PARTNERSHIP FOR
ENERGY SECTOR
CLIMATE RESILIENCE
U.S. DEPARTMENT OF ENERGY

A Review of Climate Change Vulnerability Assessments: Current Practices and Lessons Learned from DOE's *Partnership for Energy Sector Climate Resilience*

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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.

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I. Introduction

Companies that joined the Department of Energy's (DOE) Partnership for Energy Sector Climate Resilience committed to identifying "priority vulnerabilities to energy infrastructure assets and operations from extreme weather and climate change impacts" within nine months. In addition, the Partners committed to develop climate resilience solutions within 18 months of joining. To date the Partnership has focused on electric utilities. DOE provided guidance on assessing vulnerabilities, but encouraged each Partner to determine the approach, level of detail, and specificity that was appropriate for their organization. Vulnerability assessment activities under the Partnership Agreement were designed to be flexible and adopt an "iterative-continuous improvement" process since Partners have varying energy assets, a range of climate related risks and different levels of expertise and experience working with climate-related vulnerabilities.

Changes in climate and extreme weather, including increasing temperatures, decreasing water availability, more intense storm events, and sea level rise have already damaged or disrupted electricity services. In the absence of concerted action to improve resilience, the ability of electric utilities to produce and transmit electricity, adjust to changes in population and the economy, and meet consumer energy demands are vulnerable. Impacts will vary by region, and the vulnerabilities faced by utilities may differ significantly depending on their specific exposure to the condition or event. An assessment of potential impacts and vulnerabilities can help utilities to better prepare for and be resilient to changing climate and extreme weather.

Examples of various approaches are highlighted throughout the report in order to demonstrate the current practices and begin to identify best practices in vulnerability assessments. This report also identifies common data gaps and resource limitations in an effort to inform areas of future research and investment that can help energy companies prepare for future climate change impacts. The appendix summarizes each of the vulnerability assessments that were submitted in order to provide useful examples for future efforts.

In general, Partners elected to follow a stepwise framework for conducting a vulnerability assessment covering (1) the scope of the assessments, who was involved, and timeframes used, (2) the approach used to identify climate stressors, climate risks analyzed, and data sources used, (3) vulnerability assessment approach, types of vulnerabilities examined, and (4) needs and lessons learned.

Table 1 provides a summary of the various elements included in Partners' vulnerability assessments. This shows the diversity in approaches and data used, and can provide a reference for future iterations of vulnerability assessments.

Table 1: Partner vulnerability assessment summary table

	Goals and Constraints		Climate Stressors										Vulnerabilities		Solutions
	Scope	**Timeframe**	**Approach to identify stressors**	**Average temperature**	**Extreme temperature (hot or cold)**	**Sea level rise**	**Water availability**	**Flooding & precipitation changes**	**Fire**	**Summer storms (hurricanes, thunderstorms, wind)**	**Winter storms (ice, snow, wind)**	**Other**	**Vulnerability assessment approach**	**Vulnerabilities identified**	**Resilience solutions**
Con Edison	Total assets	Not identified	Internal assessment					X					Risk assessment - quantitative	Quantitative (# of assets, specific assets)	X implemented, planned, needed
Dominion	Subset of assets	2100	Internal assessment			X				X			Risk assessment - quantitative	Quantitative (# of assets)	X implemented
Entergy	Total assets	45 years	Internal assessment							X			Risk assessment - quantitative	Quantitative (% of assets)	
Exelon	Assets and operations	2050, 2100 mostly	Literature	X	X	X	X	X		X			Risk assessment - quantitative	Qualitative (types of assets, specific assets)	X implemented, underway, needed
Great River	Subset of assets	Not specified	Literature					X		X	X		Risk assessment - qualitative	Qualitative (specific assets)	
Hoosier	Subset of assets	Not specified	Internal assessment		X		X	X	X	X	X		Risk assessment - qualitative	Qualitative (specific assets)	
IUSAN (Iberdrola)	Assets and operations	2050	Internal assessment and literature review	X		X	X	X		X	X		Risk assessment - quantitative	Quantitative (% of assets)	X implemented, planned, needed

