC 2013). For the United States, an increase in intense tropical cyclones in the North Atlantic since the 1970s has been observed (USGCRP 2014). The frequency, intensity, and duration of hurricanes in the North Atlantic (including Category 4 and 5 hurricanes) have increased substantially since the early 1980s (USGCRP 2014). A challenge in developing clear

[16] NOAA, Sea Level Rise and Coastal Flooding Impacts v2.0, http://coast.noaa.gov/slr/. Accessed April 2016.
[17] DOE, Sea Level Rise and Storm Surge Effects on Energy Assets for Select Major Metropolitan Areas, http://energy-oe.maps.arcgis.com/apps/MapSeries/index.html?appid=244e96e24b5a47d28414b3c960198625. Accessed April 2016.

trends is the lack of confidence in tracking these storms prior to the 1970s and the advent of space-based satellite data.

While this is an area of active research and debate, the general consensus of scientists is that the intensity of the strongest tropical cyclones will increase over the coming century, although the frequency may not increase. In other words, the total number of hurricanes may not change but the hurricanes that do develop may be more intense (i.e., a greater number of higher category hurricanes) (Knutson et al. 2010; Ingram et al. 2013). Projected changes in the hurricane track (i.e., where they will strike) is an active area of research (e.g., Emanuel 2013; Jagger et al. 2001; Murnane et al. 2000). Information about historical hurricane tracks can be an important starting point for understanding the potential for future hurricane impacts, especially on shorter time scales (e.g., the next ten years).

There are a number of websites that provide information on past storm events, including:

- Local Office of the National Weather Service website
- FEMA Disaster Declarations website[18]
- NOAA Storm Event Database[19]
- NOAA Historical Hurricane Tracks[20]

While historic information can provide insights into past events (see Figure 13) that have affected specific locations, uncertainties associated with the potential for changes in the future should be recognized.

Storm surge does not necessarily increase with hurricane category. For example, a tropical storm may create a larger storm surge than a Category 2 hurricane. A number of factors come into play such as the angle of approach of the storm, conditions of the tide (e.g., high tide), the size of the storm, the speed of the storm, and damage caused to natural barriers during recent past storms. However, if storm surge from tropical cyclones or mid-latitude cyclones (such as a nor'easter in New England) have occurred in the past, it is important that future planning consider possible storm surge vulnerabilities.

[18] FEMA, Disaster Declarations, https://www.fema.gov/disasters. Accessed April 2016.
[19] NOAA, Storm Events Database, https://www.ncdc.noaa.gov/stormevents/. Accessed April 2016.
[20] NOAA, Historical Hurricane Tracks, http://coast.noaa.gov/hurricanes/. Accessed April 2016.

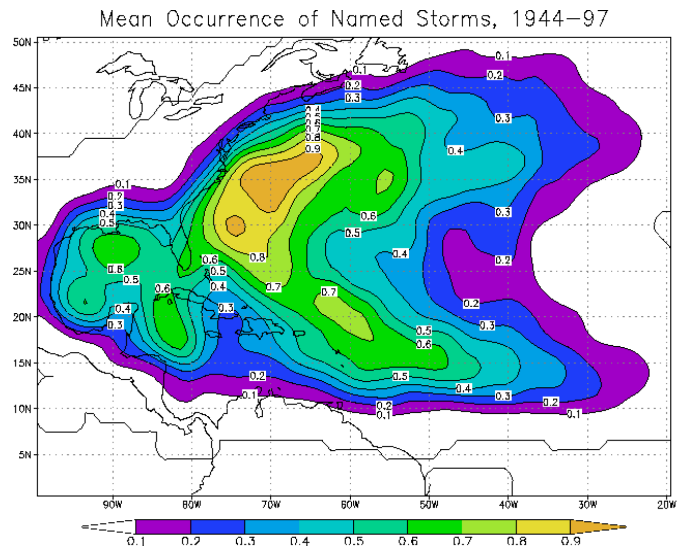


Figure 13. Mean occurrence of named tropical cyclones in the Atlantic Basin, based on counts of storms and hurricanes observed within about 100 miles between 1944 and 1997 (source: NOAA, Central Pacific Hurricane Center, Tropical Cyclone Climatology: http://www.prh.noaa.gov/cphc/pages/FAQ/Climatology.php).

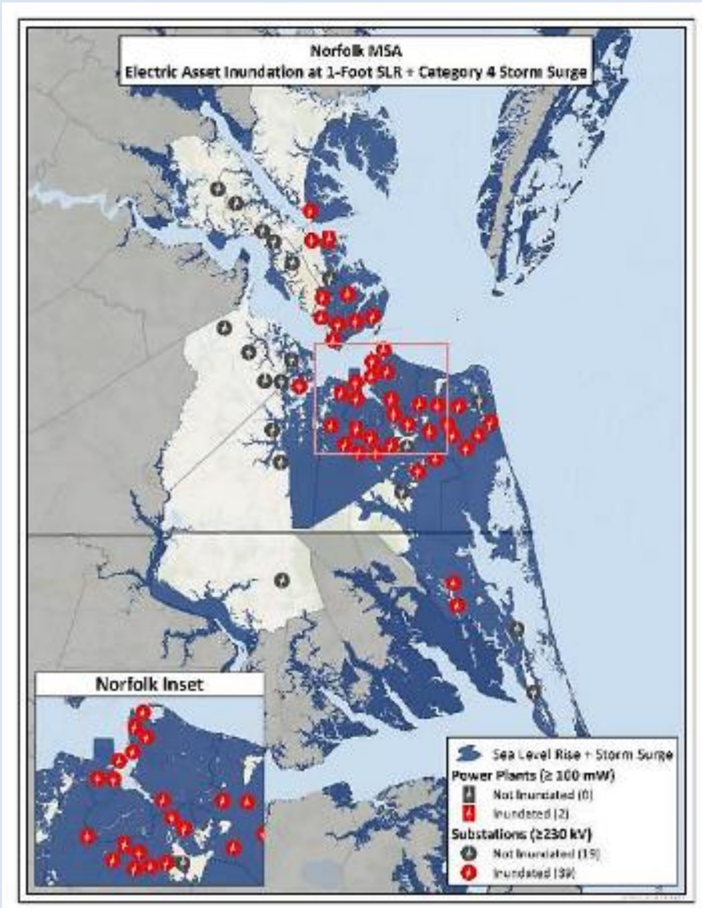
3.3 Consider Sea Level Rise and Storm Surge Hazards in Combination

There is a variety of methods available for combining storm surge and wave modeling with SLR scenarios. The appropriate method will depend on the available resources (e.g., time, expertise, and financing), the detail needed to inform the decision of interest, and the risk tolerance. For "screening" analysis designed to provide a basic understanding of potential exposure, models of SLR that determine flooding based on elevation without accounting for dynamic processes (sometimes termed a "bathtub" approach), can be combined with storm surge levels. For example, to determine the electricity assets that may be exposed to inundation in the mid-Atlantic coastal region, one available approach adds storm surge modeled inundations as developed by NOAA's National Weather Service using the Sea, Lake and Overland Surges from Hurricanes (SLOSH) model[21] on top of projected sea levels (e.g., Maloney and Preston 2014). For decisions that require greater spatial accuracy, such as engineering design of a new power generation facility, modeling approaches that consider the dynamics of the coastal environment that influence water levels can provide higher resolution and accuracy. A variety of models exist to characterize the dynamic processes of storm surge and waves and wave run-up in the coastal environment, including the ADvanced CIRCulation (ADCIRC) model,[22] SWAN,[23] WAVEWATCH III,[24] and the Coastal Modeling System,[25] among others.

[21] NOAA, National Hurricane Center. Sea, Lake, and Overland Surges from Hurricanes (SLOSH), http://www.nhc.noaa.gov/surge/slosh.php. Accessed April 2016.
[22] ADCIRC, http://adcirc.org/. Accessed April 2016.
[23] DELFT University of Technology, SWAN, http://www.swan.tudelft.nl/. Accessed April 2016.
[24] NOAA, Storm Surge and Coastal Inundation, http://www.stormsurge.noaa.gov/models_obs_modeling.html. Accessed April 2016.
[25] USACE, Coastal Modeling System, http://www.erdc.usace.army.mil/Media/FactSheets/FactSheetArticleView/tabid/9254/Article/484188/coastal-modeling-system.aspx. Accessed April 2016.

Identification of Energy Assets Exposed to SLR and Storm Surge Threats using GIS

The U.S. Department of Energy Office of Electricity Delivery and Energy Reliability (OE) undertook work to assess the potential exposure of energy facilities in nine metropolitan statistical areas (MSA) to a general rise in sea level and from storm surge at these higher sea levels. The analysis focuses on the risk in 2050 and 2100.



In the Norfolk MSA, the analysis includes more than 180 energy assets comprising electricity assets (including power plants and substations), natural gas assets (including a liquefied natural gas [LNG] storage facility and pipelines), and petroleum assets (including terminals, a refinery, and a pipeline).

The method used GIS overlay of asset locations with geographic information on inundation due to SLR and storm surge. The method uses the approach from the pilot study for estimating SLR impacts (DOE 2014b) and adapts the approach developed by Oak Ridge National Laboratory (Maloney and Preston 2014) that adds storm surge modeled inundations as developed by NOAA's National Weather Service using the Sea, Lake and Overland Surges from Hurricanes (SLOSH) model (http://www.nhc.noaa.gov/surge/slosh.php; accessed April 2016).

The Norfolk MSA has many large assets clustered near the coast and a 1-foot SLR (by 2050 under an intermediate-high scenario) in conjunction with a storm surge associated with a Category 4 storm would inundate large and critical electricity assets including 39 substations (>230 kV) and two power plants (>100 MW), as well as many other natural gas and petroleum assets (see figure).

The results for all nine MSAs (Norfolk, Los Angeles, Houston, Boston, Baltimore, Mobile, New York, Philadelphia, and Miami) are available through an interactive web tool: http://energy-oe.maps.arcgis.com/apps/MapSeries/index.html?appid=244e96e24b5a47d28414b3c960198625 (accessed April 2016).

In any analysis that combines storm surge and/or wave modeling with projections of future SLR, it is important to be aware of the influence of the manner in which these different components are combined. Storm surge and water levels (including changing water levels due to SLR) may interact in non-linear ways, especially in shallow water where the bottom friction and storm surge momentum respond non-linearly to changes in shoreline configuration and changes in bottom cover as depth changes (Zhang et al. 2013). The addition of modeled storm surge water levels on top of SLR projected levels can provide adequate estimates of total water levels for certain decisions. However, for decisions that require greater accuracy and have a lower risk tolerance, such as large capital expenditures, storm surge simulations should directly account for the changes in SLR, with wave models incorporating the results.

Key Considerations for Understanding the Exposure of Electricity Assets to Sea Level Rise and Storm Surge Hazards

Identify areas where nuisance flooding is already problematic and consider the implications associated with an increase in exposure to flooding.

Consider any changes in the natural environment due to coastal erosion and barrier island migration that might affect exposure to SLR and storm surge. Obtain locally specific information about these potential changes from coastal scientists.

Select the global SLR scenarios most appropriate for the analysis and decision-making context, including the aversion to risk and time horizon.

Use nearby tide gage stations to identify how local sea level has changed relative to global sea level. Use this information to generate a rough estimate of the local correction that should be applied to the global scenarios to determine the amount and timing of local SLR for a given scenario. The inherent uncertainty in estimating future global SLR should not preclude action.

Identify past storms that had damaging coastal flooding associated with storm surge and the infrastructure that was exposed; future planning should determine whether storm surge is an issue or could become one within the planning timeline, as storm events are projected to increase in intensity for many regions.

4 Determine Vulnerability and Costs from Sea Level Rise and Storm Surge

After gathering information and completing analyses to understand the threat from SLR and storm surge as it relates to the decision context, utilities should determine the associated vulnerability and costs.

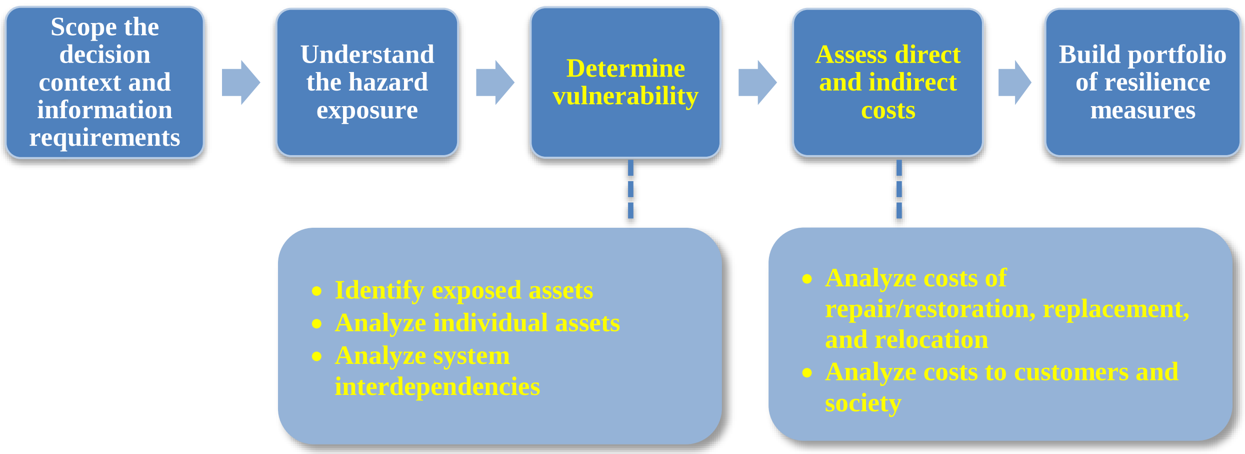


Figure 14. Key steps of methodology for determining vulnerability and costs from SLR and storm surge.

Vulnerability is defined in this methodology as the susceptibility of an asset to lose functionality or availability due to a threat, which may be due to sensitivity to damage or the lack of ability to recover quickly. Analyzing the vulnerability of the electricity system assets provides insight into damage that can occur from different levels of threat. It also sheds light on the specific types of vulnerability that could be addressed through resilience measures.

Impacts caused by the exposure of vulnerable assets to SLR and storm surge can incur a variety of costs that utilities will need to consider. Direct costs resulting from damages due to SLR and storm surge include:

- Cost of repair or restoration
- Cost of replacement
- Cost of relocation

Utilities face uncertainty as to whether these types of direct costs will be recoverable after an event due to a number of factors. There may be prohibitions against "single issue" ratemaking, as opposed to a periodic general rate case. If cost recovery is considered, regulators may consider whether costs were prudently incurred, deferral of storm related costs and, if allowed, recovery of carrying costs, among other issues.

Indirect costs include:

- Cost to customers from loss of service
- Broader societal costs (e.g., lost economic productivity, job loss) from loss of service
- Cost of damages to interlinking infrastructures (e.g., oil and gas infrastructure connected to electric power sector)[26]

The direct and indirect costs associated with the impacts to vulnerable assets serve as a primary metric for understanding the asset value at risk, and they inform analyses of the costs and benefits of resilience measures, which will be explored in subsequent sections.

4.1 Determine Vulnerability of Potentially Exposed Electricity Assets and the Power System

Electricity sector vulnerability can be characterized as a function of the sensitivity and recoverability[27] of an asset and the power system to climate change stressors to which they are exposed (e.g., SLR and storm surge hazards, including nuisance flooding, gradual permanent inundation, and short-term flooding from extreme weather events). Sensitivity refers to the type and degree of impacts that an electric power asset would experience when exposed to these hazards, including the threshold at which the impacts are observed. Different assets and the components within them (e.g., transformers and control cabinets within a substation) may have different sensitivities to SLR and storm surge hazards. In addition, the power system may be more or less sensitive to inundation and flooding hazards, depending on the system configuration and interdependency. Electric sector vulnerability is also a function of recoverability—how quickly an asset can be replaced or restored and able to deliver reliable electricity supply. An asset whose functionality is difficult to recover is more vulnerable than one where function can be quickly restored or replaced (through repair, replacement, or system redundancy).

The electricity industry is in the midst of significant changes, which are affecting investments in assets and systems. When assessing vulnerabilities (and potential resilience solutions), asset owners should consider possible changes in deployed assets and systems.

4.1.1 Identify Exposed Assets

Utilities should narrow the scope of vulnerability assessments early by identifying coastal electricity assets that are likely to be affected by SLR and storm surge hazards. Geographic information systems (GIS) can be used to overlay electricity assets on potential storm surge and SLR threats (for example, see box below; Maloney and Preston 2014; DOE 2014b, Bradbury et al. 2015). In some instances, assets may appear to be outside of flood or inundation zones, but utilities should confirm that access points to assets are not blocked by potential flooding, as this would contribute to vulnerability (DOE 2014b). For example, if a substation position is outside of an area exposed to flooding, but the only road to access that substation crosses through a nearby flood zone, then access to the substation for repair or restoration during and following an

[26] Costs to other sectors will not be specifically addressed in this report.
[27] Recoverability is used here as an indicator of adaptive capacity relevant to the energy sector.

event, extending the time needed to address the substation impacts. The results of the geographic overlay analysis identify the assets that are potentially exposed.

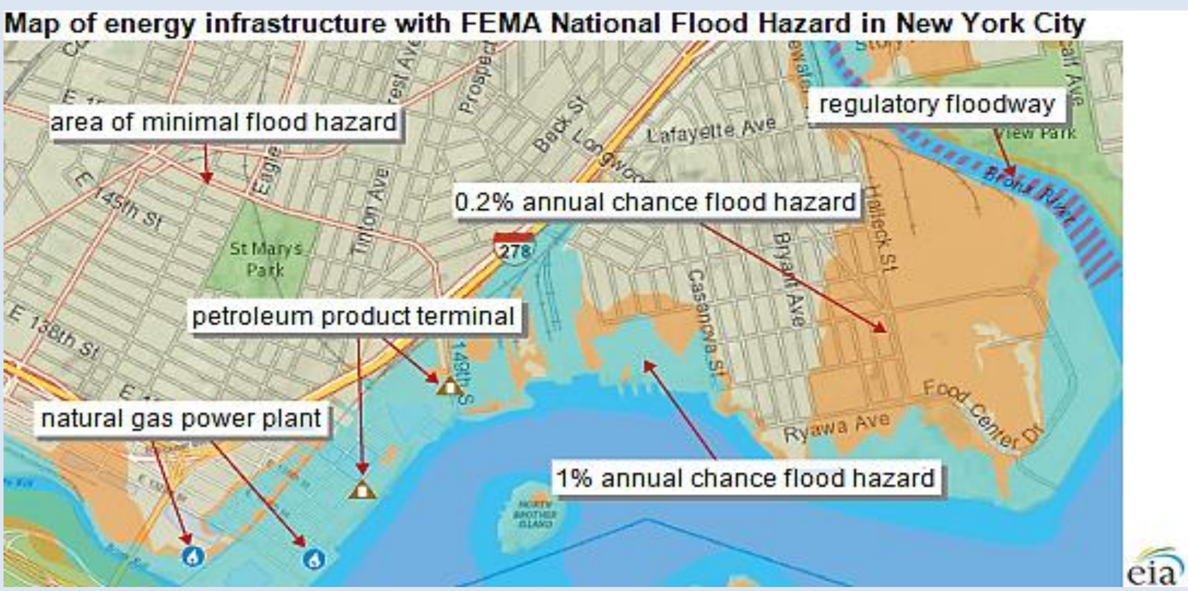
Asset owners and utility planning authorities will generally have the detailed information regarding asset location and characteristics, but this may be proprietary. Public sources, such as the Energy Information Administration (EIA) databases, can help to identify geospatial positions and characteristics of electricity assets.[28]

EIA Mapping Tool Shows Which U.S. Energy Facilities Are in Areas at Risk of Flooding

A new component of EIA's Energy Mapping System allows users to view critical energy infrastructure that may be vulnerable to coastal and inland flooding. These new map layers enable the public to see existing energy facilities that could potentially be affected by flooding caused by hurricanes, overflowing rivers, flash floods, and other wet-weather events.

The mapping tool combines flood hazard information from the Federal Emergency Management Agency (FEMA) with EIA's existing U.S. Energy Mapping System that shows power plants, oil refineries, crude oil rail terminals, and other critical energy infrastructure. The maps can help readers understand what energy infrastructure assets are exposed to current flood risk based on existing data. These maps do not include scenarios of potential future conditions of flooding hazards due to SLR or future energy asset configurations, which should be considered in a vulnerability assessment whenever possible.

The maps show areas that have a 1 percent and 0.2 percent annual chance of flooding (a 1-in-100 and 1-in-500 return period, respectively). The tool also contains regulatory floodways, levees, areas with levees (and therefore reduced flood risk), and areas with conditions that might be identified in the future as having a 1 percent annual flood hazard.



Source: EIA, “EIA mapping tool shows which U.S. energy facilities are in areas at risk of flooding,” (http://www.eia.gov/todayinenergy/detail.cfm?id=17431; accessed April 2016).

[28] USEIA, Maps, http://www.eia.gov/maps/. Accessed April 2016.

In addition, the Homeland Infrastructure Foundation-Level Data (HSIP) database is a unified infrastructure geospatial data inventory, including generation and transmission assets, developed by the Department of Homeland Security and National Geospatial-Intelligence Agency (NGA). HSIP is composed of two datasets, *HSIP Gold* and *HSIP Freedom*. *HSIP Freedom* is a subset of the *HSIP Gold* dataset that is license-free and distributable to public stakeholders.[29] Data from subscription sources can help to confirm the information obtained through the HISP database. SNL offers a subscription database[30] on power plant location, technology type, operating capacity, plant operator/owner information, operating status, upcoming projects and fuel data. Ventyx,[31] another subscription source, offers similar energy asset information and coverage. These examples and any other public or subscription information should be supplemented with utility-specific information to obtain an accurate assessment of the assets in the area of interest.

4.1.2 Analyze Individual Assets: Information on Sensitivity of Electricity Assets

Information on electricity asset sensitivity can be drawn from a variety of sources. In many cases, expert opinion can serve as a primary source of information regarding asset sensitivity. Design standards also provide key background for understanding sensitivity of many asset types. Utilities responsible for building a variety of electricity assets adhere to the National Electric Safety Code (NESC), Sections 24 (Grades of Construction), 25 (Loading Requirements), and 26 (Strength Requirements). This safety code is also used as an engineering design code when no other guidance exists. Often, a utility evaluates the various codes and standards that are applied during design and construction of its assets, evaluating any new equipment to ensure it meets or exceeds these standards. Most utilities have developed their own standards for their systems from the NESC baseline (NIST 2015). The baseline NESC standards and utility standards may provide information about the weather-related thresholds that certain assets are known to be able to withstand. However, standards may not address desired performance in the face of changing climate or weather conditions (e.g., if the frequency or duration of inundation increases) (NIST 2015).

For the older infrastructure elements of the energy system, the design criteria used for hazards varies greatly. In many cases, little to no consideration was given to the forces and loads imparted onto this infrastructure because the infrastructure pre-dated the modern codes, such as ASCE 7, that provide criteria to calculate and apply such loads (NIST 2015). Information about the age of electricity assets in the system is also an important input to understanding sensitivity (Panteli and Mancarella 2015; NIST 2015), although information on age of electricity assets is often limited, beyond central station generation assets.[32] In some cases, age of assets can be inferred based on analysis of electricity asset inventory over time (e.g., Harris Williams & Co. 2010).

Historical storm reports or post-event reports can provide useful information on vulnerability of assets to past flooding from storm surge associated with extreme storm events (e.g., DOE 2013c;

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[29] USDHS, Infrastructure Information Partnership, https://www.dhs.gov/infrastructure-information-partnerships. Accessed April 2016.
[30] SNL, S&P Global Market Intelligence, http://www.snl.com/. Accessed April 2016.
[31] ABB, Enterprise Software, http://new.abb.com/enterprise-software. Accessed April 2016.
[32] USEIA, Electricity, http://www.eia.gov/electricity/data/eia860/index.html. Accessed April 2016.

PSE&G 2013). These reports may provide general information on the types of assets that failed and under what conditions, lending insight into vulnerabilities.

Publicly available information rarely includes detailed information on specific assets and the exact threat intensity. For some types of assets, damage functions or fragility curves may be available, which describe the relationship between threat intensity or magnitude and asset damage or degree of impact, based on the sensitivity of the asset and its components (ICF 2015; Panteli and Mancarella 2015). The Hazus model[33] provides basic damage functions for key energy asset types generically, which can help in high-level assessments of vulnerability. In addition, insurers or catastrophic modeling companies may have proprietary information on fragility curves for energy assets.

Superstorm Sandy's Direct Impact on Electricity Assets

Public Service Electric & Gas (PSE&G) is New Jersey's largest regulated gas and electric utility, serving nearly 1.8 million gas customers and 2.2 million electric customers in more than 300 urban, suburban, and rural communities. In 2012, Hurricane Sandy caused an estimated nearly $295 million in damages to PSE&G's power system assets (PSE&G 2013). The storm is estimated to have affected power supply in nearly one-third of PSE&G's transmission circuits, half of its sub-transmission circuits, and three-quarters of its distribution circuits (PSE&G 2013). On the distribution network, nearly 2,400 utility poles had to be replaced due to storm damage. The associated storm surges also damaged PSE&G's coastal switching stations and substations.

Consolidated Edison Inc. (commonly referred to as Con Edison or ConEd) is a regulated utility that supplies electricity and gas to New York City and Westchester County in New York State. In 2012, Hurricane Sandy caused an unprecedented 1.15 million (approximate) customer outages across Con Edison's service territory (Con Edison 2014). The storm caused widespread damages at an estimated nearly 30,000 individual assets. Approximately 50 distribution substations, 2100 transformers, and 900 miles of distribution lines were damaged during the storm event (DOE 2013c).

These examples of impacts are meant to be illustrative of the types of impacts that could occur from intense storms in the future, but do not relate to a specific projection of future climate change–related impacts.

[33] FEMA, Hazus, http://www.fema.gov/hazus. Accessed April 2016.

Damage Functions and Fragility Curves: Use in Assessing Sensitivity

Damage and fragility information provides insight into the potential for damage given exposure to a range of hazards. This response information is developed via expert judgement, observations, empirical models, model-based analyses, and a combination of other approaches, and is generally asset and hazard specific. Damage and fragility curves are used to integrate information into impact models to assess economic loss or physical damage to assets given different magnitudes of hazard loads. Fragility curves provide a probability of an asset or a system being in a damaged state given a certain load, while damage function gives the magnitude of damage to an asset as a function of the given load (ICF 2015). For example, the Hazus model library provides generic flood depth-damage functions for generic electricity assets in the United States (see table below for an example). Hazus is designed to produce loss estimates by drawing on extensive national databases and locally developed inventories and other data about the local environment (FEMA Hazus-MH).

Electric Power Classifications, Functionality Thresholds and Damage Functions

Label	Earthquake Classification	Specific Occupancy	Functionality Threshold Depth	Percent Damage by depth of flooding in feet[2]											Comments
				0	1	2	3	4	5	6	7	8	9	10	
ESSL	ESS1, ESS2	Low Voltage Substation	4	0	2	4	6	7	8	9	10	12	14	15	Control room damaged starting at 0 feet, and maximized at 7' depth. Additional damage to cabling and incidental damage to transformers and switchgear.
ESSM	ESS3, ESS4	Medium Voltage Substation	4	0	2	4	6	7	8	9	10	12	14	15	
ESSH	ESS5, ESS6	High Voltage Substation	4	0	2	4	6	7	8	9	10	12	14	15	
EDC	EDC1, EDC2	Distribution Circuits Elevated Crossings	N/A	0	0	0	1	1	1	1	2	2	2	2	Low vulnerability due to flooding of ends of buried cables and possible barge traffic impacting transmission towers
EDC	EDC1, EDC2	Distribution Circuits Buried Crossings	N/A	0	0	0	0	0	0	0	0	0	0	0	No damage due to submergence.
EDC	EDC1, EDC2	Distribution Circuits (non-crossing)	N/A	0	0	0	0	0	0	0	0	0	0	0	No damage due to submergence.
EPPS	EPP1, EPP2	Small Power Plants	4	0	2.5	5	7.5	10	12.5	15	17.5	20	25	30	Support facilities damaged on ground level. Control and generation facilities damaged when water elevation reaches 2nd level.
EPPM	EPP3, EPP4	Medium Power Plants	4	0	2.5	5	7.5	10	12.5	15	17.5	20	25	30	
EPPL	EPP3, EPP4	Large Power Plants	4	0	2.5	5	7.5	10	12.5	15	17.5	20	25	30	

[2]*Assumes electrical switch gear is located 3-feet above grade.*

Damages are expressed in terms of physical damage or percent damage, which is typically translated into economic losses. Fragility curves are used to describe the range of probability of asset damage under a range of hazard loads. Some damage and fragility information includes "functionality states." For example, the Hazus Technical Manual gives functionality threshold depths for electricity infrastructure, expressing the depth of flooding that renders the asset no longer functional (FEMA Hazus-MH 2015).

Summary of Vulnerabilities for Electricity Assets

Asset vulnerabilities may be generalized for screening-level analyses, but utilities will need to consider specific design and site characteristics for individual assets when detailed analyses are required. General information on vulnerability for key categories of electricity assets is provided below. Appendix B provides more extensive information on specific examples of asset vulnerability.

Generation

Many of the fixed generating assets built in coastal areas at grade or sub-grade levels—to take advantage of access and cooling waters—may be exposed to SLR and storm surge. Many of the electrical, plumbing, and other critical equipment in buildings located at sub-grade levels can be flooded (FEMA 2013), including permanent inundation by gradual SLR. Saltwater from flooding associated with storm surge, increased nuisance flooding due to SLR, or permanent inundation can be especially damaging to components, due to the corrosive nature of saltwater. A recent DOE analysis (see Section 3.3 for details) determined that an intermediate-high SLR scenario in 2050 (approximately 1 foot locally) in combination with a Category 4 storm would affect the two large (>100MW) power plants in the Norfolk MSA, and 1 foot of local SLR in combination with a Category 4 storm would affect five of the 13 large (>100MW) power plants in the Boston MSA.[34] Flooding from storm surge events can also impede access to generation facilities, delaying restoration, and recovery.

Transmission

Transmission infrastructure is primarily made up of wires and towers that carry high voltage power from generators to distribution substations and transmission substations. Transmission assets may be damaged by direct impact from fallen trees and other debris that are generated during flood events (see Figure 15). Flooding associated with storm surge during extreme events, such as hurricanes, can cause erosion of pole foundations on the sides of hills, which exposes underground cabling to the movement of water (NIST 2015).

[34] DOE, Sea Level Rise and Storm Surge Effects on Energy Assets for Select Major Metropolitan Areas, http://energy-oe.maps.arcgis.com/apps/MapSeries/index.html?appid=244e96e24b5a47d28414b3c960198625. Accessed April 2016.

Figure 15. Failure of transmission line lattice tower on the Neches River (Ocean Springs to Moss Point) near Bridge City, Texas, following Hurricane Rita. Credit: NIST 2006.

Distribution

The distribution system is the largest part of an electricity system and is necessary for delivering power to most customers. The distribution system includes wires and poles that carry power from distribution substations to customers. Like transmission infrastructure, poles and wires may be damaged during flooding events by erosion of pole foundations or storm-associated debris (NIST 2015) as shown in Figure 16. Distribution systems are typically built and constructed along roadsides but, in some cases run through less accessible back lots and other rights-of-way (NIST 2015), making them more difficult to repair quickly. In addition, many distribution wires are underground. This undergrounding can be sensitive to inundation or flooding in extreme events if not adequately protected. Underground wires may also be vulnerable to damage due to saltwater intrusion associated with SLR.

Figure 16. Damage to coastal distribution assets from storm surge flooding. Credit: Pepco Holdings, 2013.

In terms of recoverability, overhead distribution infrastructure may have more widespread failures during an event, but often will take just days to a week or two to recover. However, because of the difficulty in accessing underground sites, widespread below-ground failures may result in several weeks of recovery time to restore full functionality of the system (NIST 2015) making these assets highly vulnerable. Undergrounding does provide benefit to resilience to other hazards (e.g., wind, ice).

Substations

Substations are a key component of electricity infrastructure, performing a variety of functions in generation, transmission, and distribution systems. Substation equipment includes circuit breakers, instrument transformers, switches, relay panels, communications panels, marshalling cabinets, and back-up batteries (CIGRE 2015). Substation loss can result in prolonged outages and extensive repair or restoration costs. Flooding may affect substation access and egress, cause corrosion and damage due to contaminants deposition on the equipment, or expose grounding contacts that result in reduced equipment life in the long term. Inundation from gradual changes in SLR or flooding from extreme events can lead to water ingress into transformers and control switches, which can cause damage (see Figure 17). Water from inundation or flooding may follow electrical lines back to underground conduits and vaults, damaging underground substations and splices. The leading cause of transformer failure is "insulation failure" (Bartley 2001), and clustered, below-grade transformers in underground vaults are particularly sensitive to flooding or inundation conditions as a result of SLR (NIST 2015).

Figure 17. Substation damaged by surge and waves on US Route 82 in Louisiana following Hurricane Rita. Credit: NIST 2006.

Substations also support a variety of communication and information technology functions. Utility service can be highly dependent on these functions, especially in newer (<10 years old) infrastructure (NIST 2015). In general, energy systems may be vulnerable to communications and control failures in extreme conditions in the future (NIST 2015).

Toronto Hydro-Electrical System Vulnerability Assessment for Electricity Distribution Infrastructure

Toronto Hydro-Electrical System Limited, the largest municipal electrical distribution utility in Canada, analyzed the potential impacts to components of the distribution infrastructure to weather- and climate-related hazards. Characterization of the hazard and the vulnerable components enabled them to have a better understanding of the different sources of vulnerability and the relative priorities to be addressed. The table below is modified from their results to show the weather- and climate-related hazards and vulnerable components deemed to be at medium or high risk. This analysis focuses on a wide range of weather- and climate-related hazards, and only on current or historical conditions, but provides an example that could be applied to future climate hazards as well.

Events	Feeders Impacted				Components
	Area A (all)	Area B B-2	Area B B-1	Area C (all)	
Medium Risk					
High Temp, Heat Wave, Extreme Humidity, Severe Heat Wave	•	•	•	•	Transformers Vaults and cable chambers
High Temp, Heat Wave, Extreme Humidity, Severe Heat Wave	•	•			Overhead conductors
High wind/downburst	•	•			Pole mounted switches and transformers
Heavy Rain, Heavy 5 Day Total Rainfall	•	•	•	•	Below-grade switches
Freezing Rain, Ice Storms	•	•			Overhead conductors Pole mounted switches and transformers
Freezing Rain, Ice Storms	•	•	•	•	Vault and cable chambers
Lightning strikes on equipment	•	•			Overhead switches and poles Overhead conductors
High Risk					
High wind/downburst	•	•			Poles Overhead conductors
Lightning strikes on equipment	•	•			Overhead transformers

Source: AECOM 2012.

4.1.3 Determine System Vulnerabilities

The power system is highly interconnected. It is, thus, important to determine system-level vulnerabilities in addition to understanding the vulnerability of individual assets. Electricity asset owners may already be responsible for carrying out similar analyses under existing performance requirements.[35] The loss of key assets in a power system network can lead to cascading failures, amplifying the magnitude of the outage. For example, the 2003 Northeast Blackout started with several events in the Midwest that within hours had propagated across an area with a population of 50 million (U.S.-Canada Power System Outage Task Force 2004). It affected other power-dependent infrastructure systems, such as communication, water, and transportation (NIST

[35] For example, see NERC, Standard TPL-001-4 – Transmission System Planning Performance Requirements, http://www.nerc.com/files/TPL-001-4.pdf. Accessed April 2016.

2015).[36] In addition to the electricity interconnections, modern power systems are also internally dependent on functioning communication and information technology systems. Substations support communication functions that help relay load information to a utility operation center, which can be especially important during post-event situations (NIST 2015).

In situations that may not require quantitative values, such as high-level vulnerability screening, historical reports of previous events and expert opinion can provide valuable qualitative insights on system vulnerabilities. Qualitative rankings (e.g., high, medium, low) may be sufficient for screening of key vulnerabilities.

More detailed analyses of vulnerability may require detailed network analysis and power flow modeling to determine vulnerabilities associated with outages. Power systems are traditionally designed to withstand single outages ("n-1" outages) (Panteli and Mancarella 2015). Utilities can model the response of the power system to threat scenarios to determine the sensitivity of the grid to different levels of threat or outages. For example, the operation of the transmission system can be simulated using power flow tools such as GE-PSLF™, PSS®E or PowerWorld®, with the impacts of storm surge flooding or inundation modeled by including constraints on affected generation and transmission facilities. The modeling will simulate the operation of the grid under normal and contingency conditions such as the unplanned loss of transmission facilities. Results of power flow modeling can be used to inform the indirect costs of different hazards (see Section 4.2.2, below).

There are several considerations when deciding whether to conduct detailed power flow modeling. Standard power flow modeling typically assesses the ability of the system to continue operating reliably following the loss of one or two critical elements. However, flooding or inundation from SLR and storm surge events may cause common failures across the system due to impacts on individual assets, as described above. This could result in even greater number of outages. Such "common cause failures" reduce the ability of the overall system to resist new outages and also reduce the ability of functioning assets and resources to cope with the event (Panteli and Mancarella 2015). Because the time horizon for SLR and potential storm surge events is often far enough in the future that there may be significant changes to network configuration, it may also be important to include modeling of future scenarios of network configuration (Panteli and Mancarella 2015). Such changes to network configuration should be based on utility planning documents. As a result, detailed modeling may require significant computer processing capabilities and significant costs. The need to conduct power flow modeling should therefore be informed by the requirements of the decision to be informed. For example, the information provided through power flow modeling may be important to decisions requiring detailed information, including annual reliability planning. Some strategic or screening-level analyses may not require the detailed information provided through power flow modeling.

[36] Additional interdependency of the power system to fuel systems may be important. For example, the interdependent nature of supplying gas for consumer automobiles with the supply of power, but is not discussed as part of this report.

4.2 Assess the Direct and Indirect Costs of Impacts of Sea Level Rise and Storm Surge

There are potential direct and indirect costs to the electricity asset owner and society of impacts from SLR and storm surge hazards. In general, transmission outages, despite occurring less frequently than distribution outages, have much greater costs (Ofori-Atta et al. 2004). The focus of this section is on the costs that utilities will need to identify to inform investment in resilience measures.

4.2.1 Determine the Direct Costs of Impacts

The direct costs of impacts from SLR and storm surge hazards on the electric power sector can be assessed by economic loss due to direct asset impacts. Damages to energy assets from severe storm events are likely to incur repair, restoration, or replacement costs specific to each asset type. Episodic nuisance flooding and less-severe storm events are likely to incur repair and restoration costs, whereas permanent inundation will have specific replacement and relocation costs. Table 2 provides examples of direct costs from impacts for different types of threats from SLR and storm surge events.

Restoration Costs for Utilities

Utilities incur substantial repair and restoration costs after climate or weather disasters. A select survey of 81 storm events in the United States between 1994 and 2004 by Edison Electric Institute (EEI) estimates the damage costs at around $2.7 billion (in 2003 U.S. dollars). In Florida, over a six-week period in July and August of 2004, six hurricanes damaged power assets worth $1 billion (in 2003 U.S. dollars). The hurricanes necessitated the replacement of more than 31,700 electric poles, 22,295 transformers, and 3,192 miles of conductor wires. The cost of power disruptions was estimated to be greater than the actual equipment damage costs. These examples of impacts are meant to be illustrative of the types of impacts that could occur from intense storms in the future, but do not relate to a specific projection of future climate change–related impacts.

Source: EEI 2004.

Table 2. Examples of Direct Costs of Impacts from SLR and Storm Surge.

SLR and Storm Surge Impact	Direct Costs of Impacts
Nuisance Flooding	• Repair costs including parts and labor • Replacement costs for damaged assets including parts and labor
Permanent Inundation	• Relocation costs • Costs to connect relocated assets • Replacement costs
Extreme Storm Surge Event	• Repair costs including parts and labor • Replacement costs for damaged assets including parts and labor

Costs for assets and labor will vary by region, manufacturer, design specifications, and contract relationships, among other factors. Costs for relocation, especially if new land must be acquired, will also be specific to the setting. Asset owner personnel and databases will often have the most relevant cost information. Utilities generally do not publicly report detailed damage estimates from storm events based on asset type and location. Utility capital investment plans can provide information on new asset costs, which are related to total replacement costs. Information is also available from surveys regarding grid vulnerability and resilience (e.g., Markey and Waxman 2013; GAO 2014; Lawton et al. 2003). Utility filings with regulators provide data on needed investments, which may relate to the costs incurred from storm events or may be forward-looking regarding investments to promote resilience to future impacts.[37] Several representative examples of costs are provided in boxes in this section (see cost information in Appendix C and D).

For the most generalized total cost estimates, utilities can assume a standard cost of replacement for generic asset types and that an exposed asset would be completely lost and need to be replaced, and utilize their accounting rules. Multiplying each exposed asset by the appropriate standard cost will give a general estimate of total value that may be lost. Due to the threat of permanent inundation from SLR, utilities will also need to include potential costs of relocating assets, which will be highly context specific. For screening-level estimates, information from previous relocation investments may be sufficient.

For more detailed and precise estimates, vulnerability information that relates the level of damage to the level of threat assets are exposed to should be used to determine the projected level of damage for each asset and the associated cost for repair or replacement. Utilities should consider the number of potential events an asset is likely to encounter over the service life to reflect the total costs more completely. Information will also be needed on relocation costs, which utilities may need to determine on a case-by-case basis because of variability in siting costs, especially when more accuracy is needed. Future load should also be considered; in situations where localities are permanently inundated due to relative SLR, future power service may not be necessary. Also, recent trends of relatively greater population growth in coastal areas are expected to continue in the coming decades (USGCRP 2014).

Analysis of projected potential costs of impacts from SLR and storm surge events in the future should consider the potential timing of these events.[38] The net present value of the costs should then be calculated to assist in comparison to potential resilience measure investments (Feigel 2013; Ofori-Atta et al. 2004). Because of the long time horizons considered with climate-related threats, selection of discount rate can have an important influence on conclusions (Goulder and Williams 2012).

4.2.2 Determine the Indirect Costs of Impacts

The potential indirect costs from impacts to electricity assets due to the exposure and vulnerability of assets or power systems to SLR and storm surge threats include the cost of power outages on customers, social and economic costs in other sectors, loss of jobs, and

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[37] For example, see Con Edison, 2013 Rate Filings, http://www.coned.com/publicissues/2013ratefilings.asp. Accessed April 2016.

[38] Timing of events should be based on information gathered as part of understanding the hazard, see Section 3.1.

reduced energy reliability. In other parts of the energy sector, failure of electrical equipment (e.g., electrical lines, pumps), can cause shut down of steam boilers, cooling towers, pumps, and electrically operated safety control mechanisms of oil and gas infrastructure, resulting in lost revenue and costs associated with equipment damage in these sectors. Social costs and economic losses in interdependent sectors (e.g., transportation, healthcare, or water), should also be considered by electric utilities (NERC 2010). Such costs may not be recoverable through traditional rate-based mechanisms. Table 3 summarizes examples of possible indirect costs from SLR and storm surge impacts.

Table 3. Examples of Indirect Costs from SLR and Storm Surge.

Impact of SLR and Storm Surge	Indirect Cost of Impacts
Nuisance Flooding	• Cost of energy outage to customers • Forgone income loss to society from outage • Loss of economic activity (GDP loss) due to outage
Permanent Inundation	• Cost of reduced energy reliability • Cost of permanent job losses • Loss of economic activity (GDP loss)
Extreme Storm Event	• Cost of energy outage to customers • Forgone income loss to society from outage • Loss of economic activity (GDP loss) due to outage • Increased risk to public livelihood, health, and welfare • Destruction of property in coastal areas • Overtime costs for public service sector

The value of lost load (VOLL) is a measure used by utilities and others to determine the costs to society and different customer classes from loss of power service. VOLL represents the value customers place on reliable electricity service (London Economics 2013) and quantifies the indirect costs of power outages, sometimes referred to as a customer damage function (Goel and Billinton 1994). VOLL is usually measured in dollars per unit of power (e.g., megawatt-hour, "MWh"). In general, VOLL can be classified under two types: marginal VOLL and average VOLL. Marginal VOLL measures the marginal value of the next unit of unserved power at peak periods (i.e., when customers place the highest value on power). The average VOLL represents the VOLL over a given period (e.g., month or year), which tends to be lower than marginal VOLL, as it averages out the value that customers place on electricity, including periods during which customers have little or no need for electricity (e.g., when customers are not at home or businesses are closed). Average VOLL is commonly used to inform transmission and generation investment, where it may be more appropriate to estimate customers' willingness to pay over longer periods of time. Methodological approaches to calculating VOLL are summarized in Table 4.

Table 4. A Summary of Methodological Approaches to Calculation of VOLL.

Approach	Description	Application
Proxy Methods	Uses observable variables that are linked indirectly to supply security: • Expenditure on standby generating facilities. • Monetized value of lost income and production output. • Other losses.	• Suitable in cases where anticipated losses can be expressed with sufficient precision by such observable variables.
Case Studies/ Historical Data	Performed after massive and major blackouts that affect large areas and large populations causing serious and severe economic losses.	• Yields most accurate and reliable data since they are carried out just after the actual events. • Rare and limited by geographic constraints as well as characteristics and duration of specific outage; expensive strategy.
Indirect Analytical Methods *(Macroeconomic Analysis)*	Uses publicly declared and available, easy to reach, objective data to study outage costs. These data include GDP, annual energy consumption, peak power, electricity tariffs.	• Easy, simple method; cheaper, less time, and highly objective estimations. • Yields coarse results since all customer segments with distinct electric power consumption characteristics are analyzed together.
Customer Surveys	By designing hypothetical outage scenarios with a carefully prepared questionnaire, the customer is asked to estimate the economic losses incurred during that predefined scenario.	• Most popular tools chosen and utilized by the electric power industry and utilities to make estimations about outage costs.

Sources: Lawton et al. 2003; London Economics 2013; Kufeoglu and Lehtonen 2015.

The VOLL depends on multiple factors such as the type of customer affected, regional economic conditions and demographics, time and duration of outage, and other specific traits of an outage. As a result, while analysis of available macroeconomic data and electricity consumption can be used to arrive at a rough estimate of "average" VOLL for a region, an accurate estimate of VOLL requires surveying end-use customers in the region to determine their willingness to pay to avoid a specific type of outage (London Economics 2013).

Insurance is an important risk management strategy for electricity asset owners (DOE 2013e). Filings from insurance claims may be a useful source of data for the value of the costs of impacts to the electricity sector.[39] Existing insurance mechanisms and related filing information may not capture the full picture of financial risk (DOE 2013e), but should be evaluated as a potential source of quantitative data on damages.

[39] For examples of activities related to climate change and the insurance sector relevant to the energy sector, see Green Insurance, http://insurance.lbl.gov/opportunities.html. Accessed April 2016.

The Interruption Cost Estimate (ICE) Calculator was designed to be an electric reliability planning tool for utilities, government organizations, and other entities aiming to estimate interruption costs and the benefits of reliability improvements in the United States (Sullivan et al. 2015).[40] In order to obtain cost estimations from the ICE Calculator, users are required to provide a variety of information about their demographic and utility operations including: number of customers; the state in which their service territory is located; their SAIDI,[41] SAIFI,[42] and CAIDI[43] values; the initial year of the intended reliability investment; the expected lifetime of the investment; and an estimated discount and inflation rates. With these data, the ICE Calculator can estimate costs to consumers of several distinct classes (large, medium, and small industrial; large and small commercial; and residential) for outages ranging from a few moments up to 24 hours. The ICE Calculator is used to estimate costs of interruptions of power service, based on forecasted reliability estimates that compare the cost scenarios with and without reliability improvements.

There are some known limitations to this tool in its current state including that it is still not possible to make cost estimations for interruptions of 24 hours and longer (even though the updated model contains more data on outages lasting longer than eight hours than earlier versions). For resiliency considerations that involve planning for long duration power interruptions of 24 hours or more, the nature of costs change over time and the indirect, spillover effects to the greater economy must be considered. These factors are not captured in this meta-analysis or tool. Additionally, the survey data used in the model is very sparse for certain areas and lacks any data from the Northeast and Mid-Atlantic regions (Sullivan et al. 2015).

Detailed information on the customers affected by a potential future outage can be determined from results of power flow modeling. A power flow analysis will provide information on the load lost for each outage event. This information can then be combined with estimates of the value assigned by different types of affected customers to the power service. For example, it has been estimated that the value assigned by consumers to electric power service reliability is about 50–100 times its retail price (Ofori-Atta et al. 2004). The results of such an analysis are valuable for determining the potential benefit of resilience measures. However, this detailed analysis that includes power flow modeling is resource-intense and may not be necessary to inform low-risk decisions or decisions that do not require detailed information. Additionally, VOLL is traditionally used to determine value for outages of relatively short duration (e.g., 8 hours) compared to outages of very long duration (weeks to months) following low frequency but very high impact events, such as storm surge associated with a strong hurricane on top of SLR. Estimates of VOLL related to these long-term outages do not yet exist.

[40] USDOE. Interruption Cost Estimate Calculator, http://icecalculator.com/. Accessed April 2016.
[41] System Average Interruption Duration Index.
[42] System Average Interruption Frequency Index.
[43] Customer Average Interruption Duration Index.

Estimated Value of Service Reliability for Electric Utility Customers in the United States

Lawrence Berkeley National Lab undertook an analysis of the value of reliable electricity service for different classes of customers across the United States, and updated the study in 2015. The review draws on a variety of studies, including VOLL analyses following a survey approach, from different regions of the United States. The review estimated interruption costs for different types of customers and of different duration. The findings highlight the increasing costs with increasing duration of outages. However, maximum outage time reported is 16 hours, which may not capture costs associated with major outages, such as those that might follow an extreme storm surge event associated with a major hurricane.

Estimated Interruption Cost per Event, Average Kilowatt (kW), and Unserved Kilowatt-Hour (kWh) (U.S. 2013$) by Duration and Customer Class

Interruption Cost	Interruption Duration					
	Momentary	**30 Minutes**	**1 Hour**	**4 Hours**	**8 Hours**	**16 Hours**
Medium and Large C&I (over 50,000 Annual kWh)						
Cost per Event	$12,952	$15,241	$17,804	$39,458	$84,083	$165,482
Cost per Average kW	$15.9	$18.7	$21.8	$48.4	$103.2	$203.0
Cost per Unserved kWh	$190.7	$37.4	$21.8	$12.1	$12.9	$12.7
Small C&I (under 50,000 Annual kWh)						
Cost per Event	$412	$520	$647	$1,880	$4,690	$9,055
Cost per Average kW	$187.9	$237.0	$295.0	$857.1	$2,138.1	$4,128.3
Cost per Unserved kWh	$2,254.6	$474.1	$295.0	$214.3	$267.3	$258.0
Residential						
Cost per Event	$3.9	$4.5	$5.1	$9.5	$17.2	$32.4
Cost per Average kW	$2.6	$2.9	$3.3	$6.2	$11.3	$21.2
Cost per Unserved kWh	$30.9	$5.9	$3.3	$1.6	$1.4	$1.3

Source: Sullivan et al. 2015.

A complete assessment of vulnerability and the direct and indirect costs will provide an understanding of the broad range of issues that will inform the choice of resilience measures and the analysis of their costs and benefits, which will be explored in the next section.

Key Considerations for Assessing the Vulnerability and Costs of Sea Level Rise and Storm Surge Events

Combine public and proprietary sources of existing and projected asset location data with geospatial information on potential SLR and storm surge threats to determine which assets are potentially exposed. Ensure accuracy of databases, as asset inventories change over time.

Many different components within generation, transmission, and distribution assets may be vulnerable to increased nuisance flooding and permanent inundation due to SLR. Asset vulnerabilities may be generalized for screening-level analyses, but for detailed assessments, utilities will need to consider specific design and site characteristics for individual assets.

A variety of sources, including expert opinion, design standards, and post-event reports, can be used to understand vulnerability of assets to particular climate-related threats. Estimate the potential impact quantitatively or qualitatively by combining the vulnerability information for exposed assets with SLR and storm surge scenarios, depending on decision requirements.

Interdependencies within the power system may contribute to vulnerability. It may be important to model future scenarios of network configuration to address potential SLR and storm surge vulnerability to planned investments.

Use the analysis of exposed assets to focus cost estimates. Direct costs due to impacts from SLR and storm surge threats will be context specific, and incorporating available asset vulnerability information, local relocation costs, and information on timing and frequency of events will improve accuracy when detailed estimates are required.

Determine the indirect costs from SLR and storm surge threats using methods that capture key aspects of the effect of outages on other sectors, such as value of lost load (VOLL).

Engage internal and external stakeholders in prioritizing actions based on potential costs to ensure meaningful metrics are used and that they can inform the selection of resilience measures needed to address costs and meet stakeholder expectations.

5 Build a Portfolio of Resilience Measures

Faced with the potential impacts from SLR and storm surge, electric utilities can choose from a range of resilience measures, including those related to hardening existing assets; new construction and relocation; policy, planning, and operations; smart grid and microgrid; ecosystem-based measures; and risk transfer to help ensure electricity service. A portfolio of resilience measures can help to address the vulnerabilities and avoid the potential direct and indirect costs from SLR and storm surge hazards. Climate resilience measures should consider potential transformations in the future electricity system.

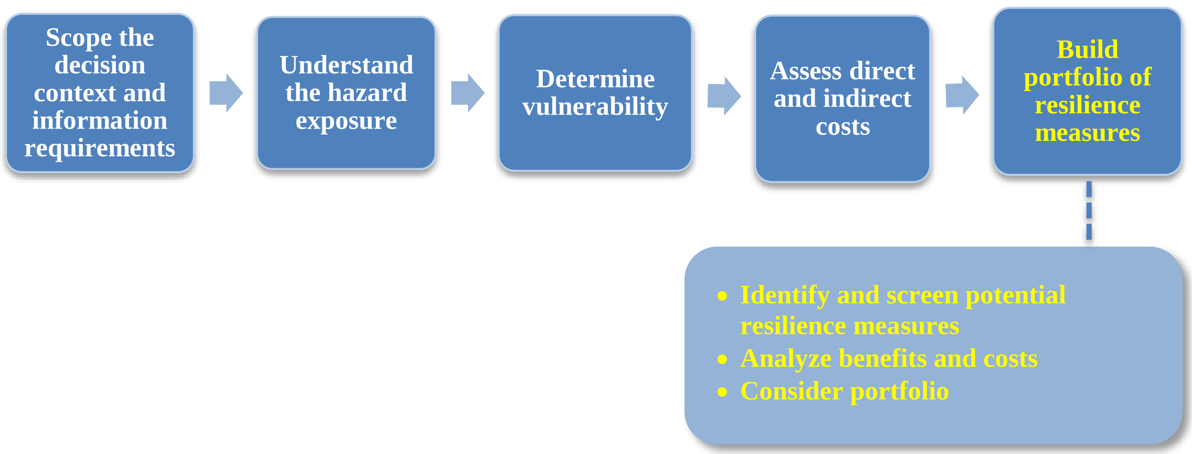


Figure 18. Overview of methodology for building a portfolio of measures, which includes consideration of costs and benefits, to improve resilience to SLR and storm surge hazards.

Based on the identified vulnerabilities and the decision context, utilities can build a portfolio of measures by first identifying a full set of possible resilience measures. This list of possible measures should then be screened for applicability based on a variety of criteria (e.g., the decision context, political or technological feasibility, and flexibility), reducing the number of measures to be further investigated. Information on costs and benefits should then be analyzed for the measures that pass the screening. The selected measures can then be evaluated in more detail based on multiple criteria, including the cost and benefit information. Finally, an asset owner can identify a portfolio of measures to help build resilience, which reflects the evaluation results, as well as the timing of investment and marginal benefit of the investment in these measures.

5.1 Identify and Screen Potential Resilience Measures

A wide range of measures can be employed to improve resilience of electricity assets and systems to SLR and storm surge. These include types of measures related to hardening (e.g., engineering changes, elevating, retrofitting, or upgrading); new construction or relocation; policy, planning, and operations; smart grid or microgrid technology such as improved observability and controllability of the grid through communications and monitoring; ecosystem-based approaches (e.g., coastal wetlands restoration); and risk transfer (e.g., indemnity insurance). The exact assignment of a particular option to a type is less important than the recognition of the multiple measures available to an asset owner. This section provides summary information regarding different types of resilience measures, and includes a discussion on the rapid screening of all possible measures to help focus subsequent analyses on priority measures.

5.1.1 Summary of Potential Resilience Measures

Resilience measures may be generalized for screening-level analyses, but utilities will need to consider specific site characteristics for individual assets and systems when detailed analyses are required. General information on the main types of resilience measures is provided below. Appendix C provides more extensive information on specific examples of resilience measures for each type.

Table 5. Example Resilience Measures.

Type of Resilience Measure	**Example Resilience Measure**	**Primary Risks Addressed**		
		Extreme Storm Surge Events	**Nuisance Flooding**	**Long-Term Inundation**
Hardening Existing Assets	Undergrounding[44]			
	Elevating substations & other assets	X	X	
	Installing guy wires	X	X	
	Hardening substations	X	X	
	Replacing wood poles & transmission structures	X	X	
	Reinforcing floodwalls	X	X	X
	Updating aging T&D equipment	X	X	
	Using submersible equipment	X	X	X
New Construction or Relocation	Building new asset or rebuilding assets in a new location	X	X	X
	Building new floodwalls & storm surge barriers	X	X	X
Policy, Planning, and Operations	Employing vegetation management	X	X	
	Using backup generators	X	X	
	Upgrading control centers & communication equipment	X	X	X
	Integrating system changes to enhance resilience in long-range planning	X	X	X
	Updating Emergency Operations Plan	X	X	
	Participating in mutual assistance groups	X	X	

[44] While undergrounding of distribution or transmission assets may not provide significant resilience benefits to SLR and storm surge hazards, it is included here because it is an important measure to increase resilience to other storm-related hazards, such as wind and ice.

Type of Resilience Measure	Example Resilience Measure	Primary Risks Addressed		
		Extreme Storm Surge Events	Nuisance Flooding	Long-Term Inundation
	Acquiring standby equipment & backup restoration supplies	X	X	
Enhancing Smart Grid and Microgrid Capabilities	Installing advanced metering infrastructure	X	X	
	Installing microgrid	X	X	X
Ecosystem-Based Approaches	Integrating coastal wetlands restoration	X	X	X
Risk Transfer	Utilizing indemnity-based insurance	X	X	X

Hardening Existing Assets

Utilities commonly conduct programs to harden existing assets to hazards related to extreme storm events. Hardening measures include initiatives to make physical and structural improvement to lines, poles, towers, substations, and supporting facilities (DOE 2010). Elevation of existing assets, such as substations, and reinforcing existing floodwalls may also be included. Many of the same measures will help promote resilience to SLR and storm surge. However, existing hardening measures may need to be modified to address changing conditions, especially the threat of increased nuisance flooding or greater storm surge associated with the combination of SLR and more intense storms, as discussed in previous sections. Hardening measures may not be effective against permanent inundation associated with gradual SLR.

For upgrades or retrofitting of existing assets, design and construction standards for upgrades should be based on the local conditions of the facilities (EEI 2014). Not all assets should be hardened or upgraded in the same way, as some resilience measures will be much more effective in cost and outcome than others will. Updating assets also requires further decisions with regard to the level of upgrade. Many of the existing issues with aging infrastructure (e.g., clustered and below-grade transformers, fuses not breakers in many locations, underground ducts running close together and crossing in many shallow manholes) do not have explicit codes and regulations. When utilities make upgrades, they must consider the measure(s) that will provide the most cost-effective resilience for their particular assets (NIST 2015).

New Construction or Relocation

Building new assets or protective features, or relocating exposed assets to locations that reduce the exposure to hazards, can help improve resilience. This type of measure includes building new substations, as well as building new floodwalls and storm surge barriers in locations without any protection. Generally, building a new substation in a new location can address risks associated with extreme storm surge events and nuisance flooding, as well as gradual inundation (see Table 5). For screening analyses, knowing that an asset has been flooded repeatedly may provide sufficient justification to consider relocation, but detailed information regarding SLR projections for the area should be used for investment decisions for a new location. Building a substation or other new assets requires thought not only to location to protect from SLR and storm surge, but also to design a generally better performing asset—new construction requires decisions pertaining to updated building standards (NIST 2015).

Policy, Planning, and Operations

Initiatives grouped in this category all have to do with preparation and altering existing operations to create increased resilience. This category includes improved vegetation management, acquiring backup generators and other standby equipment, upgrading communication equipment, and improving or creating new emergency management and response capabilities, such as emergency operations plans and mutual assistance groups.[45] Additional elements for consideration could include internal staffing and assignments; contractor support; logistics; emergency preparedness plans; restoration material and equipment inventory; joint services agreements; and others. Generally, these measures protect against short-term events and nuisance flooding as they often address emergency outages rather than long-term increases in sea level. For example, PSEG Long Island's Emergency Restoration Implementation Procedures (ERIPs) and Logistics Support Emergency Procedures (LSEPs) dictate the response to large-scale storms and other disasters involving equipment failure. Included in these procedures are measures like storm anticipation actions (e.g., placing remaining segments of the barrier containment system for flood control at the substations that may be affected due to flooding, ensuring that all substations are prepared for storm conditions by securing loose items, removing any scaffolding, and tying down material and equipment), crew guide instructions, and the Mutual Assistance Crew's Guidebook (PSEG Long Island 2014).

[45] Mutual assistance groups are those in which member utilities share staff and equipment in a coordinated response to electrical outages (DOE 2010).

New York Power Authority (NYPA): Strategic Vision 2014–2019

NYPA is planning a new system with traditional elements and innovative features like microgrids, clean distributed power sources near customer locations, and sophisticated smart grid devices. The explicit goal is to improve reliability, resilience, and environmental protection and allow customers to manage their own power use.

Short-Term	Medium-Term	Long-Term
The short-term focus is on near term actionable opportunities with minimal complexity and capital investments	The medium-term focus is on optimizing processes and activities within the current operating structure	The long-term focus is on incorporating large strategic ideas into the organizational direction
Examples: ▪ Quick win process improvements ▪ Life cycle asset management ▪ Workforce planning and better use of knowledge / data	Examples: ▪ Business process optimization ▪ Sensory monitoring of the grid	Examples: ▪ Innovative R&D and technology integration i.e. integration of renewables ▪ Process optimization business function ▪ Customer suite of services and technologies

NYPA's Strategic Vision is developed around three key themes that reflect the many changes in the energy industry and the economy: customer empowerment, infrastructure modernization, and resource alignment. The plan also provides steps NYPA will take in the short, medium, and long term, which provide an opportunity for incorporation of SLR and storm surge resilience measures.

Measurement Strategies: This plan also covers trends in the current New York Energy Market including changes in customer energy priorities, change in generation and transmission structures, and changes in organizational norms. Included in this plan are NYPA's strategies to measure success, including financial effectiveness, operational effectiveness, and value from energy. Financial effectiveness includes measuring the debt service coverage ratio. NYPA will look at the operational performance of generation and transmission assets, the carbon intensity of operations, and success in meeting customer needs in order to measure operational effectiveness. Measuring value from energy includes the carbon intensity of customer consumption, the extent to which economic development is stimulated, and the penetration within the customer base.

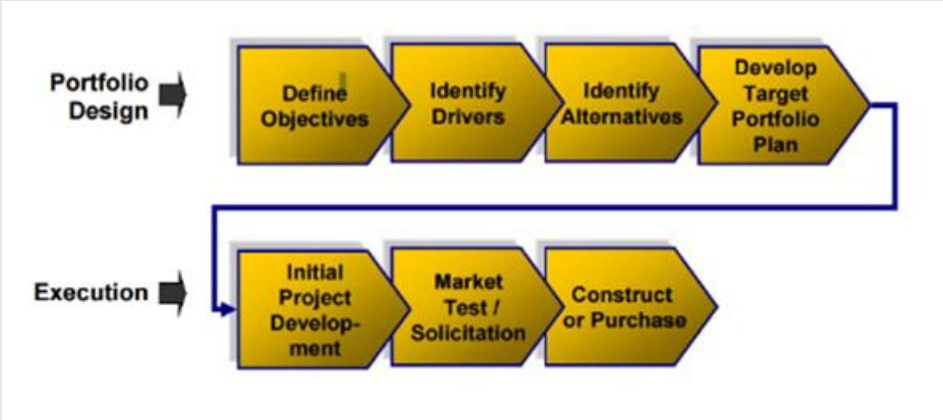
Source: NYPA 2012.

In order to prepare for the future, most utilities carry out a medium- to long-range strategic planning process. Electric utilities produce these strategic plans to discuss general changes in the electric industry, environmental pressures, technology changes, and ultimately the way that the asset owner plans to face these changes over the next five to 20 years (NYPA 2014). These plans provide an opportunity for utilities to address resiliency and make changes to their planning and asset management that can build resilience to gradual inundation from SLR, more frequent nuisance flooding and increased risks to flooding due to the combination of SLR and storm surge.

Planning and operations measures often involve limited additional cost. Most utilities already have existing vegetation management and emergency operations plans, so making changes to address specific threats from short-term and nuisance flooding events does not require much input of resources.

Strategic Resource Plan: An Integrated Resource Plan for the Entergy Utility System and the Entergy Operating Companies 2009–2028

The Strategic Resource Plan (SRP) is a framework that includes a set of principles and objectives that guide long-term portfolio design. The SRP planning process creates scenarios regarding potential future portfolio resource decisions including resource timing, location, and technology. In essence, the SRP is a process for long-range planning that allows for a flexible approach to resource selection.



Plan Details: Entergy is seeking to upgrade the generation supply and power supply resources to develop a more diverse, modern, and efficient portfolio of energy supply resources to meet customer needs. This plan describes key uncertainties for resource planning like power plant construction cost, environmental concerns, and market conditions. It is emphasized that decisions for actual resource development will be made as the plan is implemented over time and will depend on a range of factors controlled by long-term uncertainty.

Entergy's SRP includes an Action Plan to be implemented over one to five years.

Source: Entergy Corporation 2009.

Enhancing Smart Grid and Microgrid Capabilities

This category includes the relatively advanced controls and communication technologies that can help to improve the resiliency of the grid, assuming that these enhancements are themselves made resilient to changing climate conditions. New smart grid technologies help to detect outages and remotely reroute electricity to undamaged circuits and feeders (EEI 2014). An example of specific smart grid capability is advanced metering infrastructure, which helps to automatically control the route of electricity in the event of an outage and reduce the impact of the outage on the customers. [46] A key element of implementing this technology is designing the distribution system as a looping system that provides for the rerouting of power rather than a

[46] For an example project see SmartGrid.gov – Electric Power Board of Chattanooga, https://www.smartgrid.gov/project/epb_smart_grid_project.html. Accessed April 2016.

radial linear system (EEI 2014). During time of need, microgrids can isolate from the bulk grid and become self-sustainable, thus reducing the strain on the grid's ability to operate reliably.

Microgrid technology allows portions of the grid to function as an isolatable distribution network that can connect and disconnect from the main grid. Gaining benefits from this type of resilience measure involves a large investment in these newly developed technologies that are not yet in standard use. Microgrids can be implemented on the customer level as well as the utility level, and it should be noted that they are not simple interchangeable systems. Microgrids can provide increased resilience to critical facilities that manage the response to planned and unplanned events: hospitals and medical centers, local government facilities, federal facilities and military bases, and key business like grocery stores, drug stores, and gas stations (NIST 2015).

Ecosystem-Based Approaches

While not generally part of electricity asset-owner oversight or regulated functions, investment in sustainable ecosystem management or sound environmental management can be an important resilience measure. Ecosystem-based approaches to resilience —sometimes referred to as ecosystem-based adaptation, soft engineering, eco-disaster risk reduction, and green infrastructure (Royal Society 2014)—are generally thought of as the use of biodiversity and ecosystem services as part of an overall portfolio of measures to improve resilience to the adverse effects of climate change (Secretariat of the Convention on Biological Diversity 2009). Unlike traditional engineering solutions, which are designed based on an assumption that natural systems fluctuate within current variability or based on a climate projection that may turn out to be inaccurate, ecosystems have the ability to adapt to unforeseen changes in environmental conditions (Jones et al. 2012). Electricity asset owners may choose to identify collaborations with ecosystem managers or owners—such as state resources agencies, the U.S. Fish and Wildlife Service, or NGOs—to pursue ecosystem-based approaches that provide benefit to electricity sector resilience.

Ecosystem-based resilience measures generally offer strong co-benefits. Healthy ecosystems not only provide advantages such as flood abatement and coastal protection, but also have livelihood benefits (International Union for Conservation of Nature 2009). In addition, ecosystem-based approaches can provide co-benefits related to protection against numerous hazards, inexpensive installation, and saving on maintenance (National Wildlife Federation 2014). Evidence regarding effectiveness of ecosystem-based measures varies (National Wildlife Federation 2014). Some hybrid approaches combine engineering options and ecosystem resilience measures to gather benefits from both strategies (Royal Society 2014).

For coastal hazards, such as SLR and storm surge associated with strong storms, restoration of degraded wetlands can help to protect against floods or storm surge inundation while having the additional co-benefits of sustained provision of livelihood and employment opportunities, potential revenue from recreation activities, sustainable logging of planted trees, conservation of wetland flora and fauna, and reduced emissions from soil carbon mineralization (Secretariat of the Convention on Biological Diversity 2009). Coastal wetlands help to reduce flooding by increasing drag on water motion, which acts to reduce erosion and absorb wave energy (Costanza et al. 2008). Wetlands promote the deposition of sediment, which maintains shallow water depths and decreases wave strength (Secretariat of the Convention on Biological Diversity

2009). As one example, wetlands of the Mississippi Delta are valuable ecosystems providing services worth an estimated $12–$47 billion per year (Jones et al. 2012).

Risk Transfer

Risk transfer measures are useful to providing resilience against low-frequency, high-severity weather events. Risk transfer measures are financial mechanisms, such as indemnity-based insurance, parametric index solutions, and catastrophe bonds (Economics of Climate Change Adaptation Working Group 2009). They can significantly reduce the cost of prevention and mitigation by bearing the risk of rare events, therefore allowing physical measures to provide enough resilience while still being cost effective. While insurance is a form of financial risk management, it technically does not reduce actual disaster consequences or reduce hazard likelihood (DOE 2013d).

Risk transfer measures act to limit the losses and reduce volatility, while increasing the willingness of decision makers to invest in development. Risk transfer measures, like indemnity insurance, can be an appealing addition to a resilience portfolio because it can both lessen the impact of climatic events on policyholders while incentivizing other resilience measures.

If the cost of purchasing third-party insurance is too great, the perceived risk is small, or the risk is so new that it is not well understood, energy infrastructure owners might self-insure (DOE 2013d). With self-insurance, asset owners and operators set aside funds to cover specifically the costs of potential damage. The U.S. Government acts as an insurer, through such programs as the National Flood Insurance Program, as well as playing a role in ensuring the viability of private insurance. Public insurance, while sometimes necessary, may be offering affordable insurance premiums that neither accurately reflect price signals of risk nor have enough money to fund the recovery from a disaster (DOE 2013d).

5.1.2 Screen Resilience Measures

Identifying all possible resilience measures, drawing on utility experts and resources like those provided in Appendix C, is an important step toward developing a desired portfolio of measures. Not all of these measures may be applicable to the local decision context, and a rapid screening can help focus further consideration of measures (Economics of Climate Change Adaptation Working Group 2009). This screening can be effectively accomplished through qualitative analysis, informed by stakeholder and expert input.

This rapid screening should be used to consider issues such as the political feasibility of the measure, the technological capability for implementation, and the flexibility (i.e., the extent to which a measure can adapt to, or be revised or reversed in response to changing conditions, needs, or regulatory requirements) of the measure (Economics of Climate Adaptation Working Group 2009). For example, smart grid technologies or construction of new coastal storm surge barriers may not be appropriate given local regulatory or political conditions. In other cases, measures such as upgrading of transmission assets may not be within the authority of the utility. In some cases, additional screening criteria can be included to reflect unique decision requirements or stakeholder priorities. For example, cross-state coordination or prioritization of co-benefits may be an important screening criterion.

Once resilience measures have been screened using relevant criteria, utilities can consider the costs and benefits, as well as other important criteria, for evaluating a narrowed list of measures more fully.

Example of Questions to Screen Resilience Measures

As part of a sub-regional pilot project to assess adaptation options for a subset of key transportation assets vulnerable to SLR in Alameda County, the Metropolitan Transportation Commission (MTC), the San Francisco Bay Conservation and Development Commission (BCDC), the California Department of Transportation, District 4 (Caltrans), and San Francisco Bay Area Rapid Transit District (BART) formed a collaborative partnership.

The questions below were used to help screen the 124 strategies down to 17 for more detailed evaluation. This pilot's collaborative approach across multiple agencies meant that strategies with multiple co-benefits applicable to multiple areas and requiring agency collaboration were prioritized. Similar questions could be adapted for the electricity sector to screen measures.

- Does the strategy address the vulnerability of multiple assets?
- Does the strategy address multiple vulnerabilities of an individual asset (informational, governance, functional, physical)?
- Does the strategy require significant multi-agency coordination to be effective?
- Can the strategy be used by more than one agency?
- Does it make sense to start working on this strategy in the next five years?
- Does the strategy address multiple transportation modes?
- Does the strategy accomplish or contribute to other critical operational objectives (congestion management)?
- Does the strategy reduce consequences (impacts) on society/equity?
- Does the strategy provide a positive impact on the environment?
- Does the strategy provide a positive impact on the economy?

Source: MTC 2014.

5.2 Determine Costs of Select Resilience Measures

In many electricity asset-owner decision processes, cost information for resilience measures will be important. Utilities should focus the determination of cost on the screened list of potential resilience measures from the previous section. The total lifecycle costs should be considered for resilience measures, including up-front capital costs of materials and labor, as well as costs of maintenance and repair over the lifetime of the measure (Economics of Climate Adaptation Working Group 2009). Much of the available cost information comes with the embedded assumption that the total costs would be incurred primarily to increase resilience to SLR and storm surge hazards. However, utilities may choose to invest in various measures, such as microgrids or distribution line undergrounding, for reasons unrelated to resilience. In those cases, resilience can be viewed as an added co-benefit, and utilities should consider the incremental costs that are appropriate to include in an evaluation of resilience measures.

Information on costs of resilience measures presented here largely draws on previous DOE review. The DOE material has been augmented with additional, publicly available information, primarily from public filings by utilities, DOE reports, and a recent review (EEI 2014). Utility databases and experts will likely have additional detail on costs, especially related to local conditions. A summary of cost information is provided in the following sections, including range of costs for different example measures. Please see Appendix C and D for detailed information from publicly available sources on costs of resilience measures.

Potomac Electric Power Company (Pepco) Reliability Investments

On November 30, 2012, Pepco proposed accelerated specific reliability investments to improve priority feeders, accelerate tree trimming, and underground existing overhead distribution feeders. Associated with the accelerated investment is a cost recovery mechanism referred to as the Grid Resiliency Charge. This plan is in response to the Report of the Grid Resiliency Task Force ("Weathering the Storm: Report of the Grid Resiliency Task Force," 2012). The Task Force Report contains 11 recommendations, including four for which it urged immediate action "to accelerate resiliency improvements and provide Marylanders with a tangible benefit in a short period of time." *These investments are provided as examples of actions that could improve resilience to climate change, but may not specifically consider future climate conditions or be designed to address changes in climate in the future.*

Key measures to improve reliability:

- Improve priority feeders: this measure involves upgrading and hardening of 24 overhead distribution feeders over two years. The objective is to improve the performance of selected feeders on a storm inclusive bases as measured by the industry standard indices of SAIFI and SAIDI. The forecasted benefits of the program are improvements in both the aggregate storm inclusive and exclusive SAIFI of 32 percent and SAIDI of 45 percent of the group of 12 feeders to be replaced in 2015. The baseline against which these benefits will be measured will be the groups' aggregate performance for the 12-month period ending December 2012.
- Accelerate tree trimming.
- Install underground overhead distribution feeders.

Funding: Pepco proposed the Grid Resiliency Charge to recover the costs of accelerated capital and operations and maintenance projects resulting from currently planned reliability work. This charge will be in effect only until the incremental project costs are incorporated into Pepco's base rates. Pepco proposed a customer credit if it does not meet the minimum reliability standards and an incentive for achieving the accelerated reliability standards.

Potomac Electric Power Company (Pepco) Reliability Investments (continued)

Pepco Maryland: Grid Resiliency Work – Estimated Cost

Project	Scope	Overall Cost	Specific Cost	Construction Period
Priority feeders	Accelerating the hardening of an additional 24 feeders over two years	$12 million per year capital investment	12 feeders/ year at an average of $1 million per feeder	Two years (2014 and 2015)
Vegetation management	Accelerating the next four-year trim cycle of scheduled clearance tree trimming from four years to three years	$17 million O&M expense	No detail provided	One year (2014)
Selective undergrounding	Undergrounding six 13kV distribution feeders	$151 million capital investment	Estimated $25 million per feeder	Three years (7/2013–1/2016)

Table modified from original source: Office of Governor O'Malley 2012; Maryland 2012. Case number 9331.

5.2.1 Hardening Existing Assets

The costs of hardening existing assets and upgrades span several orders of magnitude, with examples ranging from approximately $600 for adding guy support to one pole to $30,000,000 for undergrounding a mile of transmission line (see Table 6). While some of these measures are widely used by electric utilities, others are either new technology or are not commonly used, and therefore are not widely discussed in the literature. The range of costs is reflective of the fact that much information exists specific to the cost of undergrounding, but submersible equipment is not widely referenced and therefore less cost information exists.

Table 6. Asset Hardening Cost Examples.

Example Resilience Measure	General Range or Example Cost	Notes
Installing guy wires	$600–$900 per pole	(DOE 2010)
Upgrading wood poles	$16,000 to $40,000 per mile	Cost depends on material (steel is more expensive than concrete); there are many possible upgrades in use (replace entire pole, replace wood cross-arms, reduce spans between poles) (Quanta Technology 2009; DOE 2010; Florida Power & Light Company 2013). See Appendix C for additional information and references.
Using submersible equipment	>$130,000 per vault	Cost depends on location and type of submersible equipment needed (Florida Power & Light Company 2013).
Upgrading transmission lines	>$400,000 per mile	Cost depends on specific upgrade (Quanta Technology 2009).
Substation hardening	$600,000 per substation	Wide range of cost is available depending on specific hardening measure needed for each location (Florida Power & Light Company 2013).
Elevating substations	>$800,000 to >$5,000,000 to elevate	Standard cost is difficult to determine due to variation in height needed for each location (Quanta Technology 2009; Johnson 2013).
Reinforcing floodwall	$8,000,000 for existing seawall	Cost depends on length, height, and location of floodwall (DOE 2010).
Undergrounding distribution lines	$100,000 to $5,000,000 per mile	Cost depends on area (urban is most expensive) and new construction or conversion from overhead (new construction is more expensive) (EEI 2014; Quanta Technology 2009; DOE 2010). See Appendix C for additional information and references.
Undergrounding transmission lines	>$500,000 to $30,000,000 per mile	Cost depends on area (urban is most expensive) and new construction or conversion from overhead (new construction is more expensive) (EEI 2014; Quanta Technology 2009; Hall 2013). See Appendix C for additional information and references.

5.2.2 New Construction or Relocation

Undertaking a project to build a new floodwall or substation requires a large investment, with example estimates between $1,500,000 and $6,000,000 (see Table 7). Obviously, much of the cost will depend on the type of new construction the utility is planning. The cost of construction will also depend on the specific design parameters, including resilience measures. For relocation, costs will be primarily driven by whether land is already available within the utilities holdings, or by additional costs in local real estate markets. For screening-level analyses, proxy information regarding general estimates of real estate values for potential relocation sites may be available could be supplemented with local tax assessment records. Additional costs associated with connecting existing transmission or distribution infrastructure to new construction or relocated assets will also be incurred, although no specific costs examples were found in publicly available sources.

Table 7. New Construction or Relocation Cost Examples.

Example Resilience Measure	General Range or Example Cost	Notes
Building new floodwalls	$4,000,000 per mile	Cost depends on location and height of wall (DOE 2010).
Building new substation	$6,000,000 per substation	Cost depends on new location and design of substation (Quanta Technology 2009).

5.2.3 Policy, Planning, and Operations

Policy, planning, and operations measures are generally less expensive than many engineering-based resilience measures. The measures listed here range from inexpensive vegetation management to an example of $20,000 in backup generator cost per substation (see Table 8). In addition to these resilience measures, there are also a range of other planning measures like long-range strategic planning, updating emergency operations plans, and participating in Mutual Assistance Groups, which can act to increase the resilience of a utility (DOE 2010). Cost information does not exist for these planning measures.

Table 8. Policy, Planning, and Operations Cost Examples.

Example Resilience Measure	General Range or Example Cost	Notes
Vegetation management	$12,000 per mile	Cost depends on the functionality of the existing vegetation management plan in place and the level of vegetation clearing that the utility chooses (tree maintenance, tree removal, enhanced tree trimming vs. routine tree trimming) (Quanta Technology 2009; Potomac Electric Company 2010; State Vegetation Management Task Force 2012). See Appendix C for additional information and references.
Backup generators	$20,000 per substation	Cost depends on the size of the substation and the amount of power needed in a backup situation (Quanta Technology 2009; DOE 2010).

5.2.4 Enhancing Smart Grid and Microgrid Capabilities

Installing smart grid and microgrid capabilities are the most expensive resilience measure found in the literature, with a variety of costs depending on the technology and project specific context (see Table 9). For example, Siemens estimated that it would cost $150M to install a microgrid with an average load of 40MW (Dohn 2011). To create a microgrid capable of islanding an entire substation area, SDG&E estimates cost of approximately $15M (NYSERDA 2010). A pilot program in Massachusetts was estimated to cost $44M to test smart-grid technologies to reduce outages, improve operational efficiency of the grid, and to integrate renewable resources.

This pilot includes five substations and more than 15,000 customers.[47] These technologies are still developing, meaning that much of the initial investment cost and maintenance costs are still uncertain (DOE 2010).

Table 9. Smart Grid and Microgrid Capabilities Cost Examples.

Example Resilience Measure	General Range or Example Cost	Notes
Installing microgrid	$150,000,000 for 40MW average load	Cost depends on size of the microgrid and the average load needed; this is a not yet deployed widely so costs are uncertain (Dohn 2011).
Advanced metering infrastructure	$240 to > $300 per smart meter installed	The cost depends on the size of the network and the number of meters installed; this is a new technology that is still developing, so costs are uncertain (Energy and Environmental Economics; Inc. and EPRI Solutions, Inc. 2007).

5.2.5 Ecosystem-Based Approaches

Ecosystem-based resilience measures is a broad category that can include diverse approaches such as major restoration activities over a large coastal area, localized integration of green infrastructure with engineered measures, and habitat protection of any size. Similarly, costs will vary by specific measure and local conditions. A recent example of the cost of using ecosystem-based measures for reducing flood risk by employing marsh restoration in the San Francisco Bay illustrated that by using a tidal marsh in combination with a levee constructed on the landward edge of the marsh, the size of the levee could be reduced significantly while still providing the same level of flood protection benefit as would be provided by a large levee without the marsh. The cost of the levee with the tidal marsh will be about half that of just the traditional levee. The total cost for the levee alone over 50 years is more than $12 million per mile. With a 200-foot wide marsh in front of the levee, the cost is reduced to about $5.5 million per mile. Restoring a 200-foot wide marsh on its own was estimated to cost about $0.8 million per mile (The Bay Institute 2013). In another example, to restore the wetlands of New Orleans and use them as part of the coastal defense system, the estimated cost would be $2 per square meter for marshland stabilization and $4.30 per square meter for marshland creation (Jones et al. 2012). Utilities may look to collaborate with managers or owners of local ecosystems, such as tidal marshes, to identify opportunities to improve resilience through ecosystem-based approaches.

5.2.6 Risk Transfer

Due to the highly context-specific nature of risk transfer measures, such as insurance, and the proprietary nature of these rates for the insurers, public information was not discovered. Generally, many risk transfer solutions have a large cost-benefit ratio because insurers need to charge expected loss plus an extra fee for production and distribution (Economics of Climate

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[47] NYS SmartGrid Consortium, http://nyssmartgrid.com/wp-content/uploads/2013/01/NYSSGC_2013_WhitePaper_013013.pdf. Accessed April 2016.

Adaptation Working Group 2009). Costs of risk transfer may still be economically attractive, due to the high cost of building resilience to very low frequency, high-impact events.

5.3 Assess Potential Benefits of Resilience Measures

Resilience measures may provide a variety of benefits, including direct benefits from avoided costs (based on potential cost of impact), as well as co-benefits to the electricity sector (e.g., system reliability benefits, enhanced energy efficiency, reduced GHG emissions, etc.) and other sectors, ecosystems, and society, and potentially additional revenue streams. Capturing the value of these benefits has proven difficult (NCA 2011). Utilities will need to consider economic and non-economic metrics appropriate for the decision context and requirements. Since the primary direct benefits of resilience measures are the avoided potential costs of impacts from SLR and storm surge hazards, which are described in Section 4, this section only provides a brief summary of these avoided costs and focuses on potential metrics and qualitative considerations for additional benefits, where available. This diverse set of metrics can help to inform the overall value (economic and non-economic) of investing in resilience measures (NCA 2011; Royal Society 2014; Mihlmester and Kumaraswamy 2013).

5.3.1 Direct Benefits from Avoided Costs

The direct costs of impacts from SLR and storm surge hazards on the electric power sector can be assessed by economic loss due to direct asset impacts. Damages to energy assets from severe storm events are likely to incur repair or restoration, and replacement costs specific to each asset type. Permanent inundation will have specific replacement and relocation costs, whereas episodic nuisance flooding and less-severe storm events are likely to incur repair and restoration costs. In addition, the potential indirect costs from impacts to electricity assets due to the exposure and vulnerability of assets or power systems to SLR and storm surge threats include the cost of power outages on customers, social and economic costs in other sectors, loss of jobs, and reduced energy reliability. See previous sections for additional detail on estimating potential costs.

5.3.2 System Benefits

Resilience measures can provide benefits not only to particular assets, but also to the broader electricity systems. Some of these benefits can be captured through reliability and resilience metrics. Electricity reliability is critical for economic productivity and social wellbeing. A large variety of metrics exists to measure electricity system reliability at the distribution level, which generally apply to interruptions or outages of less than 24 hours and further development is needed to understand applicability to potential outages of longer duration possible with very high-impact, low-frequency events (e.g., storm surge associated with a major hurricane).

Common reliability metrics for distribution systems include:

- *System Average Interruption Frequency Index (SAIFI)*—a measure of the average frequency of interruptions per total number of customers. It is the number of interruptions divided by the total number of customers served.
- *System Average Interruption Duration Index (SAIDI)*—a measure of the average duration of service interruptions for the total number of a utility’s customers. It represents the “minutes interrupted” divided by “total number of customers served.”

- *Customer Average Interruption Duration Index (CAIDI)*—the average outage duration that any given customer would experience. It represents the "minutes interrupted" divided by the number of customers affected. It can also be viewed as the average restoration time.

There is no generally agreed upon method to quantify the resilience of a system (Watson et al. 2014). The development of resilience metrics is an area that is often cited as needing improvement and further research (e.g., Watson et al. 2014; Roege et al. 2014). However, researchers have proposed a variety of resilience metrics that help to assess the resilience of electricity systems and provide insights into the system-level benefits of resilience measures. For example, Sandia National Laboratories describes metrics that are represented as probability density functions of consequences that may result from one or more threats to a system, and creates a framework in which the resilience metrics rely on the performance of the system as opposed to attributes of the system. An integral aspect of this resilience framework is the underlying system models used to determine the behavior of infrastructure when subjected to a threat. The majority of these models are based on measuring reliability, which can be used as a proxy for some elements of resilience (Watson et al. 2014). Other metrics, such as "Customer Restoration-90" (CR-90)—defined as the number of hours it takes from the start of the outage event to restore power to 90 percent of the affected customers of a given utility (Mihlmester and Kumaraswamy 2013)—specifically apply to consideration of major high-impact events where power is lost to a large number of electric customers, such as might occur from storm surge flooding associated with a strong hurricane. Additional research is needed to develop metrics that effectively capture long-term resilience benefits in the electricity system.

5.3.3 Co-Benefits

In addition to increasing resilience to SLR and storm surge hazards, some measures may provide co-benefits to other sectors, society, or ecosystems. Similarly, some actions may be initially undertaken for an unrelated reason, but result in improved resilience for electricity infrastructure. In general, some co-benefits to building resilience to SLR are energy and national security, economic growth and job creation, emergency management and preparedness, public health, agricultural productivity, and ecosystem conservation (DOE 2013a). As new generation sources are built as part of measures to improve climate resilience, the bulk of new capacity is likely to come from a transition away from coal to natural gas and renewable energy, potentially reducing greenhouse gas emissions while building resilience (DOE 2015a).

Some resilience measures with environmental co-benefits, like wetlands restoration and maintaining existing vegetation, may be preferred over other measures because they are "low-regret" in comparison to other options (Royal Society 2014). These measures may have low investment needs and high reduction potential of expected losses, and avoid investing solely in actions that are exclusively benefiting infrastructure. Even if maintaining existing vegetation is not the most effective option in building resilience, its positive co-benefits in other sectors could be a strong driver for implementation alongside more expensive and effective measures.

By expanding resilience plans to include resilience measures with possible co-benefits, utilities can lower the burden of resilience on strictly engineering and hardening investments (Entergy Corporation 2010). However, measures and data to determine the co-benefits of different actions have been very difficult to develop, especially for diffuse co-benefits to society (Sussman et al.

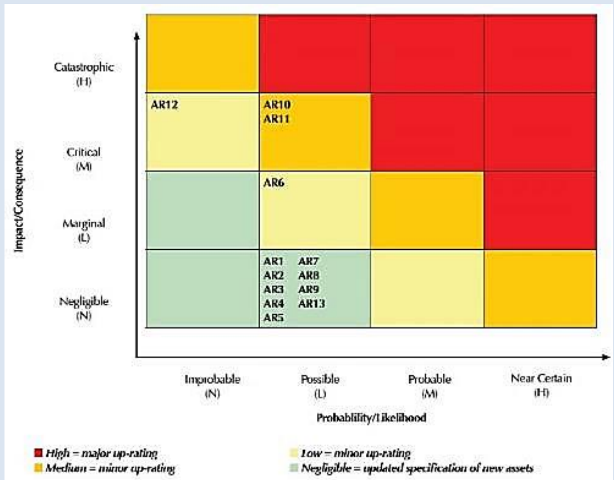
2014). Utilities should include at least qualitative consideration of potential co-benefits in evaluation of resilience measures.

5.4 Consider a Portfolio of Resilience Measures

There is no single or best set of resilience measures for maintaining a resilient power supply in the face of changing climate conditions and the hazards associated with SLR and storm surge. The choice and prioritization of a portfolio of resilience measures depends on stakeholder input (Watson et al. 2014), the culture of decision-making, specific problems, societal management objectives, and the relative scarcity of available resources (natural, human, and financial capital), along with costs and the relative susceptibility and vulnerability to climate risks (Stakhiv and Pietrowsky 2009). Effective portfolio selection requires balancing these different considerations and assessing the tradeoffs of different resilience measures given priority selection criteria (Mihlmester and Kumaraswamy 2013).

Ranking Anticipated Business Consequences – Northern Powergrid

Northern Powergrid developed a system to define relative impacts using a "negligible" through "catastrophic" ranking of the anticipated business consequence should a hazard occur. The overall risk of an impact is determined based on the combined effects of the likelihood and consequence. Risks are organized into a color-coded matrix, seen at right, which allows for visualization of risks classified into categories. By taking into account both the probability of a hazard occurring and the anticipated resulting business consequence, Northern Powergrid is able to make informed decisions about resilience measure priorities.



Source: Northern Powergrid 2012.

The process for building a portfolio of resilience measures begins with evaluation of measures using a variety of criteria, including costs and benefits, related to resilience improvements for individual assets and the electricity system. This will further refine the screened list of measures to those most appropriate to include in a final portfolio. Additional consideration of the marginal benefit to resilience from increased investments in resilience measures should be used to inform decisions about the level of investment an asset owner will make. Lastly, choice of timing of investments and the resultant benefits will vary due to asset or system condition and assumptions about future impacts, and implementation of a portfolio of resilience measures should consider these influences.

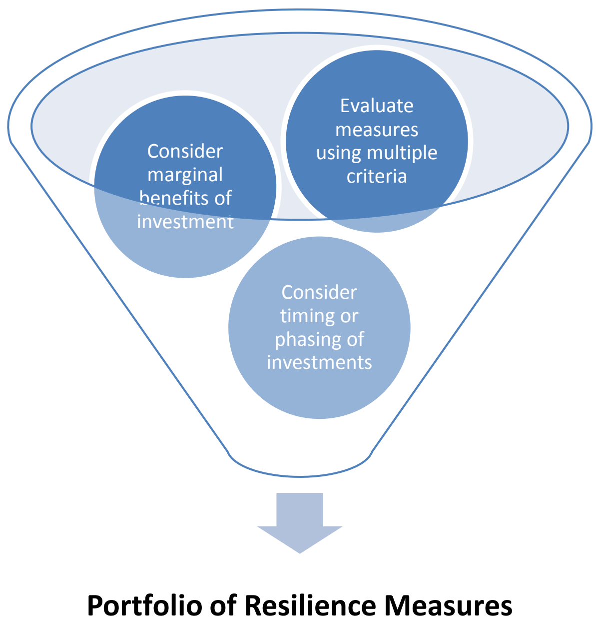


Figure 19. Utilities can build a portfolio of resilience measures by evaluating individual measures using multiple criteria, including benefit-cost analysis, and then analyzing the complete portfolio for ways to improve marginal benefits and timing of investments.

5.4.1 Evaluation of Resilience Measures

An evaluation of resilience measures using multiple criteria is needed to inform the choice of a portfolio of measures an asset owner will take to improve resilience. While many decision processes have been designed to consider results of a benefit-cost analysis (BCA), it is important to consider other metrics alongside the BCA information. Additional metrics of benefits, as described in the previous section can be important inputs into the evaluation. Other metrics, qualitative or quantitative, that relate to the robustness, timeliness, and flexibility of the resilience measure should be included (see box below for definitions of evaluation criteria). Utilities should engage stakeholders and experts to define the full set of evaluation metrics appropriate for the decision process, emphasizing transparency in rationale (Li et al. 2014).

Example Criteria for Evaluating Resilience Measures

Robustness: Performance of a risk management measure under a wide range of possible climate futures. It may be relatively costly to select an option that is more robust, so the incremental cost of additional robustness may need to be taken into consideration.

Effectiveness: A measure of how well the risk management measure reduces the specific climate risks of concern and generates the primary benefits sought (e.g., damages reduced, costs avoided, lives saved) over an appropriate time horizon. The decision maker may have specific benefits categories, which will define effectiveness.

Reversibility and Flexibility: The extent to which a measure can adapt to, or be revised or reversed in response to changing conditions, needs, or regulatory requirements. Flexibility may be an especially important consideration for measures that are intended to be long-lived, are relatively costly, and/or have irreversible consequences.

Cost: The cost of implementing the measure, including initial costs (i.e., materials, labor, etc.) and longer-term costs of operation and maintenance. This is typically a critical consideration when selecting a risk-management measure, it is often weighed against resource constraints, competing priorities, and uncertainties of climate change, and the potential magnitude of avoided consequences vis-à-vis other risk management measures.

Co-Benefits: The extent to which a risk management measure might provide additional benefits, in addition to reducing the specific climate-related risks of concern. Co-benefits may include positive economic impacts on other sectors, improved health and security of vulnerable populations, or benefits to ecosystems.

Rapidity: The speed with which disruption can be overcome and safety, services, and financial stability restored are critical considerations particularly for operational management of climate variability and extreme events. The measure could be implementation of structural solutions, operational actions to mitigate damages, or involve the timely dissemination of advanced warning, guidance, and resources to vulnerable populations.

Sources: Nelson et al. 2007; NIST 2015; Stakhiv and Pietrowsky 2009; and USAID 2014.

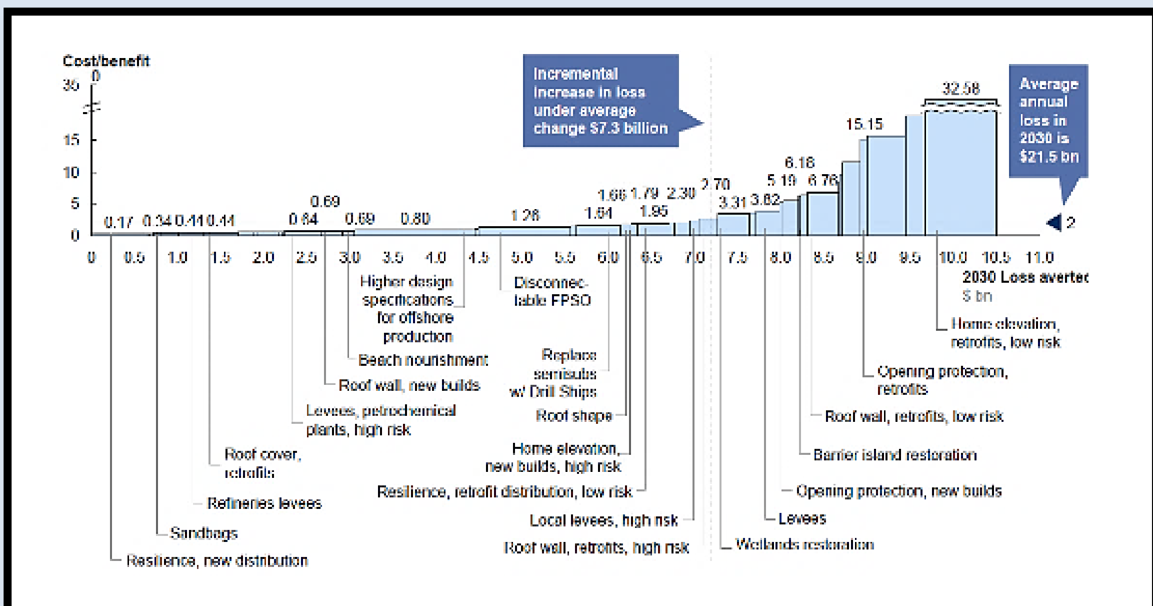
The choices of how to implement investments in the portfolio of resilience measures will be influenced by the opportunities presented by an electricity asset owner’s normal planning and upgrade cycle, repair and restorations needed following damaging events, as well as the financing opportunities. Asset owners should look for opportunities in the long-term planning processes to incorporate resilience measures into planned replacement or upgrades due to asset lifecycles, thus accelerating improvements in resilience in a cost-effective manner. Evaluation of the benefits and costs of resilience measures made at different points in time can help to identify priority “adaptation pathways” (e.g., Rosenzweig and Solecki 2014). Decision analytic techniques can be applied to consider multiple potential scenarios of investments across multiple scenarios of future climate impacts (e.g., Chao and Hobbs 1997). In addition, an understanding of priority resilience measures will allow asset owners to rebuild strategically following events that cause loss or damage to assets, rather than trying to identify resilience measures in the wake of a major event or recreating vulnerabilities in the system based on previous assumptions about future conditions.

Benefit-Cost Analysis Considerations

BCA is applied to many electricity asset-owner investment decisions. However, there are many conceptual, practical, and methodological issues that mean BCA may not capture all aspects of economic and social value (NCA 2011; Sussman et al. 2014). For example, up-front costs for new construction or ecosystem-based approaches may be prohibitively high because the benefits achieved in return are spread out over the long lifetime of the measure. Resilience measures that are part of investments planned for other goals may end up included in a typical BCA carrying the high-cost of constructing a new asset, when in fact the investment is primarily driven by another purpose, such as normal lifecycle replacement (see below regarding taking advantage of these planned replacement cycles). The discount rate applied to BCA of resilience measures is also a subject of much debate. As noted above, many types of benefits are difficult to quantify in economic terms and therefore are often excluded from or insufficiently captured in BCA.

Example of Using Cost-Benefit Ratio to Compare Potential Resilience Measures: Entergy

The Gulf Coast is vulnerable to growing environmental risks today with more than $350 billion of cumulative expected losses by 2030. The key uncertainties involved in addressing the vulnerability include the impact of climate change, cost and effectiveness of measures to adapt, and the ability to gain alignment and overcome obstacles. This analysis includes coastal counties and parishes comprising a strip of land up to 70 miles inland across the shoreline in southern Texas, coastal Mississippi, and Alabama. This area is threatened by hurricanes that primarily drive damage through extreme winds, storm surge, and flooding.



This study attempts to determine potentially attractive measures using a cost-to-benefit ratio of less than 2, while recognizing that the potential loss aversion is uncertain. The measures are compared on an overall cost curve in which the width of each bar represents the total potential of that measure to reduce expected loss up to 2030 for a given scenario, and the height of each bar represents the ratio between costs and benefits for that measure. Approximately $44 billion of public funding will be required over the next 20 years to fund key infrastructure projects, along with $76 billion in private funding.
Source: Entergy Corporation 2010.

For economic analyses, such as BCA, probabilities of climate events occurring (and damages occurring) can be used to weight benefits and costs in evaluation of resilience measures. For detailed analyses, Monte Carlo methods can also be used to project benefits and costs when probabilities are available for input data or other aspects of the analysis. Monte Carlo methods are frequently used for applications such as analyzing extreme weather and natural disaster events.[48]

When probabilities of key variables—such as projected climate, costs, outage duration—are unknown or cannot be estimated reliably, utilities will need to consider approaches for dealing with this uncertainty in evaluation techniques, including BCA. Sensitivity analysis, ranges, and assumed probabilities can be used to evaluate the importance of climate, cost, or other uncertain data on the outcome and results. Other approaches, such as breakeven analysis, scorecard analysis, or worst-case analysis may be useful for dealing with uncertain information and resilience investments (e.g., Fox-Penner and Zarakas 2013). Public Service Electric and Gas employed a breakeven analysis approach in the prioritizing of its resilience investments as part of its Energy Strong Program (see box below). Robust optimization approaches are a way of restructuring the decision problem that is particularly useful in situations where probabilities are unknown, and more classic risk management techniques cannot be used. Similarly, "robust decision making" (RDM) can be implemented using relatively simple approaches that array the options and results under a range of climate futures, and display the information in ways that are salient for decision makers. RDM can also be a more sophisticated undertaking, in which stakeholder and decision-maker weights are identified, and more complex mathematical algorithms are used to obtain the results (Lempert 2015).

[48] Monte Carlo analysis is a computerized mathematical technique widely used to analyze problems where there is inherent uncertainty in predicting future events. Software packages for Monte Carlo simulation, such as *@Risk* and *Crystal Ball*, are widely available as plug-ins to Microsoft Excel at prices that would be affordable to most utilities.

Example of Evaluating Resilience Measures: Public Service Electric and Gas (PSE&G)

PSE&G used the experience of Superstorm Sandy as the basis of a method for developing a proposal for resilience investments. The PSE&G Energy Strong proposal included numerous hardening and resiliency programs. A Superstorm Sandy-type event and its effects were assumed for the breakeven analysis, then the results were extrapolated to less strong events, using the following assumptions (1) entire customer base experiences outages, (2) multiple outage causes (flooding, wind, etc.), and (3) outage duration defined as five days for station flooding, three days for other outages.

PSE&G calculated the number of customers that could benefit from each investment, along with a reduction of outages and outage duration. A conservative estimate was made on the impact that each program would have on the count and duration of outages. Using 2012 FERC Form 1 data, the PSE&G customer base was subdivided into categories, which PSE&G used to calculate the average kW per customer lost for each customer class (kW/customer). Total outage reduction per class was calculated by using the total outage hours saved (avoided and reduced), percentage of customers within that class, and the average kW per customer consumed by that class. VOLL was calculated using the eight-hour interruption figure for each customer class.

The results of the analysis showed that that the Energy Strong investments mitigate the costs of system-wide electrical outages lasting more than 72 hours.

Source: The Brattle Group, Analysis of Benefits: PSE&G's Energy Strong Program, Table III-12

In any analysis, there are always more data that can be gathered, more costs or benefits that can be quantified, more possible refining of estimates, and more tools that can be used. One of the important features of a good BCA will be the efficient use of resources: expending more effort on the analysis when that effort produces a more robust result or an outcome that resonates with decision makers. In some cases, general estimates are all that are needed for some aspects of the analysis (such as the magnitude of system impacts or maintenance costs). In other cases, refining the numbers may be important—particularly when up-front financial costs vary across resilience measures, and those costs are critical to the bottom line.

5.4.2 Analyze the Portfolio of Potential Resilience Measures

Once utilities have an understanding of the various criteria that define the characteristics of different resilience measures, these criteria can be considered in combination to inform a preferred portfolio of resilience measures that is designed to meet the asset owner and stakeholder goals.

There are qualitative and quantitative approaches to evaluating multiple criteria simultaneously. The choice of method should be driven by the nature of the decision. Multi-criteria decision-making tools may be appropriate for decisions that require more detailed analysis. For screening-level decisions, qualitative evaluation can be informative. Weighting can be applied to the selected criteria, and utilities should include rationale for the weighting choices and equal weighting across all criteria may be a helpful starting point to ensure adequate consideration of the co-benefits alongside direct cost benefits. Trade-offs and synergies among resilience measures should be considered in the evaluation. Visualizations of the comparison of measures may aid in evaluation (see Figure 20 for an example). The output of the evaluation analysis is an important input into selection of a portfolio of measures but should not be viewed as the only basis for deciding which measures to include. Stakeholder and expert input will be needed to refine the results for the local conditions and decision context.

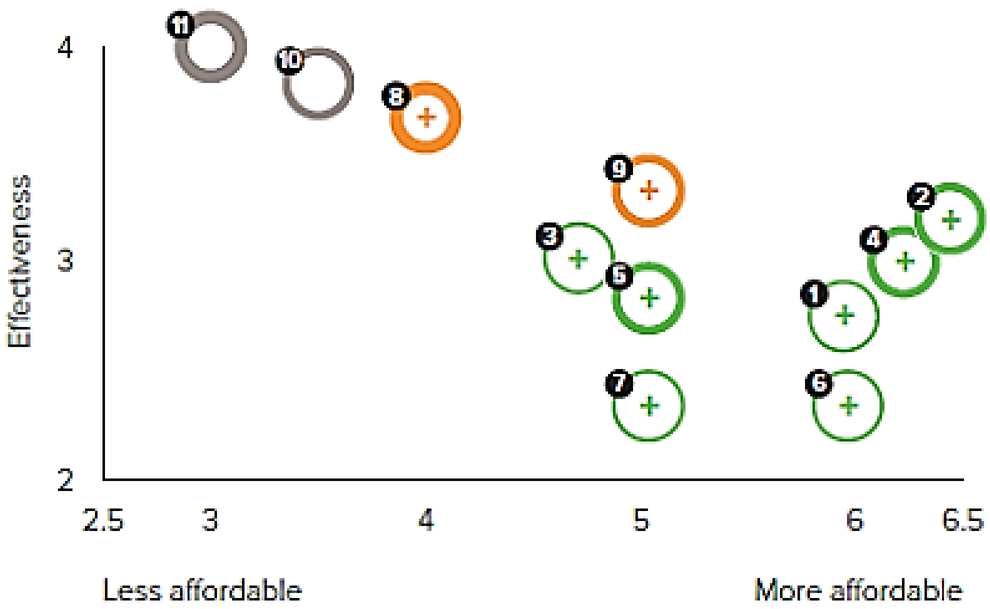


Figure 20. Example of resilience measures for coastal flooding. Numbers correspond to risk management measures evaluated. The color of the circles indicates the category of measure (e.g., grey = engineering, green = ecosystem-based, orange = hybrid), the thickness of the circle indicates the weight of evidence in the literature that supports the effectiveness and affordability determination, and the + indicates potential additional co-benefits (Royal Society 2014).

Example of Prioritizing Resilience Measures: Consolidated Edison Company (Con Edison)

On January 25, 2013, Con Edison submitted a proposal for new rate plans for electric, gas, and steam services. The new rate filings include approximately $1 billion in potential storm hardening structural improvements over four years that are intended to reduce the size and scope of service outages from major storms. The investments are designed to address issues related to severe weather, but may not specifically address climate change resilience; the information is provided to be illustrative of a prioritization process.

The plans include strategic undergrounding and flood protection projects, such as:

- Elevating equipment
- Enhancing seals around connections
- Preemptively de-energizing non-operationally critical equipment to protect against control/power supply short circuits
- Installing flood barriers, watertight doors, sluice gates, and flood pumps to prevent the migration of water into the stations
- Eliminating facilities by converting the local distribution system to 13kV or 27kV autoloops
- Using fiber optic-based communications and control in order to provide more effective fault protection during flooding

Example of Prioritizing Resilience Measures: Consolidated Edison Company (continued)

Con Edison developed a prioritization process to implement solutions based on realizing the greatest benefits for the costs expended. The storm hardening prioritization process considers factors such as public safety, population impact, critical infrastructure reliance on the electric system, the vulnerability of the systems, and the financial expenditures necessary to achieve hardening. The Con Edison Risk Assessment (RA) and Cost-Value Analysis (CB) models are macro-level tools designed to illustrate risk-based allocations of investments. The RA model was developed to estimate the current level of climate-associated risk – the product of the probability of climate-related damage and the impact of that damage (number of customers multiplied by the expected outage duration) – associated with each electric system asset being targeted for resiliency work. In addition, Con Edison estimated the additional societal impact to critical infrastructure served by extended outages at each asset to capture the societal impact the loss of these customers would have, beyond the pure outage hours experienced by these critical customers. Once these societal impact estimates were combined with the customer outage hour estimates, an initial estimate of the current level of risk, or "pre-storm hardening risk," was quantified for each asset. Engineering estimates of the expected improvements in risk—as a result of the storm hardening projects targeting each asset – were then incorporated into the RA model to produce a "post-storm hardening" measure for each asset. The risk reduction levels—defined as the difference between pre-storm hardening risk and post-storm hardening risk—were then examined, across asset type, to compare the amount of benefit each asset was receiving in terms of customer outage hours avoided.

In addition to the RA model, a CB model was created to demonstrate a dollar-to-dollar comparison of capital project cost to the benefit of economic loss avoided, by asset. Net present value (NPV), benefit to cost, and benefit minus cost metrics were calculated for each asset to provide multiple ways of comparing dollars spent vs. dollars saved. In total, the model estimated that Con Edison's storm hardening program would avoid customer economic losses in excess of over $5 billion over the next 20 years.

Sources: Con Edison 2013a; Con Edison 2013b.

Improvements to resilience of the electricity system do not scale linearly with the investments, as investments needed to remove all residual risk from the system become increasingly expensive and those needed to achieve the resilience across the system to all hazard scenarios are generally cost prohibitive (Mihlmester and Kumaraswamy 2013; Economics of Climate Adaptation Working Group 2009). Utilities can evaluate the ability of a portfolio of risk reduction measures to deliver high marginal improvements in resilience against a variety of metrics. For example, analysis of the cost of improving CR-90 (i.e., reducing the time needed to restore power to customers following a severe storm) against the cost associated with improved resilience of the system from the portfolio of selected measures, can be used to determine the point at which the resilience investments begin to show diminishing returns (see Figure 21). Utilities may wish to conduct a similar analysis using other reliability metrics. In addition, analysis should be considered to understand the investment benefits from the portfolio against the hazard of permanent inundation from SLR, which will occur over much longer timescales than storm outages, and will be dominated by costs associated with relocation.

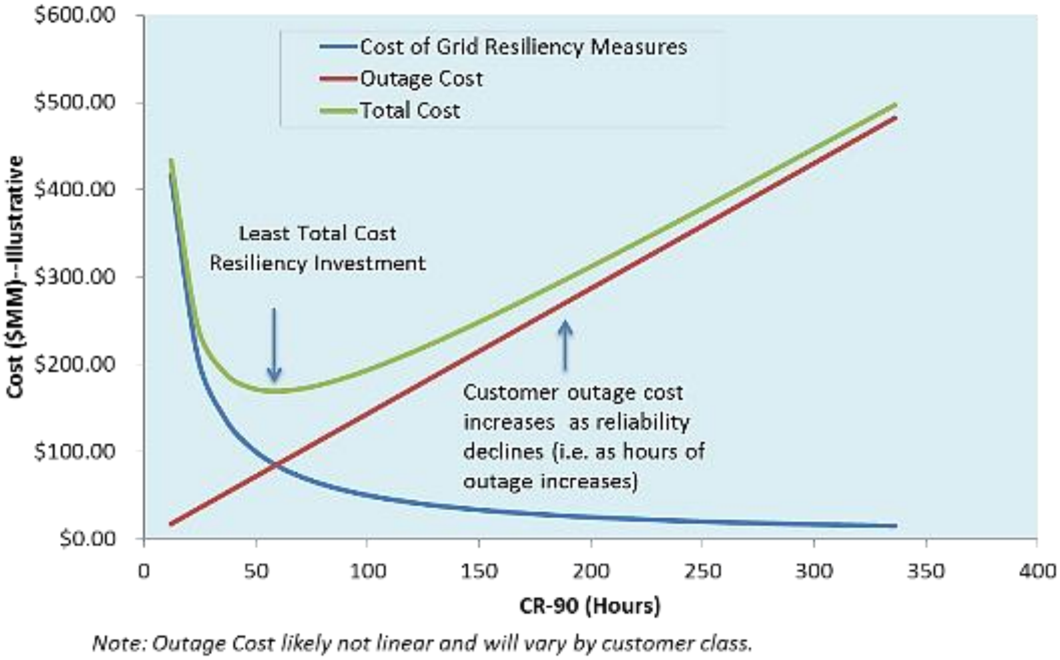


Figure 21. A “Total Cost Analysis” of grid resilience measures.

Another important consideration when choosing effective and appropriate strategies is the lifetime of the infrastructure compared to the severity of climate impacts (Savonis 2011). For example, some electricity assets may have a relatively short design or use lifetime, which may suggest that an appropriate strategy is to monitor conditions over the near term and to be prepared to provide recommended changes in asset composition as needed. A power generation facility, on the other hand, has a long lifetime where it may be worthwhile to design with some consideration to changes in future threats. Some resilience measures may be immediate or support a short-term objective while others may occur over a long period of time. It is important that the resilience measure planning horizon is consistent with the lifetime of the infrastructure.

Key Considerations for Building a Portfolio of Resilience Measures

There are many types of resilience measures that can address different aspects of vulnerability and that can be applied to different spatial or temporal scales. Utilities should use available resources, stakeholder input, and in-house expertise to identify as many potential resilience measures as possible. This list of measures will provide a foundation for building the portfolio of measures appropriate for the decision context and goals.

Screen potential resilience measures to help ensure that measures considered basic criteria related to the political and technological feasibility of each measure, effectiveness, flexibility, and other screening criteria deemed appropriate by stakeholders.

The cost and benefits of resilience measures may vary significantly. While there are potential low-cost resilience measures, some will require significant investments, which may be supported through transparent processes for assessing benefits and considering a portfolio of measures.

Resilience measures may have important co-benefits that should be included in an assessment of benefits. In some cases, economic metrics may be available, but more often the value of co-benefits to public health, ecosystem conservation, national security, or other sectors or aspects of society can be assessed qualitatively or with non-economic measures. Utilities may need to engage outside expertise for assistance in appropriately assessing co-benefits as part of more detailed analyses.

A variety of metrics exists for system reliability, which could be informative to assessing some aspects of the benefits of resilience measures. However, existing reliability metrics do not apply to assessing long-duration outages (i.e., days to weeks), Metrics that can be used to assess the system benefits from resilience measures to long-term gradual change, such as SLR, are not well developed, but utilities should at least consider the potential qualitative benefits of measures to address SLR hazards.

Use multiple criteria to inform the choice of a portfolio of resilience measures. While benefit-cost analysis will be important to many decision processes, it is important to consider other metrics alongside the benefit-cost analysis information.

There are potential limitations to capturing the full range of resilience benefits in a benefit costs analysis. Consideration of incremental costs related to resilience, incorporation of uncertainty of future conditions (including timing and amount of SLR) and flow of benefits will be necessary. Methods have been proposed to address some of these considerations, but the application of economic analysis to resilience measures remains an active area of research.

After evaluating individual resilience measures, consider how a portfolio of measures will meet decision goals. Adjust the final portfolio to take advantage of opportunities related to timing of investments, synergies between measures, concerns over breadth of approaches and coverage, or other decision-relevant priorities.

6 Additional Considerations for Conducting Regional Analyses

This section provides an overview of the key considerations related to scaling an analysis of the exposure, vulnerability, direct and indirect costs, and resilience measures to large geographic regions, such as the entire Gulf Coast or Atlantic Seaboard. Expanding the geographic range of an analysis is challenging, especially when detailed results are needed to inform action. In general, the quality and cross-comparability of data related to the threats of SLR and costs of damage vary from location to location and span government-generated geographic and climate-related data, demographic data, and utility-specific data. Moreover, there are challenges for designing a meaningful portfolio of resilience measures, given the importance of site-specific details affecting risk and engineering costs. [49] Additional research is needed to determine appropriate ways to address many of these challenges.

For any analysis, it will be important to use a consistent set of SLR and storm surge scenarios across the entire geographic scope. For analysis over large areas, there are likely to be different preferences and risk tolerances among stakeholders and tradeoffs may need to be made in the choice between total number of scenarios and available resources. In an analysis of impacts over a large region, indirect costs from a storm that hits land in one area may be widespread. However, it would not be realistic to assume that a storm would land on all parts of a coast simultaneously (although a storm hitting more than one area in rapid succession is plausible). Therefore, scenarios used to inform analysis of indirect costs (see below) will need to be based on choices about a set of storms landing in different places along the coast; results from each scenario would demonstrate the relative magnitude of potential direct and indirect costs.

Information about exposed assets, including available public sources used in previous DOE analyses, would be appropriate for analysis over large geographic regions. For detailed analyses that include utility-specific data, issues regarding asset characteristics and data consistency between areas are a possible challenge. Coordination between electricity asset owners would be needed to ensure appropriate alignment of information across databases. Utility data can provide important quality control for the publicly available sources, especially because asset inventories change over time.

Methodological considerations for the analysis of system interdependencies over large geographic areas also depend on the level of detail of the analysis. In situations that may not require quantitative values, such as high-level vulnerability screening, historical reports of previous events and expert opinion can provide valuable qualitative insights on system vulnerabilities. This approach would be appropriate at local or large geographic extents. For more detailed analysis, power flow modeling can be used to determine system vulnerabilities associated with outages. Such detailed modeling analysis can identify the impact of an outage of a single element or a group of elements from SLR and storm surge on the reliable operation of the bulk power grid. Steady-state power flow analysis of the outage, supported by dynamic

[49] For an example of a relatively large-scale analysis of coastal vulnerabilities and sustainability measures see Coastal Protection and Restoration Authority Current Coastal Master Plan, http://coastal.la.gov/a-common-vision/2012-coastal-master-plan/. Accessed April 2016.

stability studies, can help to identify the severity of the impact and determine if widespread instability, uncontrolled separation, or cascading[50] will occur (Peak Reliability 2015). Results of these widespread impacts will need to be considered for multiple scenarios, as discussed above. Asset owner data representing the system parameters and dynamics are critical for conducting accurate power flow and dynamic stability analyses.

The direct costs of impacts will likely vary considerably from area to area within a large region. While possible, simplifying assumptions about asset costs will introduce significant uncertainty when applied over large geographic areas. Expert input may be effective for quickly improving the estimates over a large area for screening-level analyses, but for more detailed analysis, utility- and area-specific data will need to be acquired.

The potential indirect costs from impacts to electricity assets due to the exposure and vulnerability to SLR and storm surge threats include the cost of power outages on customers, social and economic costs in other sectors, loss of jobs, and reduced energy reliability. A methodological approach that uses the VOLL to determine the costs to society and different customer classes from loss of power service may be appropriate over large geographic areas. While results of VOLL estimates vary from region to region, results from Lawrence Berkeley National Laboratory (Sullivan et al. 2015) can be used to support estimates over large areas. However, for detailed analysis, region-specific studies and electricity asset-owner data should be considered, and new VOLL estimates may be required for some areas within the analysis.

The methodological approach to building a portfolio of resilience measures in one location (described in Section 5) could be applied over a large geographic region. However, resilience measures and their associated costs and benefits will be location specific. For screening-level analysis over large areas, assumptions about a limited set of generic resilience measures and their associated generic costs could capture a general order of magnitude for a large area (Neumann et al. 2015); the value of this information will depend on the decision it is meant to inform and should be designed in consultation with stakeholders. A process that determines a portfolio of resilience measures and the associated costs for individual areas first, and then sums these to determine the cost over a large geographic extent will improve the estimates. Similarly, analysis of major metropolitan areas along the coast could be completed, and then results could be extrapolated to areas not analyzed based on metrics that compare analyzed regions to unanalyzed regions (Neumann et al. 2015). However, synergies or conflicts between resilience measures across analysis areas will not be captured. Co-benefits and non-cost metrics for some measures may be difficult to quantify (see Section 5.4.1), but this challenge should not change significantly based on the extent of the analysis.

For detailed analysis, cost information may not be available in all locations, and new information would need to be collected. Specific cost information from utilities is essential in producing accurate, detailed estimates of direct cost of impacts of SLR and storm surge and costs of resilience measures. Public data often do not contain a specific breakdown of repair, relocation, and similar costs, so accessing electricity asset-owner information is important for achieving

[50] Cascading is defined by NERC as the uncontrolled successive loss of system elements triggered by an incident at any location. Cascading results in widespread electric service interruption that cannot be restrained from sequentially spreading beyond an area predetermined by studies.

accurate large-scale estimates. Similarly, costs associated with resilience measures are difficult to generalize over a large geographic region. For example, the cost of undergrounding transmission lines may vary between approximately $500,000 and $30,000,000 per mile depending on utility- and location- specific factors (EEI 2014; Quanta Technology 2009).

7 Conclusion

As described in this guide, an assessment of vulnerabilities to SLR and storm surge should inform the design of a portfolio of resilience measures that can be implemented to help build resilience in the electricity sector. For some, this may serve as the first step toward consideration of climate vulnerabilities and resilience. For others, this may help augment the assessment of vulnerabilities to other climate-related hazards. Considering all relevant climate hazards will help to identify a complete portfolio of actions that can be integrated with other actions designed to address non-climate hazards, such as cybersecurity and physical threats, not addressed in this document.

The electricity industry is in the midst of significant change that could affect the vulnerability and resilience of electricity assets and service in the future. This report identifies key considerations for electricity assets, with an emphasis on utilities and the regulatory and market environment in which they operate today. Asset owners may need to supplement this document with guidance from stakeholders and regulators, and adjust to changes in the regulatory and economic environment.

Several aspects of resilience assessment can be further developed in the future to help build resilience in this dynamic environment. For example, as utilities come to rely more on generation assets owned by independent power producers and merchant generators, and integrate significant increases in distributed energy resources and energy storage, it will be important to consider how the reliance on these diverse assets may increase or decrease resilience. Utilities will need to evaluate these evolving interdependencies across the electricity sector in resilience planning, as well as the interdependencies across their supply chains and with other sectors.

Resilience planning will also need to address those segments of society, particularly vulnerable populations that may be disproportionately affected due to less capacity to prepare for, respond to, and recover from climate-related hazards and effects.

In addition, utilities will need to continue to work with stakeholders and customers to find innovative changes to technology and behavior that can unlock energy efficiency, adoption of smart grid, microgrids, distributed generation and storage, and reduce peak loads (e.g., demand response). Additional work is needed to support development and integration of such programs into a portfolio of resilience measures.

This report provides a foundation for moving forward on climate resilience in the electricity sector, and may be updated as new information on climate hazards and implementation of resilience measures becomes available.

Nomenclature and List of Acronyms

ADCIRC	ADvanced CIRCulation Model
BCA	Benefit-cost analysis
CAIDI	Customer Average Interruption Duration Index
CIGRE	International Council on Large Electric Systems
DHS	U.S. Department of Homeland Security
DOE	U.S. Department of Energy
EEI	Edison Electric Institute
EIA	Energy Information Administration
EIMA	Energy Infrastructure and Modeling and Analysis Division
ENSO	El Niño–Southern Oscillation
EPSA	Office of Energy Policy and Systems Analysis
EPRI	Electric Power Research Institute
ERIP	Emergency Restoration Implementation Procedure
FEMA	Federal Emergency Management Agency
GIS	Geographic information system
GDP	Gross domestic product
HSIP	Homeland Infrastructure Foundation-Level Data
ICE	Interruption cost estimate
ICF	ICF International
IPCC	Intergovernmental Panel on Climate Change
kV	Kilovolt
kW	Kilowatt
kWh	Kilowatt-hour
LBNL	Lawrence Berkeley National Laboratory
LNG	Liquefied natural gas
LSEP	Logistics Support Emergency Procedures
MSA	Metropolitan statistical area
MW	Megawatt
MWh	Megawatt-hour
NARUC	National Association of Regulatory Utility Commissioners
NCA	National Climate Assessment
NED	National elevational dataset
NEMA	National Electrical Manufacturers Association
NERC	North American Electric Reliability Corporation
NESC	National Electric Safety Code
NGA	National Geospatial-Intelligence Agency
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NPV	Net present value
NRC	National Research Council
NYPA	New York Power Authority
OE	Office of Electricity Delivery & Energy Reliability
OMS	Outage management system
PDO	Pacific Decadal Oscillation
PMU	Phasor measurement unit

REP	Reliability Enhancement Program
RDM	Robust decision making
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SLOSH	Sea, Lake and Overland Surges from Hurricanes Model
SLR	Sea level rise
SRP	Strategic resource plan
USACE	U.S. Army Corps of Engineers
USAID	U.S. Agency for International Development
USEPA	U.S. Environmental Protection Agency
USGCRP	U.S. Global Climate Research Program
VOLL	Value of lost load

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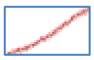
Appendix A: Bibliography of Key Resources

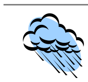
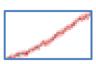
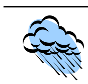
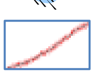
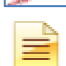
Having ready access to relevant information is an important element in strengthening electricity asset-owners' efforts to enhance resilience to climate change. This annotated bibliography builds on a compilation of existing information about the data, tools, plans, and actions critical to aiding the power sector in its efforts to enhance its resilience (see DOE 2015a). The bibliography organizes the available information by source (government, academic, or nongovernmental organizations) and utilities. The website URLs were accessed April 2016. It also identifies the type of information contained in the document with the following icons:

 Source contains information on impacts and vulnerabilities

 Source contains information on future climate change

 Source contains information on resilience plans and actions

Table 10. Bibliography of Key Resources.

Government	
 	1. U.S. Global Change Research Program, *Third National Climate Assessment* (April 2014) Observed and projected changes in many climate (or climate-related) variables, including temperature, precipitation, and sea level, both at the national and regional level. Assessment of vulnerabilities for a variety of sectors, including energy, water, and transportation. Some discussion of potential adaptation options and activities underway. *Full report:* http://nca2014.globalchange.gov/ *Technical input for Energy Supply and Use:* http://www.esd.ornl.gov/eess/EnergySupplyUse.pdf *Technical input for Energy-Water-Land:* http://www.pnnl.gov/publications/abstracts.asp?report=404278 *Technical input for Coasts:* http://www.ssec.wisc.edu/~kossin/articles/NCA_Coasts.pdf *Technical inputs for various regions:* http://www.globalchange.gov/engage/process-products/NCA3/technical-inputs
  	2. Climate Resilience Toolkit This U.S. Government website provides access to a wide variety of tools designed to support various aspects of climate resilience assessment, including assessing vulnerability and planning resilience measures. See: https://toolkit.climate.gov/

3. Climate Data Initiative

This U.S. Government website provides access to a wide set of federal datasets relevant to assessing climate resilience. This information portal includes an energy theme they will relevant to electricity asset owners.

See: http://www.climate.data.gov

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4. Executive Office of the President, *Economic Benefits of Increasing Electric Grid Resilience to Weather Outages* (August 2013)

This report estimates the annual cost of power outages caused by severe weather between 2003 and 2012 based on estimates of damages including lost output and wages, spoiled inventory, delayed production, inconvenience and damage to the electric grid. The report also describes various strategies for modernizing the grid and increasing grid resilience, and features case studies of efforts to improve grid resilience across the country.

See: http://energy.gov/sites/prod/files/2013/08/f2/Grid%20Resiliency%20Report_FINAL.pdf

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5. Hurricane Sandy Rebuilding Task Force, *Hurricane Sandy Rebuilding Strategy: Stronger Communities, A Resilient Region* (August 2013)

As part of the Administration's efforts following the damage caused by Hurricane Sandy, this interagency task force was created in 2012 and charged with developing and implementing guidelines for investing federal funds for the purpose of the resilient rebuilding of areas hit by the storm. The resulting Rebuilding Strategy includes 69 recommendations for guiding a coordinated federal, state, and local response to making communities more resilient to future extreme weather events.

See: http://portal.hud.gov/hudportal/documents/huddoc?id=HSRebuildingStrategy.pdf

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6. U.S. Department of Energy (DOE), *U.S. Energy Sector and Climate Change: Regional Vulnerabilities and Resilience Solutions* (October 2015)

Overview of current and potential future impacts of climate change on the U.S. energy sector at the regional level, and regional resilience actions that are being adopted to develop and deploy a climate-resilient energy system.

See: http://www.energy.gov/sites/prod/files/2015/10/f27/Regional_Climate_Vulnerabilities_and_Resilience_Solutions_0.pdf

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7. U.S. Department of Energy (DOE), *U.S. Energy Sector Vulnerabilities to Climate Change and Extreme Weather* (July 2013)

Overview of the ways in which weather and climate can affect energy demand and disrupt or damage portions of the energy supply chain, ranging from fuel production to power generation, transmission, and distribution.

See: http://energy.gov/sites/prod/files/2013/07/f2/20130716-Energy%20Sector%20Vulnerabilities%20Report.pdf

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8. U.S. Department of Energy (DOE), Effect of Sea Level Rise on Energy Infrastructure in Four Major Metropolitan Areas. (2014)

Analysis of sea level rise exposure for energy assets in Miami, Los Angeles, New York, and Houston. Includes methodology for rapid assessment that relies on public data and could be replicated in other areas.

See: http://energy.gov/oe/downloads/effect-sea-level-rise-energy-infrastructure-four-major-metropolitan-areas-september

9. U.S. DOE, *Hardening and Resiliency: U.S. Energy Industry Response to Recent Hurricane Seasons* (August 2010)

This study focuses on the measures that refiners, petroleum product pipeline operators, and electric utilities in the Gulf Coast have taken to harden their assets and make energy supply to the Southeast more resilient.

See: http://www.oe.netl.doe.gov/docs/HR-Report-final-081710.pdf

10. U.S. DOE, *The Water-Energy Nexus: Challenges and Opportunities* (June 2014)

This report describes potential challenges within water and energy systems posed by climate change and other factors, and describes DOE's efforts to address these challenges through technology, modeling, and other projects.

See: http://energy.gov/sites/prod/files/2014/07/f17/Water%20Energy%20Nexus%20Full%20Report%20July%202014.pdf

11. U.S. Government Accountability Office (GAO), *Energy Infrastructure Risks and Adaptation Efforts* (January 2014)

This report describes various measures that can reduce climate-related risks and adapt energy infrastructure to climate change, including examples implemented by various energy companies.

See: http://www.gao.gov/assets/670/660558.pdf

12. New York State Energy Research and Development Authority (NYSERDA), *Responding to Climate Change in New York State: Technical Report*, Chapter 8: Energy (November 2011)

This chapter provides information on climate change impacts and adaptation for the energy sector in New York State. Case studies are used to examine specific vulnerabilities and potential adaptation strategies within the energy sector.

See: http://www.nyserda.ny.gov/-/media/Files/Publications/Research/Environmental/EMEP/climaid/ClimAID-Energy.pdf

13. Florida Energy Resiliency, *Florida Energy Resiliency Report* (December 2013)

In this document, Florida's 11 Regional Planning Councils identify and assess approaches and strategies that can be used to enhance energy resilience. Case studies of these types of strategies in action are highlighted.

See: http://www.tbrpc.org/edd/pdfs/FlEnergyResiliencyReport_Dec2013.pdf

14. ICE Calculator

The Interruption Cost Estimate (ICE) Calculator is a tool designed for electric reliability planners at utilities, government organizations or other entities that are interested in estimating interruption costs and/or the benefits associated with reliability improvements.

See: http://icecalculator.com/

15. U.S. Energy Information Administration (EIA), Flood Risk Mapping Tool

A new component of EIA's Energy Mapping System allows users to view critical energy infrastructure that may be vulnerable to coastal and inland flooding. These new map layers enable the public to see existing energy facilities that could potentially be affected by flooding caused by hurricanes, overflowing rivers, flash floods, and other wet-weather events.

See: http://www.eia.gov/todayinenergy/detail.cfm?id=17431

Academic or Non-Governmental Organizations

1. Electric Power Research Institute (EPRI), Enhancing Distribution Resiliency: Opportunities for Applying Innovative Technologies (January 2013)

This report describes innovative technologies related to the distribution system being developed by EPRI, its members, and collaborators in the areas of prevention, recovery and survivability. EPRI has initiated a multi-year research initiative for participating members to provide them with information for making decisions on investments in enhancing the resilience of distribution systems.
See:
http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001026889

2. Edison Electric Institute (EEI), *Before and After the Storm: A Compilation of Recent Studies, Programs and Policies Related to Storm Hardening and Resiliency* (March 2014)

A detailed compilation of studies related to system hardening and resilience measures adopted by electric utilities to address the risks of extreme weather. The report also looks in detail at state-by-state cost recovery mechanisms, regulatory decisions, and legislative proposals.
See:
http://www.eei.org/issuesandpolicy/electricreliability/mutualassistance/Documents/BeforeandAftertheStorm.pdf

3. GridWise Alliance (GWA), *Improving Electric Grid Reliability and Resilience: Lessons Learned from Superstorm Sandy and Other Extreme Events* (June 2013)

In January 2013, GWA conducted a workshop entitled “Grid Modernization Impacts During Superstorm Sandy and Other Very Large Scale Grid Events” to explore electric system-related challenges experienced during recent significant events and potential opportunities to help alleviate their effects. This report summarizes key lessons learned and recommendations for electric utilities to enhance resilience in the following areas: (1) preventing power outages; (2) restoring power to affected customers; (3) communicating with stakeholders; and (4) serving or restoring critical loads.

See:
http://www.gridwise.org/documents/ImprovingElectricGridReliabilityandResilience_6_6_13webFINAL.pdf

4. National Electrical Manufacturers Association (NEMA), *Storm Reconstruction: Rebuild Smart – Reduce Outages, Save Lives, Protect Property* (2013)

This report describes various strategies and technologies for resilience, including smart grid solutions, microgrids, energy storage, distributed/decentralized energy systems, and backup generation.

See: https://www.nema.org/Storm-Disaster-Recovery/Documents/Storm-Reconstruction-Rebuild-Smart-Book.pdf

5. America’s WETLAND Foundation, *Beyond Unintended Consequences: Adaptation for Gulf Coast Resiliency and Sustainability* (2012)

This report offers 30 recommendations for Gulf Coast sustainability based on research and testimony from a series of leadership forums held in 11 communities from Texas to Florida during a 14-month period in 2011 and 2012.

See: http://www.futureofthegulfcoast.org/AmericasWETLANDFoundation_Beyond.pdf

6. Center for Climate and Energy Solutions, *Weathering the Storm: Building Business Resilience to Climate Change,* Case Study: National Grid (July 2013)

This case study describes how National Grid assessed future climate risks and evaluated strategies to address these risks.

See: http://www.c2es.org/docUploads/cs-national-grid.pdf

7. National Association of Regulatory Utility Commissioners, *Resilience in Regulated Utilities* (November 2013)

This report looks at the critical issue of defining a metric for resilience planning and investment decisions. It discusses a variety of definitions of resilience and looks at the applicability of existing metrics currently used by the utility industry to measure reliability. It suggests ways that existing metrics might be modified to better accommodate concerns about resilience in regulatory proceedings.

See: https://pubs.naruc.org/pub/536F07E4-2354-D714-5153-7A80198A436D

8. National Association of Regulatory Utility Commissioners, *Resilience for Black Sky Days* (February 2014)

This report focuses on the need for reliability metrics related to "black sky days," those natural or manmade hazardous events that have impacts well beyond recent major outage events. The paper defines such events as those that result in more than 90 percent of customers experiencing outages of greater than 25 days. It suggests that utilities may want to incorporate the potential for such extreme events into their enterprise risk management systems.

See: http://www.sonecon.com/docs/studies/Resilience_for_Black_Sky_Days_Stockton_Sonecon_FINAL_ONLINE_Feb5.pdf

9. Cradden and Harrison, "Adapting Overhead Lines to Climate Change: Are Dynamic Ratings the Answer?," *Energy Policy* (December 2013)

Using future temperature projections, the authors investigate potential lowering of ratings of overhead transmissions and distribution lines in the United Kingdom. They find that the impacts from temperature, especially if combined with increases in cooling demand and renewable penetration, are relatively modest, and might best be addressed by dynamic ratings rather than infrastructure upgrades.

See: http://www.sciencedirect.com/science/article/pii/S0301421513008562

10. Jaglom, et al., "Assessment of Projected Temperature Impacts from Climate Change on the U.S. Electric Power Sector using the Integrated Planning Model®," *Energy Policy* (October 2014)

Assessment of changes in temperature, heating degree-days, cooling degree-days, and electricity demand through 2050. Using scenarios that assume the implementation of greenhouse gas reduction policies, the impacts on electricity fuel mixes and prices are examined.

See: http://www.sciencedirect.com/science/article/pii/S0301421514002675

11. Sathaye et al., *Estimating Impacts of Warming Temperatures on California's Electricity System*, California Energy Commission, Publication Number: CEC-500-2012-057 (July 2012)

This report outlines the results of a study of the impact of climate change on the energy infrastructure of California , including (1) high temperature impacts on power plant capacity, electricity generation, transmission lines, substation capacity, and peak electricity demand; (2) wildfire impacts near transmission lines; and (3) sea level encroachment upon power plants, substations, and natural gas facilities.

See: http://www.energy.ca.gov/2012publications/CEC-500-2012-057/CEC-500-2012-057.pdf

12. Audinet et al., "Climate Risk Management Approaches in the Electricity Sector: Lessons from Early Adapters," *Weather Matters for Energy*, pp. 17–64 (January 2014)

Energy sector actions to manage climate change risks and take advantage of future opportunities remain limited and patchy, and mostly in the developed world. The sector has focused on climate data analysis and research on impacts rather than on concrete capital, technological and/or behavioral adaptation responses. This experience holds a number of lessons regarding partnerships, the importance of operational adaptations, and the need incentives that reward adaptation action.

See: http://link.springer.com/chapter/10.1007/978-1-4614-9221-4_2

Utilities

1. Consolidated Edison Co. of New York and Orange and Rockland Utilities (Con Edison), *Post Sandy Enhancement Plan* (June 2013)

Following Superstorm Sandy, Con Edison developed this plan that includes a broad array of measures to improve the resiliency of energy systems in the face of future storms and other natural disasters.

See: http://www.coned.com/publicissues/PDF/post_sandy_enhancement_plan.pdf

2. Con Edison, *Sandy 2-Year Update* (October 2014)

Con Edison summarizes measures it has implemented as part of reaching the midpoint in its four-year, $1 billion plan, *Fortifying the Future*, to make its facilities and operations more resilient to extreme weather. This progress report includes descriptions of investments in hardening facilities, enhancing or replacing equipment, and redesigning networks. It also reports that these measures have prevented 25,000 storm-related outages this year. See: http://www.coned.com/newsroom/news/pr20141027.asp

Fortifying the Future: http://www.coned.com/fortifying-the-future/index.html

3. Public Service Electric and Gas (PSE&G): Energy Strong Program (May 2014)

In the wake of Superstorm Sandy, PSE&G received approval for a $1.2 billion, program for capital investments over the next 3--5 years aimed at enhancing the resilience of their electricity and natural gas distribution systems. For its electricity customers, these investments will include protecting, elevating or relocating substations most vulnerable to flooding, creating increased system redundancy and deploying smart grid technologies to enhance monitoring of operations. The plan also calls for enhanced communication systems to inform customers of outages and restoration times, enhanced storm training for implementing restoration strategies.

See: http://assets.njspotlight.com/assets/14/0521/2037

Energy Strong Program: https://www.pseg.com/family/pseandg/energy_strong/index.jsp

4. Florida Power and Light (FPL), 2013–2015 *Electric Infrastructure Storm Hardening Plan* (May 2013)

In May 2013, FPL announced a 3-year, $500 million investment in enhancing the resilience of its service to customers. This initiative builds investments in system hardening totaling nearly $460 million begun in 2007. The planned investments include additional hardening directed at servicing critical facilities, replacing transmission facilities with wind-tolerant concrete structures, and installing real-time water-level monitoring systems in flood-prone substations. The 2014 update to the plan was filed with the Florida PSC on March 3, 2014.

Plan: http://www.floridapsc.com/library/FILINGS/13/02408-13/02408-13.pdf

2014 update: http://www.psc.state.fl.us/Files/PDF/Utilities/Electricgas/DistributionReliabilityReports/2014/2014%20Florida%20Public%20Utilities%20Company%20Distribution%20Reliability%20Report.pdf

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5. Exelon, Summary of Exelon Responses to Stakeholder Feedback Ceres Stakeholder Review Meeting (May 2014)

This document summarizes stakeholder suggestions for Exelon in addressing climate change risks and the company's responses, including examples of resilience strategies in place or in development.

See: http://www.exeloncorp.com/assets/environment/docs/Ceres_stakeholder_responses_final.pdf

2013 Sustainability Report: http://assets.fiercemarkets.net/public/sites/energy/reports/exelonkeyreport.pdf

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6. San Diego Gas & Electric (SDG&E), *Smart Grid Deployment Plan* (2014)

This plan describes SDG&E's efforts to improve the reliability and resilience of its energy through smart grid deployment.

See: http://www.sdge.com/sites/default/files/documents/337677296/Smart%20Grid%20Deployment%20Plan%202014%20Annual%20Report.pdf?nid=12436

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7. Entergy, Building a Resilient Energy Gulf Coast: Executive Report (October 2010)

This report assesses the current costs to the Gulf region from tropical storms, as well as the potential future costs from climate change. The report provides a suite of adaptation measures, with estimates of both the marginal benefits and costs.

See: http://entergy.com/content/our_community/environment/GulfCoastAdaptation/Building_a_Resilient_Gulf_Coast.pdf

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8. Tennessee Valley Authority (TVA), *Climate Change Adaptation Action Plan* (June 2012)

TVA completed a high-level vulnerability assessment and developed this adaptation plan which summarizes planning activities and projects.

See: https://www.tva.gov/file_source/TVA/Site%20Content/About%20TVA/Guidelines%20and%20Reports/Sustainability%20Plans%20and%20Performance/TVA_Climate_Change_Adaptation_Plan_2012-2.pdf

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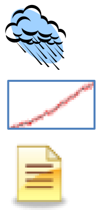
9. National Grid, *Climate Change Adaptation Report* (September 2010)

In accordance with the UK Climate Change Act, National Grid conducted a risk assessment of its assets and operations using climate scenarios provided by the government to operators of critical national infrastructure. The report contains detailed information about anticipated climate change in the United Kingdom, vulnerabilities of specific asset types, potential adaptation options, and ongoing risk management strategies.

See: http://www.c2es.org/docUploads/cs-national-grid.pdf



10. Northern Powergrid, *Climate Change Adaptation Report* (October 2011)

Similar to the National Grid Climate Change Adaptation Report, Northern Powergrid conducted a risk assessment of its assets and operations. This report identifies climate change impacts on the functions of the two licensed electricity distribution companies, Northern Powergrid (Yorkshire) and Northern Powergrid (Northeast), operated by Northern Powergrid and the proposed mechanisms for monitoring and actions to respond to the likely impacts of climate change.

See: http://www.northernpowergrid.com/asset/0/document/194.pdf

Appendix B: Key Sensitivities of Electricity Assets to Sea Level Rise and Storm Surge

Sensitivity refers to the type and degree of impacts that an electric power asset would experience when exposed to hazards, including the threshold at which the impacts are observed. Table 11 provides examples of sensitivities of a range of electricity assets to SLR and storm surge hazards.

Table 11. Key Sensitivities of Electricity Assets to SLR and Storm Surge.

Electric Power Sector Category	Electricity Asset Type	Key Sensitivities	Source
Generation	Electrical substation	Flooding can affect sub-station access and egress; induce corrosion in equipment; cause damage to substation equipment like circuit breakers, communication panels, relay panels, transformers, etc. due to deposition of contaminants; and expose grounding contacts.	CIGRE 2015
	Back-up power supply sources	Flooding can affect air intake vents for diesel generators; cause water seepage into fuel tanks or diesel generators; and affect the at-grade/underground battery bank.	Hamilton 2007
Transmission	Substation assets	Saltwater flooding promotes rapid corrosion of internal electrical components (seen in low-lowing power substations in Mississippi and Louisiana during Hurricanes Katrina and Rita; even equipment that was pressure washed with fresh water immediately after the storm had to be replaced).	DOE 2010
		The most prevalent cause of damage to substations in coastal regions is flooding from storm surge.	DOE 2010
		Floodwater not only contaminates the control cabinets and the mechanisms with silt and chemicals, but in many cases moisture may leak into the live part chambers.	CIGRE 2015
		Flood can cause ground wash-aways in substations, creating movement of foundations and settlement of HV equipment, breaking of HV connectors because of elongation of stranded conductor, and sinking of cable ducts and shortening of control cable connections.	CIGRE 2015
		Metallic items in a substation are prone to problems with corrosion; water that infiltrates a brushing can produce a humid condition that is ideal for oxidation of the metal. In this case, the corrosion creates penetrable paths for the SF6 gas leakage and water vapor ingress, which can eventually lead to a catastrophic event when the lightning impulse breakdown strength of the SF6	CIGRE 2015

Electric Power Sector Category	Electricity Asset Type	Key Sensitivities	Source
		is lower than the lightning overvoltage that can occur prior to a brushing explosion.	
	Circuit breakers	Gas insulated circuit breakers (such as SF6) are more resilient than air insulated circuit breakers.	PEPCO 2013
	Transformers	Transformers are one of the most vulnerable components in transmission substations.	Quadrennial Energy Review 2015
	Underground cables	Additional repair time is often required and higher susceptibility to damage from storm surge flooding (frequent and prolonged flooding in 2004 and 2005 resulted in water intrusion and corrosion to Progress Energy's underground equipment in Florida). Gulf Power reported in 2005 that some of its underground assets in coastal communities were washed out to sea. Storm surge and wave action from Hurricane Ivan physically uncovered and destroyed miles of underground lines in Alabama in 2004—some locations remained without power for more than a year.	DOE 2010
		Restoration times after an outage are longer because of the complicated nature of the system and the inability of restoration crews to visually pinpoint the cause of disruption.	EEI 2014
	Ground grid (added to original list of assets)	Flood can affect the ground grid in two ways: flooding that erodes the substation soil and exposes the ground grid is a safety hazard and loose ground contacts can cause touch potential and ground neutral shifts; flooding could deposit sludge silt and debris that must be skimmed off and all leads and connectors must be tested.	CIGRE 2015
	Protection/ control equipment	Control houses may be physically destroyed by flood conditions; erosion created by floods can damage fences and roads, creating safety issues around substations.	CIGRE 2015
		The monitoring, protection, and control equipment housed at the transformer stations is normally located below grade in basements. Floodwater can damage this equipment and cause a mis-operation of protection and control systems. Also, if the enclosures are not weatherproofed, the controls and switchgear are more vulnerable to flooding and storm events.	NERC 2015
Distribution	Electric poles	Foundation stability presents problems for the electrical poles in wetlands.	PEPCO 2013

Electric Power Sector Category	Electricity Asset Type	Key Sensitivities	Source
General sensitivity information for multiple assets		Salt water is destructive to energy infrastructure because it corrodes metal, electrical components, and wiring.	DOE 2010
		Plaster, wallboard, insulation, and electronic components must remain permanently dry.	DOE 2010
		Wood components may be susceptible to damage from trapped moisture.	DOE 2010
		Storm surge exerts pressure on everything in its path and causes soil erosion, especially around solid objects.	DOE 2010
		Breaking waves carry floating debris that can cause extensive physical damage.	DOE 2010
		When components of electric transmission and distribution infrastructure are flooded with seawater during storm surge events, the salt water may permanently damage electrical components.	DOE 2015a
		In general, more frequent and intense coastal flooding is expected to result in increased frequency of longer-term localized outages due to flooded and corroded equipment, as well as increased damage from saltwater encroachment and structural damage due to wave action.	DOE 2015a
		More severe storms and flooding impair the ability of repair crews to respond and restore service.	DOE 2015a
		Submersion from flooding shortens the life of any asset not specifically designed to be submerged.	CIGRE 2015
		The failure of most equipment is caused by the penetration of water or moisture into a cabinet or control enclosure—the water creates short circuits and causes premature or inadvertent operation of equipment.	CIGRE 2015

Appendix C: Estimated Costs of Resilience Measures

Table 12 below provides additional information regarding costs of resilience measures from publicly available sources. Appendix D contains the publicly available source documents referenced in Table 12 in the column labeled "Source Doc ID."

Table 12. Estimated Costs of Resilience Measures.

Type of Resilience Measure	Example Resilience Measure	Cost Information	Notes/Factors Affecting Cost Data	Source Doc ID
Hardening Existing Assets	Undergrounding – general	Estimate costs between $80K and $3M per mile	Coupling installations with other major excavation projects could also reduce the costs and disruptive impacts of undergrounding	DOC01
Hardening Existing Assets	Undergrounding – general	Estimate costs to be as high as $4M per mile to underground in New York	May not be a viable option in certain utility service areas given the high costs and ongoing impact to ratepayer's bills	DOC02
Policy, Planning, and Operations	Behavioral residential electric program	Central Hudson Home Energy Reporting: $4,220,027 budget ($78/MWh target); NiMo Residential Building Practices and Demonstration: $3,697,437 ($54/MWh target); NYSEG Home Energy Reports Demonstration: $790,280 budget ($49/MWh target); RG&E Home Energy Reports Demonstration: $698,948 budget ($50/MWh target)	Moreland Commission notes that there is no metric to compare programs; also notes that there is known inaccuracy in some of the data	DOC02

Type of Resilience Measure	Example Resilience Measure	Cost Information	Notes/Factors Affecting Cost Data	Source Doc ID
Policy, Planning, and Operations	Bounty residential electric program	Central Hudson Residential Appliances Recycling: $5,565,727 budget ($457/MWh target); Con Edison Appliance Bounty: $23,842,141 budget ($349/MWh target); NiMo Residential Energy Star Products and Recycling: $15,135,000 budget ($418/MWh target); NYSEG Refrigerator and Freezer Recycling: $6,842,105 budget ($314/MWh target); NYSEG Refrigerator and Freezer Recycling: $6,842,105 budget ($314/MWh target); O&R Residential Efficient Products: $3,972,977 budget ($375/MWh target); RG&E Refrigerator and Freezer Recycling: $6,842,105 budget ($314/MWh target)	Moreland Commission notes that there is no metric to compare programs; also notes that there is known inaccuracy in some of the data	DOC02
Policy, Planning, and Operations	Comprehensive residential electric program	NYSERDA Home Performance with Energy Star: $22,321,822 budget ($612/MWh target); NYSERDA NY Energy Star Homes: $8,501,849 budget ($338/MWh target)	Moreland Commission notes that there is no metric to compare programs; also notes that there is known inaccuracy in some of the data	DOC02
Policy, Planning, and Operations	Rebate residential electric program	Central Hudson Residential HVAC: $5,999,886 budget ($1,086/MWh target); Con Edison Residential Direct Installation: $15,83,713 budget ($557/MWh target); Con Edison Residential HVAC: $26,731,475 budget ($2,241/MWh target); Con Edison Residential Room Air Conditioning: $7,942,072 ($1,203/MWh target); NiMo Enhanced Home Sealing Incentives: $6,993,600 budget ($590/MWh target)	Moreland Commission notes that there is no metric to compare programs; also notes that there is known inaccuracy in some of the data	DOC02
Hardening Existing Assets	Elevating substations	$825K to raise substation elevation by 8 ft. for flood risk reduction	From Entergy 2007 Cost Estimate Study on hardening incentives	DOC03
Policy, Planning, and Operations	Annual patrols – transmission	$136,000/year	Quanta Report to Texas PUC	DOC03

Type of Resilience Measure	Example Resilience Measure	Cost Information	Notes/Factors Affecting Cost Data	Source Doc ID
Policy, Planning, and Operations	Annual patrols – distribution	$2,760,000/year	Quanta Report to Texas PUC	DOC03
Policy, Planning, and Operations	Backup generators	$21,800,000/year	Quanta Report to Texas PUC. For substations within 50 mi. of coast	DOC03
Policy, Planning, and Operations	Backup generators	$4,152,000/year	Quanta Report to Texas PUC. For central offices within 50 mi. of coast	DOC03
Hardening Existing Assets	Undergrounding transmission	$32B for all existing transmission, $2.4B for targeted approach	Quanta Report to Texas PUC	DOC03
Hardening Existing Assets	Undergrounding distribution	$28B for all existing distribution, $320M for targeted approach	Quanta Report to Texas PUC	DOC03
Policy, Planning, and Operations	Vegetation management – distribution	Ranges from $3,000 to $12,000 per mile	Quanta Report to Texas PUC	DOC03
Policy, Planning, and Operations	Vegetation management – transmission	Ranges from $300 to $900 per mile	Quanta Report to Texas PUC	DOC03
Policy, Planning, and Operations	Vegetation management – patrol	Ranges from $17 to $65 per mile (transmission)	Quanta Report to Texas PUC	DOC03
Policy, Planning, and Operations	Vegetation management – patrol	Ranges from $1 to $25 per mile (distribution)	Quanta Report to Texas PUC	DOC03
Policy, Planning, and Operations	Ground based inspection program – transmission	2008 Transmission Inspection Costs (Actual Reported Costs): AEP – $78/mi; Cap Rock $60/mi; Center Point $536/mi; Entergy $1,340/mi; TNMP $502/mi	Differences in types of structures being inspected, number of structures per mile and whether equipment must be climbed to inspect account for variance in transmission costs; Entergy also includes the cost of sounding and boring to check for wood deterioration	DOC03
Policy, Planning, and Operations	Ground based inspection program – distribution	2008 distribution inspection costs: AEP – $74.08/mi; Cap Rock $10/mi; Center Point $395.11/mi; Entergy $230.19/mi; TNMP $40.34/mi	Estimated costs for AEP & Center Point; all others actual reported costs	DOC03

Type of Resilience Measure	Example Resilience Measure	Cost Information	Notes/Factors Affecting Cost Data	Source Doc ID
New Construction or relocation	Building new substation	$6M per substation	Estimate to build substation outside of 100-year floodplain; does not account for higher cost of land, transmission line taps and feeder extensions	DOC03
New Construction or relocation	Building new central office	$1.5M per Central Office	Estimate to build substation outside of 100-year floodplain; does not account for higher cost of land, nor the high cost for facility extensions away from the Central Office	DOC03
Policy, Planning, and Operations	Backup generators	$20,000 to purchase a 10-Kw backup generator to power substation in emergency situation	Cost of automatic transfer switch as well as the fuel source will determine total	DOC03
Hardening Existing Assets	Elevating substation	$825,000 to elevate substation by 8 ft. for flood risk reduction (Entergy estimate)	2007 estimated costs	DOC03
Policy, Planning, and Operations	Backup generators	Verizon reports costs of $860,000 to install emergency generators and fuel tanks at 8 Central Offices.	Reported actual costs	DOC03
Hardening Existing Assets	Upgrading transmission lines	Total cost – $23B ($459,000/mi or $61,000/structure) to upgrade existing lines to meet current NESC standards	Increased wind-loading requirement for transmission lines and other equipment over 60 feet. Actual reported per mile costs: Entergy $734,000/mi; Center Point & TNMP $941,000/mi; AEP (Victoria) $105,000/mi; AEP (Corpus & Brownsville) $420,000/mi.	DOC03
Hardening Existing Assets	Replacing wood Poles	Incremental cost to replace wood poles with concrete $24,000/mi; with steel poles $16,000–$39,000. Cost per mile by type of pole installed: Wood Pole: $180,000/mi; Concrete single pole: $250,000/mi; Steel monopole $240,000/mi; Steel lattice tower: $375,000	Moving Average prices for steel poles provided by Center Point based on no specific application or design. Material Costs: Wood Pole: $6,500; Concrete Pole: $8,300; Steel monopole $11,000; Steel lattice tower: $14,500	DOC03
Hardening Existing Assets	Building floodwalls	$4M for 12-foot-high, 1-mile-long floodwall	Refinery erected along Houston Ship Channel to contain a 100-year storm surge	DOC04

Type of Resilience Measure	Example Resilience Measure	Cost Information	Notes/Factors Affecting Cost Data	Source Doc ID
Hardening Existing Assets	Elevating operational assets	$500–$900 per square foot to raise assets 15–25 feet above ground	Based upon various attributes of the facility and the project design	DOC04
Hardening Existing Assets	Wind girders	Reported spending of $1.00–$1.30 per barrel of tank capacity for large sized tanks	Costs vary on a tank-by-tank basis	DOC04
Hardening Existing Assets	Upgrading hurricane shutters	Fuel supplies estimated costs to be approx. $5,000–$10,000 per site the upgrade hurricane shutters based upon size of location	Upgraded shutters can be installed quickly and with greater ease than plywood shutters	DOC04
Policy, Planning, and Operations	Backup generators	Cost for converting a retail station's wiring to handle a generator ranges reported to be $15,000 to $20,000	Florida requires retail stores within a half mile of evacuation routes to have generator power for their pumps; owners of more than 10 retail locations must have 10% powered by generator within 24 hours of an emergency declaration	DOC04
Hardening Existing Assets	Replacing wood transmission structures	Tampa Electric budgeted $10.7M to replace 584 structures with steel or concrete poles, and 99 sets of insulators with polymer replacements		DOC04
Hardening Existing Assets	Installing guy wires	Company interview revealed typical costs of $600–$900 per pole	Installing guy wires for extreme winds significantly increases cost, to $1,500–$3,100 per pole	DOC04
Hardening Existing Assets	Undergrounding – distribution	Southwestern Electric Power Company estimated a cost of $447,200 per circuit mile for underground wire		DOC04
Hardening Existing Assets	Elevating substations	Southwest Louisiana Electric Membership Corporation's Hardening plan estimated it would cost $5.2M to elevate three substations 13 ft. above sea level	Substations were flooded by hurricanes Ike and Rita	DOC04
New Construction or relocation	Moving operations complex	Entergy spent more than $25M to construct a new operations complex outside flood area in Jackson, Mississippi		DOC04
Policy, Planning, and Operations	Backup generators	2-MW trailer mounted unit costs approx. $1M with accessories and financing	Via gowpoer.com search	DOC04

Type of Resilience Measure	Example Resilience Measure	Cost Information	Notes/Factors Affecting Cost Data	Source Doc ID
Hardening Existing Assets	Reinforcing floodwall	$8M project to reinforce entire length of Port Arthur, Texas seawall		DOC04
Hardening Existing Assets	Undergrounding distribution	Con Edison estimated cost of undergrounding 30 miles of overhead circuits (strategically selected) to be approx. $200M	Focused on areas that have experienced highest storm damage impact and feeder supply facilities that are vital to maintain community support (hospital, police, fire, schools etc.)	DOC05
Hardening Existing Assets	Updating feeders and poles	FPL to spend $90M–$120M on plan to harden 91 feeders and poles at 3 highway crossings (in 2013)	Plan will impact approx. 445 miles of overhead electric circuits	DOC06
Hardening Existing Assets Upgrading	Updating circuits	FPL to spend $90M–$140M on a project which targets replacing equipment at 80–140 circuits each year	Projected annual costs	DOC06
Hardening Existing Assets	Submersible equipment	FPL to spend $1M–$3M to strengthen 15 vaults within 100-year flood levels in Miami downtown network with submersible equipment	Projected annual costs	DOC06
Hardening Existing Assets	Replacing wood transmission structures	FPL to spend estimated $45M–$70M per year to replace 1,100–1,600 wood transmission structures	Projected annual costs	DOC06
Hardening Existing Assets	Replacing ceramic insulators	FPL to spend estimated $3M–$4M per year to replace 600–640 ceramic insulators with polymer insulators	Projected annual costs	DOC06
Hardening Existing Assets	Substation hardening (flood)	FPL to spend $12M–$18M on water intrusion mitigation and installation of real-time water level monitoring systems and communications equipment inside 25 substations inside 100-year flood elevations	Projected annual costs	DOC06

Type of Resilience Measure	Example Resilience Measure	Cost Information	Notes/Factors Affecting Cost Data	Source Doc ID
Hardening Existing Assets	Undergrounding – transmission Urban – new construction	$3,500,000–$30,000,000 per mile	Urban: 150+ customers per sq. mi. Because each construction project is unique due to load, number of customers served, and various construction parameters, there is no precise cost per mile to build utility facilities of any type for any utility. The cost data in this report is not meant to be the absolute range in which utility construction costs must fall; rather, it is intended to provide a range of cost data that utilities have estimated on various projects. Also, because of the complexity of calculations involved with these costs, they are not typically updated frequently.	DOC08
Hardening Existing Assets	Undergrounding – transmission Suburban – new construction	$2,300,000–$30,000,000 per mile	Suburban: 51-149 customers per sq. mi. Because each construction project is unique due to load, number of customers served, and various construction parameters, there is no precise cost per mile to build utility facilities of any type for any utility. The cost data in this report is not meant to be the absolute range in which utility construction costs must fall; rather, it is intended to provide a range of cost data that utilities have estimated on various projects. Also, because of the complexity of calculations involved with these costs, they are not typically updated frequently.	DOC08

Type of Resilience Measure	Example Resilience Measure	Cost Information	Notes/Factors Affecting Cost Data	Source Doc ID
Hardening Existing Assets	Undergrounding – transmission Rural – new construction	$1,400,000–$27,000,000 per mile	Rural: 50 or fewer customers per sq. mi .Because each construction project is unique due to load, number of customers served, and various construction parameters, there is no precise cost per mile to build utility facilities of any type for any utility. The cost data in this report is not meant to be the absolute range in which utility construction costs must fall; rather, it is intended to provide a range of cost data that utilities have estimated on various projects. Also, because of the complexity of calculations involved with these costs, they are not typically updated frequently.	DOC08
Hardening Existing Assets	Undergrounding – distribution Urban – new construction	$1,141,300–$4,500,000 per mile	Urban: 150+ customers per sq. mi. Because each construction project is unique due to load, number of customers served, and various construction parameters, there is no precise cost per mile to build utility facilities of any type for any utility. The cost data in this report is not meant to be the absolute range in which utility construction costs must fall; rather, it is intended to provide a range of cost data that utilities have estimated on various projects. Also, because of the complexity of calculations involved with these costs, they are not typically updated frequently.	DOC08

Type of Resilience Measure	Example Resilience Measure	Cost Information	Notes/Factors Affecting Cost Data	Source Doc ID
Hardening Existing Assets	Undergrounding – distribution Suburban – new construction	$528,000–$2,300,000 per mile	Suburban: 51-149 customers per sq. mi. Because each construction project is unique due to load, number of customers served, and various construction parameters, there is no precise cost per mile to build utility facilities of any type for any utility. The cost data in this report is not meant to be the absolute range in which utility construction costs must fall; rather, it is intended to provide a range of cost data that utilities have estimated on various projects. Also, because of the complexity of calculations involved with these costs, they are not typically updated frequently.	DOC08
Hardening Existing Assets	Undergrounding – distribution Rural – new construction	$297,200–$1,840,000 per mile	Rural: 50 or fewer customers per sq. mi. Because each construction project is unique due to load, number of customers served, and various construction parameters, there is no precise cost per mile to build utility facilities of any type for any utility. The cost data in this report is not meant to be the absolute range in which utility construction costs must fall; rather, it is intended to provide a range of cost data that utilities have estimated on various projects. Also, because of the complexity of calculations involved with these costs, they are not typically updated frequently.	DOC08

Type of Resilience Measure	Example Resilience Measure	Cost Information	Notes/Factors Affecting Cost Data	Source Doc ID
Hardening Existing Assets	Undergrounding – transmission Urban – conversion	$536,760–$12,000,000 per mile	Urban: 150+ customers per sq. mi. Much of the conversion cost is reduced by the salvage value of the overhead material being removed.	DOC08
Hardening Existing Assets	Undergrounding – transmission Suburban – conversion	$1,100,000–$11,000,000 per mile	Suburban: 51-149 customers per sq. mi. Much of the conversion cost is reduced by the salvage value of the overhead material being removed.	DOC08
Hardening Existing Assets	Undergrounding – transmission Rural – conversion	$1,100,000–$6,000,000 per mile	Rural: 50 or fewer customers per sq. mi. Much of the conversion cost is reduced by the salvage value of the overhead material being removed.	DOC08
Hardening Existing Assets	Undergrounding – distribution urban – conversion	$1,000,000–$5,000,000 per mile	Urban: 150+ customers per sq. mi. Much of the conversion cost is reduced by the salvage value of the overhead material being removed.	DOC08
Hardening Existing Assets	Undergrounding – distribution Suburban – conversion	$313,600–$2,420,000 per mile	Suburban: 51-149 customers per sq. mi. Much of the conversion cost is reduced by the salvage value of the overhead material being removed.	DOC08
Hardening Existing Assets	Undergrounding – distribution Rural – conversion	$158,100–$1,960,000 per mile	Rural: 50 or fewer customers per sq. mi. Much of the conversion cost is reduced by the salvage value of the overhead material being removed.	DOC08
Hardening Existing Assets	Installing automated reclosers	Installation costs approx. $50,000 per recloser		DOC09

Type of Resilience Measure	Example Resilience Measure	Cost Information	Notes/Factors Affecting Cost Data	Source Doc ID
Hardening Existing Assets	Cable repair cost	Leaks can cost $50,000 to $100,000 to locate and repair; a leak detection system for a HPFF cable system can cost from $1,000 to $400,000 to purchase and install depending on the system technology; molded joints for splices in XLPE line could cost about $20,000 to repair; field-made splices could cost up to $60,000 to repair	Repair costs for an underground line are usually greater than costs for an equivalent overhead line	DOC11
Hardening Existing Assets	Directional drilling	The cost for directional drilling for HPGF cables costs $25 per foot per cable		DOC11
Hardening Existing Assets	Undergrounding – transmission	Installation of a new 69 kV underground single-circuit transmission line costs approximately $1.5 million per mile	Does not include cost of terminals, O&M costs, or indirect costs	DOC11
Hardening Existing Assets	Undergrounding – transmission	Installation of a new 138 kV underground line costs approximately $2 million per mile	Does not include cost of terminals, O&M costs, or indirect costs	DOC11
Policy, Planning, and Operations	Tree maintenance	Initial costs $3,000–$5,000 per mile greater for enhanced tree trimming program vs. routine trimming	Continued enhanced maintenance will result in an annual increase in the cost of the cyclical program in order to maintain the additional clearance; overall budget for vegetation management increased from approx. $1.0M to $1.5M	DOC12
Hardening Existing Assets	Undergrounding – distribution	$3,500,000–$11,500,000 per mile.	Low estimate covers conversion of only the mainline primary of the overhead feeder; high estimate reflects conversion of all existing overhead mainline primary, lateral primary taps, transformers and secondary mainline including service conductors; does not reflect cost imposed on customers to hire licensed electrician to convert overhead service to accept underground feed	DOC12

Type of Resilience Measure	Example Resilience Measure	Cost Information	Notes/Factors Affecting Cost Data	Source Doc ID
Hardening Existing Assets	Undergrounding – distribution	$1.1 B for PEPCO to underground all mainline primary	Shaw consultants estimate	DOC13
Hardening Existing Assets	Undergrounding – distribution	$2.3 B for PEPCO to underground all mainline primary and laterals	Shaw consultants estimate	DOC13
Hardening Existing Assets	Undergrounding – distribution	$5.8B for PEPCO to underground all existing overhead assets	Shaw consultants estimate	DOC13
Hardening Existing Assets	Undergrounding – distribution	$3,500,000 per mile to underground primary mainline, $1.2M per mile to underground transformers, $24,000/customer to underground secondary mainline, $7,000 per service for utility (commercial) $11,000 (residential), $16,000 per service by customer (commercial) $2,000 (residential), $316,000 per mile in streetlight costs, .38% of costs for permit fees and .77% for removal fees	2006 PEPCO cost estimate to update Feeder 14007; total cost to update 15 targeted feeders extrapolated from this estimate; estimated to be $1.06B	DOC13
Hardening Existing Assets	Undergrounding – distribution	$1.9M per mile to underground primary mainline, $3.0M when including indirect and miscellaneous costs	2010 Shaw cost estimate to update PEPCO Feeder 14007; indirect and Miscellaneous costs include (engineering, permits, removal, project management, overhead and contingency costs)	DOC13
Hardening Existing Assets	Undergrounding – distribution	City of Anaheim average cost to underground primary mainline (excluding sub-transmission) $3.5M per mile in 2007–2008 and $3.4M per mile in 2009; estimates for 2010 and beyond $3.8M per mile	Heavily developed areas and main arteries are initial focus of project.	DOC13
Enhancing Smart Grid and Microgrid Capabilities	Advanced metering infrastructure	Total cost of full AMI network ranges from $325–$680 per meter	Cost ranges developed with assistance from Itron and with input from distribution companies (Massachusetts) based on their experiences with their own programs	DOC14

Type of Resilience Measure	Example Resilience Measure	Cost Information	Notes/Factors Affecting Cost Data	Source Doc ID
Policy, Planning, and Operations	Tree maintenance	$5,000 per mile average tree maintenance cost	Formula created by CT Regulations, Legislation and Funding Working Group; notes that some municipalities may negotiate lower contract rates; average cost must be multiplied by 1.25 for urban and 0.75 for rural territory	DOC15
Policy, Planning, and Operations	Tree maintenance	PSNH spends $11M per year to trim 2,300 miles of distribution lines (approx. $4,800 per mile), up from $6M (approx. $2,600 per mile) prior to Reliability Enhancement Program (REP)	REP has shorter cycles for planned vegetation maintenance on distribution circuits and increased removal of danger and hazard trees	DOC19
Policy, Planning, and Operations	Tree maintenance	Until expended slightly over $778,000 to trim 87.5 miles ($9000 per mile) in 2008	Up from $794,000 to trim 175 miles ($5000 per mile) in 2003; report states that trimming may be excessive and cost benefit analysis should be reviewed	DOC19
Policy, Planning, and Operations	Tree maintenance	Trimming on 3-year feeder cycle for 4,454 mi of feeder lines and 6-year cycle for 2,215 mi of lateral lines FPL spent $65,200,000 in 2007 on vegetation management	Vegetation management programs generally consist of tree trimming, vine removal, herbicide applications, dead tree removal, and other maintenance performed at regular intervals; these cyclical maintenance routines are designed to prevent tree caused outages and contribute to overall system reliability	DOC20
Policy, Planning, and Operations	Tree maintenance	Trimming on 3-year cycle for 2,112 mi of feeder lines and 5-year cycle for 2,203 mi of lateral lines PEF spent 19,626,584 in 2007 on vegetation management	Vegetation management programs generally consist of tree trimming, vine removal, herbicide applications, dead tree removal, and other maintenance performed at regular intervals; these cyclical maintenance routines are designed to prevent tree caused outages and contribute to overall system reliability	DOC20

Type of Resilience Measure	Example Resilience Measure	Cost Information	Notes/Factors Affecting Cost Data	Source Doc ID
Policy, Planning, and Operations	Tree maintenance	Trimming on 3-year cycle for 363 mi of feeder lines and 3-year cycle for 945 mi of lateral lines TECO spent 10,300,000 in 2007 on vegetation management	Vegetation management programs generally consist of tree trimming, vine removal, herbicide applications, dead tree removal, and other maintenance performed at regular intervals; these cyclical maintenance routines are designed to prevent tree caused outages and contribute to overall system reliability	DOC20
Policy, Planning, and Operations	Tree maintenance	Trimming on 3-year cycle for 1,878 mi of feeder lines and 6-year cycle for 675 mi of lateral lines GULF spent 1,456,000 in 2007 on vegetation management	Vegetation management programs generally consist of tree trimming, vine removal, herbicide applications, dead tree removal, and other maintenance performed at regular intervals; these cyclical maintenance routines are designed to prevent tree caused outages and contribute to overall system reliability	DOC20
Policy, Planning, and Operations	Tree maintenance	Trimming on 3-year cycle for 36 mi of feeder lines and 6-year cycle for 54 mi of lateral lines FPUC spent 527,507 in 2007 on vegetation management	Vegetation management programs generally consist of tree trimming, vine removal, herbicide applications, dead tree removal, and other maintenance performed at regular intervals; these cyclical maintenance routines are designed to prevent tree caused outages and contribute to overall system reliability	DOC20
Hardening Existing Assets	Replacing wood transmission structures	TECO replaced 397 structure replacements with steel or concrete pols and 127 sets of insulators replaced with polymer insulators hardening 524 structures at cost of $7.5M	Also conducted above-ground and ground line inspections on 17% of transmission system (unclear if these costs included in $7.5M); TECO estimates it will cost $10.8M to harden 660 additional structures	DOC20

Type of Resilience Measure	Example Resilience Measure	Cost Information	Notes/Factors Affecting Cost Data	Source Doc ID
Hardening Existing Assets	Installing guy wires	Gulf installed guys on 150 H-frame transmission structures at a cost of approx. $1.5M	Installing guy wires increases the probable load to failure rate of the structure	DOC20
Hardening Existing Assets	Replacing wood cross-arms	Gulf to replace 727 cross arms at an estimated cost of approx. $3M	Based upon costs of 192 prior replacements	DOC20
Hardening Existing Assets	GIS systems	TELCO spent $1.8M in 2007 and projects spending $4.8M ($6.6M total) to implement at GIS system		DOC20
Hardening Existing Assets	GIS systems	FPUC installed a GIS mapping and customer outage system or a cost of $38,000	System covers NE and NW service areas	DOC20
Policy, Planning, and Operations	GIS systems	PEF estimates that total 2007 costs to consolidate and upgrade its GIS system at $1.27M	Placed all overhead and underground distribution facilities in GIS as well as 58 mi of underground transmission assets and 95% of overhead transmission assets	DOC20
Policy, Planning, and Operations	Tree removal	Estimated cost of $271.7M to increase conductor clearance 15 ft. on single-phase and 19 ft. on 3-phase distribution lines	Resulting benefit is 57% line security improvement (decrease in tree caused outages) for 3-phase lines and 49% for single phase lines	DOC24
Hardening Existing Assets	Undergrounding – distribution	Estimated $2.053M per mile to underground heavy/commercial distribution lines in NC	Resulting decrease in tree caused outages would be 100%. Total cost for entire system (Heavy/Commercial, three-phase suburban/rural and single-phase is $40.8B)	DOC24
Hardening Existing Assets	Undergrounding – distribution	Estimated $ 1.229M per mile to underground 3-phase suburban distribution in NC	Resulting decrease in tree caused outages would be 100%; total cost for entire system (heavy/commercial, three-phase suburban/rural and single-phase is $40.8B)	DOC24
Hardening Existing Assets	Undergrounding – distribution	Estimated $523K per mile to underground three-phase rural distribution lines in NC	Resulting decrease in tree caused outages would be 100%; total cost for entire system (heavy/commercial, three-phase suburban/rural and single-phase is $40.8B)	DOC24

Type of Resilience Measure	Example Resilience Measure	Cost Information	Notes/Factors Affecting Cost Data	Source Doc ID
Hardening Existing Assets	Undergrounding – distribution	Estimated $284K per mile to underground single-phase distribution lines in NC	Resulting decrease in tree caused outages would be 100%; total cost for entire system (heavy/commercial, three-phase suburban/rural and single-phase is $40.8B)	DOC24
Enhancing Smart Grid and Microgrid Capabilities	Installing synchrophasor (phasor measurement unit/PMU) network	NYISO has a $74M budget to install 39 PMUs across their service territory	PMUs deliver measurements at a sampling rate hundreds of times faster than existing SCADA technology	DOC32
Enhancing Smart Grid and Microgrid Capabilities	Advanced metering infrastructure	LIPA has approximately a $12.5M budget to install 2,500 smart meters at residential and commercial customer sites	Two-way communication devices provide operators real time service outage information	DOC32
Policy, Planning, and Operations	Upgrade control center	NYISO to spend $35.5M on build of new control center	Improves NYISO's ability to receive, process, and monitor changing conditions through the region	DOC32
Enhancing Smart Grid and Microgrid Capabilities	Technology testing pilot program	$44M for two-year pilot program in Northwest part of Worcester, Massachusetts to test Smart Grid technologies ability to reduce outages, save customers money by improving operational efficiency of the grid and to integrate renewable resources	The pilot will affect 11 feeders, 5 substations and roughly 15,000 customers; tests smart meters, fault detection, dynamic rates, volt/VAR optimization, electric vehicle charging, and energy storage	DOC32
Enhancing Smart Grid and Microgrid Capabilities	Compressed air energy storage plant	NYSEG has budget of $29,561,142 to demonstrate an advanced 150-MW compressed air energy storage facility	Utilizes an underground salt cavern to store compressed air	DOC32
Enhancing Smart Grid and Microgrid Capabilities	Smart grid feasibility study: compressed air energy storage plant	$200,000 study regarding the feasibility of constructing an air energy storage facility	Prior to receiving ARRA award to fund the demonstration project	DOC32
Hardening Existing Assets	Undergrounding – distribution & transmission	Estimated cost of $57.5B to underground Oklahoma's distribution and transmission networks	Estimate	DOC35
Policy, Planning, and Operations	Tree trimming	Oklahoma spent an estimated $63 million in 2007	4-year vegetation management cycle	DOC35

Type of Resilience Measure	Example Resilience Measure	Cost Information	Notes/Factors Affecting Cost Data	Source Doc ID
Hardening Existing Assets	Undergrounding – customer cost	Average cost for new meter base installation was approximately $400 for a utility company in Edmond, Oklahoma; other estimates range from $500–$2,000	Required to connect the home to the underground distribution network	DOC35
Hardening Existing Assets	Quick-release drop line connector (undergrounding alternative)	Quick release connector costs approximately $80; compared to $1,200 to $2,000 to bury an existing drop line	Releases power lines from utility pole before enough force is placed on the line to rip the weather head and meter off of the customer's home	DOC35
Enhancing Smart Grid and Microgrid Capabilities	Advanced metering infrastructure	SDG&E estimates it will take $1.298B to install 4.5 million smart meters (approx. $288/meter)	Estimated benefits $8.08M	DOC36
Enhancing Smart Grid and Microgrid Capabilities	Automated monitoring and controls	Progress Energy spent $14M to automate monitoring and control of all distribution feeder breakers (approx. 1000 feeder circuits)	Project took place in 1990s	DOC36
Enhancing Smart Grid and Microgrid Capabilities	Automated monitoring and controls	SCE planned to spend $6M/year on a circuit automation project and $1.2M/year on a capacitor automation project	Project began in 2004.	DOC36
Enhancing Smart Grid and Microgrid Capabilities	Upgrading PDAC system to SCADA system	PG&E estimates it will cost $30,000 per facility to upgrade PDAC systems to SCADA systems.	Project will also establish a new communications link via PG&E's radio communications systems; allows for failure of a single wire center without wide scale interference of line devices	DOC36
Enhancing Smart Grid and Microgrid Capabilities	Advanced metering infrastructure	PG&E estimates it will take $2.258B to install 9.2 million smart meters (approx. $245/meter)	Estimated benefits $2.4B	DOC36
Enhancing Smart Grid and Microgrid Capabilities	Advanced metering infrastructure	SDG&E estimates it will take $7.19M to install 2.3 million smart meters (approx. $312/meter)	Estimated benefits $7.83M	DOC36

Type of Resilience Measure	Example Resilience Measure	Cost Information	Notes/Factors Affecting Cost Data	Source Doc ID
Enhancing Smart Grid and Microgrid Capabilities	Converting reclosers for SCADA operation	PG&E estimates it will cost $40,000 per recloser to convert to SCADA operation	Also increases recloser performance, allows reclosers to operate remotely and provides load reads and indications of line faults	DOC36
Policy, Planning, and Operations	Replacing/ upgrading communications equipment	PG&E estimates it will cost $6.6M to upgrade communications equipment	Necessary to accommodate the volume of information provided by SCADA devices, replace obsolete communications equipment and to convert expensive leased line communications to radio or other more cost-effective mediums (fiber optic or cellular)	DOC36
Enhancing Smart Grid and Microgrid Capabilities	Pilot program – distribution automation	PG&E estimates it will cost $250,000 per pilot program to investigate an emerging approach to distribution automation systems	System aims to "integrate advanced features such as automatic load restoration and dynamic circuit monitoring/switching to prevent overloads and optimize voltage…using technology an industry standard protocol so future enhancements are more easily adapted for system expansion"	DOC36
Enhancing Smart Grid and Microgrid Capabilities	OMS system upgrades – distribution	SDG&E budgeted $80,000 to upgrade their outage management system (OMS) and to improve the integration of data from OMS and the SCADA system	Increases efficiency and reduces time required to identify and restore and outage	DOC36
Enhancing Smart Grid and Microgrid Capabilities	SCADA system redundancy	SDG&E budgeted $1.1M to expand the capabilities, reliability, functionality, and redundancy of SCADA system	Project supports the expansion of remote control and data acquisition from substations and field devices	DOC36
Enhancing Smart Grid and Microgrid Capabilities	OMS system upgrades – distribution	SDG&E estimates it will cost $14M per year from 2002 to 2004 to replace the existing OMS	New system improves communications through tracking of calls and web-based information for customers regarding outages; also increases the timeliness and accuracy of outage status reporting	DOC36

Type of Resilience Measure	Example Resilience Measure	Cost Information	Notes/Factors Affecting Cost Data	Source Doc ID
Enhancing Smart Grid and Microgrid Capabilities	Automated monitoring and controls	Hydro-Quebec automated 3,750 switches at a cost of $188M Canadian		DOC36
Hardening Existing Assets	Storm surge barriers	Estimated cost to be $20–$25B to erect harbor wide storm surge barriers to protect NYC.	Does not include substantial O&M costs	DOC37
Enhancing Smart Grid and Microgrid Capabilities	Installing microgrid	Siemens estimated that a $150M investment is required to install microgrid with an average load of 40MW	Includes O&M costs	DOC40
Enhancing Smart Grid and Microgrid Capabilities	Integrate distributed energy resources & building automation	NREL estimates that costs are approx. $100K to integrate each distributed energy resource/ building automation	Target for these costs is approx. $10k	DOC41
Enhancing Smart Grid and Microgrid Capabilities	Advanced battery storage	Capital costs for various battery types: Li-ion: $600–$1,200/kWh VRB: $350–$500/kWh NAS:$350–$500/kWh ZnBr: $150–$250/kWh	Source: NETL (2009)	DOC42
Enhancing Smart Grid and Microgrid Capabilities	Islanding	SDG&E estimates it will cost approx. $15M to island an entire substation area	SDG&E Beach Cities Microgrid Project	DOC42
Enhancing Smart Grid and Microgrid Capabilities	Advanced metering infrastructure	SDGE was approved to use $572M in ratepayer funds to deploy 1.4M AMI solid-state electric and 900k AMI enabled gas meters		DOC42
Policy, Planning, and Operations	Storm damage reserves fund	$90M–$200M		DOC51
Ecosystem-based Approach	Marsh restoration	Total cost of levee alone over 50 years is $12 million per mile. Total cost of levee with a 200-foot wide marsh in front is $5.5 million per mile; restoring a 200 foot wide marsh costs about $0.8 million per mile		DOC52

Type of Resilience Measure	Example Resilience Measure	Cost Information	Notes/Factors Affecting Cost Data	Source Doc ID
Ecosystem-based Approach	Marsh restoration	If the wetlands of New Orleans were to be restored, the estimated cost would be $2 per square meter for marshland stabilization and $4.30 per square meter for marshland creation		DOC53

Appendix D: Publicly Available Resources on the Costs of Resilience Measures

Table 13 provides the name and URL (accessed April 2016) of the publicly available source documents referenced in Table 12 in Appendix C. The cost information provided in these resources varies dramatically depending on a variety of factors, including location, technology, manufacturer, and design specifications. In some cases, differences between planned costs and built costs may not be provided, which may be an important source of uncertainty. Not all sources have been subjected to a consistent standard of peer review and actual estimates may vary.

Table 13. Source Document Names and URLs.

Doc ID	Document Name	URL
DOC01	Before and After the Storm (March 2014), prepared by Edison Electric Institute	http://www.eei.org/issuesandpolicy/electricreliability/mutualassistance/Documents/BeforeandAftertheStorm.pdf
DOC02	Moreland Commission on Utility Storm Preparation and Response – Final Report (June 22, 2013), prepared by Robert Abrams & Benjamin Lawsky	http://www.governor.ny.gov/sites/governor.ny.gov/files/archive/assets/documents/MACfinalreportjune22.pdf
DOC03	Cost-Benefit Analysis of the Deployment of Utility Infrastructure Upgrades and Storm Hardening Programs (March 4, 2009), prepared by Quanta Technology	http://www.puc.texas.gov/industry/electric/reports/infra/Utlity_Infrastructure_Upgrades_rpt.pdf
DOC04	Hardening and Resiliency (August 2010), prepared by Department of Energy	http://www.oe.netl.doe.gov/docs/HR-Report-final-081710.pdf
DOC05	Post Sandy Enhancement Plan (June 20, 2013), prepared by Consolidated Edison Co. of New York and Orange and Rockland Utilities	http://www.coned.com/publicissues/PDF/post_sandy_enhancement_plan.pdf
DOC06	Florida Power & Light Company 2013–2015 Electric Infrastructure Hardening Plan (May 1, 2013), filed with the Florida Public Service Commission in Docket No. 130132-EI	http://www.psc.state.fl.us/library/FILINGS/13/02408-13/02408-13.pdf
DOC07	Enhancing Distribution Resiliency – Opportunities for Applying Innovative Technologies (January 2013), prepared by the Electric Power Research Institute (EPRI)	http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001026889
DOC08	Out of Sight, Out of Mind 2012: An Updated Study on the Undergrounding of Overhead Power Lines (January 2013), prepared by Kenneth, L. Hall, P.E. of Hall Energy Consulting, Inc. for Edison Electric Institute	http://www.eei.org/issuesandpolicy/electricreliability/undergrounding/Documents/UndergroundReport.pdf
DOC09	Weathering the Storm: Report of the Grid Resiliency Task Force (September 24, 2012), delivered to the Office of Maryland Governor Martin O'Malley pursuant to Executive Order 01.01.2012.15	http://www.chevychasevillagemd.gov/assets/PEPCO/Grid%20Resiliency%20Task%20Force%20Report.pdf

Doc ID	Document Name	URL
DOC10	Weather-Related Power Outages and Electric System Resiliency (August 28, 2012), prepared by Richard J. Campbell, Congressional Research Service	http://www.fas.org/sgp/crs/misc/R42696.pdf
DOC11	Underground Electric Transmission Lines (May 2011), prepared by the Public Service Commission of Wisconsin	http://psc.wi.gov/thelibrary/publications/electric/electric11.pdf
DOC12	Potomac Electric Company Comprehensive Reliability Plan for District of Columbia, District of Columbia Order No. 15568 (September 2010)	http://www.pepco.com/uploadedFiles/wwwpepcocom/DCComprehensiveReliabilityPlan%281%29.pdf
DOC13	Study of the Feasibility and Reliability of Undergrounding Electric Distribution Lines in the District of Columbia, Formal Case No. 1026 (July 2010), submitted to Public Service Commission of the District of Columbia	http://oca.dc.gov/sites/default/files/dc/sites/oca/page_content/attachments/Study%20of%20the%20Feasibility%20%26%20Reliability%20of%20Undergrounding%20Electric%20Distribution%20Lines%20in%20DC%20%28July%201,%202010%29%20-%20ShawConsultantsforPSC.pdf
DOC14	Massachusetts Electric Grid Modernization Stakeholder Working Group Process: Report to the Department of Public Utilities by the Steering Committee (July 2, 2013), MA DPU 12-76	http://magrid.raabassociates.org/Articles/MA%20Grid%20Mod%20Working%20Group%20Report%2007-02-2013.pdf
DOC15	State Vegetation Management Task Force Final Report (August 28, 2012), issued to the Connecticut Department of Energy & Environmental Protection	http://www.ct.gov/deep/lib/deep/forestry/vmtf/final_report/svmtf_final_report.pdf
DOC16	Report of the Two Storm Panel (January 2012), presented to Governor Dannel P. Malloy	http://portal.ct.gov/Departments_and_Agencies/Office_of_the_Governor/Learn_More/Working_Groups/Governor_s_Two_Storm_Panel/
DOC17	Report on Transmission Facility Outages During the Northeast Snowstorm of October 29-30, 2011: Causes and Recommendations (May 31, 2012), prepared by the Staffs of the Federal Energy Regulatory Commission and the North American Electric Reliability Corporation	http://www.ferc.gov/legal/staff-reports/05-31-2012-ne-outage-report.pdf
DOC18	Best Practices in Vegetation Management for Enhancing Electric Service in Texas (November 11, 2011), submitted by Texas Engineering Experiment Station to the Public Utility Commission of Texas	http://www.puc.texas.gov/
DOC19	New Hampshire Public Utilities Commission, After Action Review: December ’08 Ice Storm (December 3, 2009)	http://www.puc.nh.gov/2008IceStorm/Final%20Reports/PUC%20IceStorm%20After%20Action%20Report%2012-03-09.pdf
DOC20	Report to the Legislature on Enhancing the Reliability of Florida’s Distribution and Transmission Grids During Extreme Weather (July 2008), submitted by the Florida Public Service Commission to the Governor and Legislature	http://www.psc.state.fl.us/Files/PDF/Utilities/Electricgas/EnergyInfrastructure/UtilityFilings/docs/AddendumSHLegislature.pdf

Doc ID	Document Name	URL
DOC21	Reliability Based Vegetation Management Through Intelligent System Monitoring (September 2007), prepared by Power Systems Engineering Research Center	http://pserc.wisc.edu/research/public_reports.aspx
DOC22	Report to the Legislature on Enhancing the Reliability of Florida's Distribution and Transmission Grids During Extreme Weather (July 2007), prepared by the Florida Public Service Commission and submitted to the Governor and Legislature to fulfill the requirements of Chapter 2006-230, Sections 19(2) and (3), at 2615, Laws of Florida, enacted by the 2006 Florida Legislature (Senate Bill 888)	http://www.psc.state.fl.us/Files/PDF/Publications/Reports/Electricgas/stormhardening2007.pdf
DOC23	Report on the Workshop for Best Practices in Vegetation Management (April 17, 2007), sponsored by Florida Electric Utilities	https://warrington.ufl.edu/centers/purc/docs/report_VegetationManagementWorkshop.pdf
DOC24	The Neglected Option for Avoiding Electric System Storm Damage & Restoration Costs – Managing Tree Exposure (2005), prepared by Siegfied Gueggenmoos of Ecological Solutions, Inc.	www.ecosync.com/Avoided%20Storm%20Costs.pdf
DOC25	Utility Vegetation Management Final Report (March 2004), prepared by CN Utility Consulting, LLC for the Federal Energy Regulatory Commission to support the federal investigation of the August 14, 2003 Northeast Blackout	www.ferc.gov/industries/electric/indus-act/reliability/blackout/uvm-final-report.pdf
DOC26	U.S. Energy Sector Vulnerabilities to Climate Change and Extreme Weather, Department of Energy (July 2013)	http://energy.gov/sites/prod/files/2013/07/f2/20130716-Energy%20Sector%20Vulnerabilities%20Report.pdf
DOC27	Storm Reconstruction: Rebuild Smart, Reduce Outages, Save Lives, Protect Property (2013), NEMA	http://www.nema.org/Storm-Disaster-Recovery/Documents/Storm-Reconstruction-Rebuild-Smart-Book.pdf
DOC28	New Hampshire December 2008 Ice Storm Assessment Report (October 28,2009), prepared by NEI Electric Power Engineering	https://www.puc.nh.gov/2008IceStorm/Final%20Reports/2009-10-30%20Final%20NEI%20Report%20With%20Utility%20Comments/Final%20Report%20with%20Utility%20Comments-complete%20103009.pdf
DOC29	Report on Transmission System Reliability and Response to Emergency Contingency Conditions in the State of Florida (March 2007), prepared by the Florida Public Service Commission and submitted to the Governor and Legislature to fulfill the requirements of Senate Bill 888	http://www.psc.state.fl.us/Files/PDF/Publications/Reports/Electricgas/transmissionreport2007.pdf
DOC30	The Hardening of Utility Lines – Implications for Utility Pole Design and Use (2007), North American Wood Pole Council, Technical Bulletin VII prepared by Martin Rollins, P.E.	http://woodpoles.org/portals/2/documents/TB_HardeningUtilityLines.pdf

Doc ID	Document Name	URL
DOC31	Economic Benefits of Increasing Electric Grid Resilience to Weather Outages (August 2013), prepared by the President's Council of Economic Advisers and the U.S. Department of Energy's Office of Electricity Delivery and Energy Reliability, with assistance from the White House Office of Science and Technology	http://energy.gov/sites/prod/files/2013/08/f2/Grid%20Resiliency%20Report_FINAL.pdf
DOC32	Powering New York State's Future Electricity Delivery System: Grid Modernization (January 2013), prepared by the New York State Smart Grid Consortium	http://nyssmartgrid.com/wp-content/uploads/2013/01/NYSSGC_2013_WhitePaper_013013.pdf
DOC33	Improving the Reliability and Resiliency of the US Electric Grid (2012), from Metering International Issue, authored by Debbie Haught and Joseph Paladino of the U.S. Department of Energy	http://energy.gov/sites/prod/files/Improving%20the%20Reliability%20and%20Resiliency%20of%20the%20US%20Electric%20Grid%20-%20SGIG%20Article%20in%20Metering%20International%20Issue%201%202012.pdf
DOC34	The Value of Distribution Automation (March 2009), prepared by Navigant Consulting for the California Energy Commission – Public Interest Energy Research Program	http://www.ilgridplan.org/Shared%20Documents/CEC%20PIER%20Report%20-%20The%20Value%20of%20Distribution%20Automation.pdf
DOC35	Oklahoma Corporation Commission's Inquiry into Undergrounding Electric Facilities in the State of Oklahoma (June 30, 2008), prepared and submitted by Oklahoma Corporation Commission Public Utility Division Staff	http://www.occeweb.com/pu/PUD%20Reports%20Page/Underground%20Report.pdf
DOC36	Value of Distribution Automation Applications (April 2007), prepared by Energy and Environmental Economics, Inc. and EPRI Solutions, Inc. for the California Energy Commission – Public Interest Energy Research Program	http://www.energy.ca.gov/2007publications/CEC-500-2007-028/CEC-500-2007-028.PDF
DOC37	A Stronger, More Resilient New York (June 11, 2013), from the City of New York Mayor Michael R. Bloomberg	http://www.nyc.gov/html/sirr/html/report/report.shtml
DOC38	Improving Electric Grid Reliability and Resilience: Lessons Learned from Superstorm Sandy and Other Extreme Events (June 2013), prepared by the GridWise Alliance	http://www.gridwise.org/documents/ImprovingElectricGridReliabilityandResilience_6_6_13webFINAL.pdf
DOC39	Microgrids (September 12, 2012), prepared by Lee R. Hansen, Legislative Analyst for the Connecticut General Assembly, Office of Legislative Research	http://www.cga.ct.gov/2012/rpt/2012-R-0417.htm
DOC40	The Business Case for Microgrids (2011), white paper on the new fact of energy modernization prepared by Robert Liam Dohn of Siemens AG	http://w3.usa.siemens.com/smartgrid/us/en/microgrid/Documents/The%20business%20case%20for%20microgrids_Siemens%20white%20paper.pdf
DOC41	DOE Microgrid Workshop Report (August 30 – 31, 2011), prepared by the Office of Electricity Delivery and Energy Reliability, Smart Grid R&D Program	http://energy.gov/sites/prod/files/Microgrid%20Workshop%20Report%20August%202011.pdf

Doc ID	Document Name	URL
DOC42	Microgrids: An Assessment of the Value, Opportunities and Barriers to Deployment in New York State (September 2010), prepared for the New York State Energy Research and Development Authority	http://www.ourenergypolicy.org/wp-content/uploads/2013/08/10-35-microgrids.pdf
DOC43	Microgrid: A Conceptual Solution (June 2004), prepared by Robert H. Lasseter and Paolo Piagi of the University of Madison Wisconsin	http://energy.lbl.gov/ea/certs/pdf/mg-pesc04.pdf
DOC44	America's Next Top Energy Innovator Challenge – SH Coating LP, Oak Ridge National Laboratory	http://energy.gov/americas-next-top-energy-innovator/sh-coatings-lp
DOC45	Hurricane Sandy Rebuilding Strategy: Stronger Communities, A Resilient Region (August 2013), prepared by the Hurricane Sandy Rebuilding Task for and presented to the President of the United States	http://portal.hud.gov/hudportal/documents/huddoc?id=HSRebuildingStrategy.pdf
DOC46	The October 2011 Snowstorm: New Hampshire's Regulated Utilities' Preparation and Response (November 20, 2012), prepared by the New Hampshire Public Utilities Commission	https://www.puc.nh.gov/2011OctSnowstorm/October%202011%20Snowstorm%20%2811-20-12%29%20final.pdf
DOC47	Performance Review of EDCs in 2011 Major Storms (August 9, 2012), prepared by Emergency Preparedness Partnerships for the New Jersey Board of Public Utilities	http://www.nj.gov/bpu/pdf/announcements/2012/stormreport2011.pdf
DOC48	January 2012 Pacific Northwest Snowstorm – After Action Review (June 19, 2012), prepared by KEMA for Puget Sound Energy	http://www.utc.wa.gov/_layouts/CasesPublicWebsite/GetDocument.ashx?docID=1931&year=2007&docketNumber=072300
DOC49	State of Rhode Island Division of Public Utilities and Carriers Review of National Grid Storm Preparedness, Response and Restoration Efforts (February 2012), prepared by Power Services	http://www.ripuc.org/eventsactions/docket/D_11_94_Booth.pdf
DOC50	Public Service Enterprise Group Incorporated – PSE&G Regulatory Filings	http://www.pseg.com/family/pseandg/tariffs/reg_filings/index.jsp
DOC51	Louisiana Public Service Commission Docket U-29203, Documents	http://lpscstar.louisiana.gov/star/ViewFile.aspx?Id=1a31a2a2-13bb-4e3f-9472-cb8302d33a02
DOC52	Analysis of the Cost and Benefits of Using Tidal Marsh Restoration as a Sea Level Rise Adaptation Strategy in San Francisco Bay (2013), prepared by The Bay Institute	http://climate.calcommons.org/sites/default/files/FINAL%20D211228%20Cost%20and%20Benefits%20of%20Marshes%20022213.pdf
DOC53	Harnessing Nature to Help People Adapt to Climate Change (2012), by Holly P. Jones, David G. Hole, and Erika S. Zavaleta *Nature Climate Change* 2.	http://www.nature.com/nclimate/journal/v2/n7/abs/nclimate1463.html