	Goals and Constraints		Climate Stressors										Vulnerabilities		Solutions
	Scope	**Timeframe**	**Approach to identify stressors**	**Average temperature**	**Extreme temperature (hot or cold)**	**Sea level rise**	**Water availability**	**Flooding & precipitation changes**	**Fire**	**Summer storms (hurricanes, thunderstorms, wind)**	**Winter storms (ice, snow, wind)**	**Other**	**Vulnerability assessment approach**	**Vulnerabilities identified**	**Resilience solutions**
National Grid	Subset of assets	2100	Internal assessment					X					Risk assessment - qualitative	Qualitative (types of assets, specific assets)	X needed
NYPA	Subset of assets	Not specified	Literature, internal and external assessment		X	X		X		X	X		Risk assessment - qualitative	Qualitative (types of assets, specific assets)	X implemented, planned, needed
PG&E	Assets and operations	2050 (some data for 2020-2100)	Internal assessment	X	X	X	X	X	X			Subsidence	Risk assessment - quantitative	Quantitative (% and # of assets, specific assets)	X implemented, planned, needed
PSE&G	Total assets	Not specified	Internal assessment	X	X			X		X	X		Risk assessment - qualitative	Qualitative (types of assets)	X implemented, underway
Southern California Edison	Total assets	2085	Internal assessment	X	X	X		X	X				Risk assessment - qualitative	Qualitative (specific assets)	
SDG&E	Assets and operations	2050 and 2100	Internal assessment and literature review	X	X	X	X	X	X	X			Literature review	Qualitative (types of assets)	X implemented and needed
Seattle City Light	Assets and operations	2030 and 2050	Internal assessment and literature review	X	X	X	X	X	X	X	X		Risk assessment - quantitative	Quantitative (% and # of assets, specific assets)	X planned and needed

	Goals and Constraints		Climate Stressors										Vulnerabilities		Solutions
	Scope	**Timeframe**	**Approach to identify stressors**	**Average temperature**	**Extreme temperature (hot or cold)**	**Sea level rise**	**Water availability**	**Flooding & precipitation changes**	**Fire**	**Summer storms (hurricanes, thunderstorms, wind)**	**Winter storms (ice, snow, wind)**	**Other**	**Vulnerability assessment approach**	**Vulnerabilities identified**	**Resilience solutions**
SMUD	Assets and operations	Mid century, end of century, 2030s, 2085	Internal assessment and literature review	X	X		X	X	X	X		Regional hydrology (snowpack, streamflow timing and volume)	Literature review	Qualitative (types of assets)	X implemented and needed
TVA	Assets and operations	Not specified	Literature		X		X	X		X	X	Air quality, water quality, biodiversity	Literature review	Qualitative (types of assets)	
Xcel	Assets and operations	Not specified	Literature	X	X			X		X	X	Water temp	Literature review	Qualitative (types of assets)	X implemented

II. Goals and Constraints

Scope

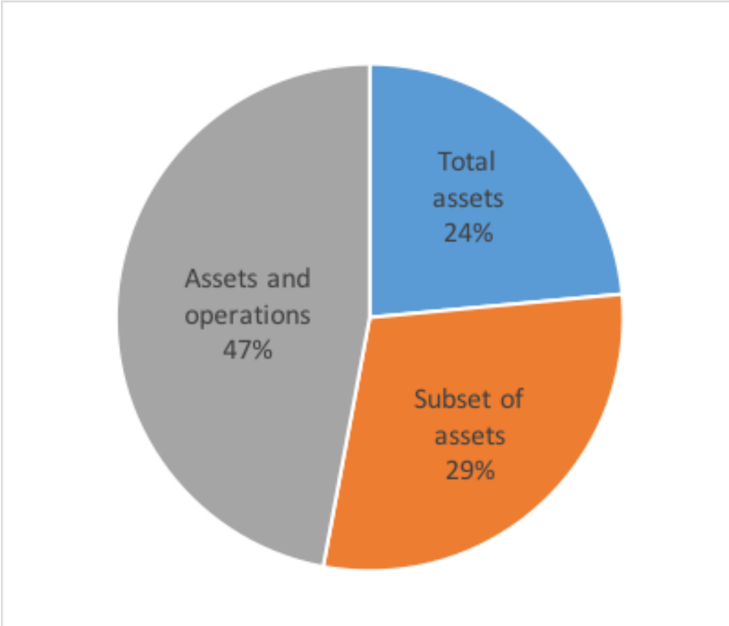
Utilities typically own a large number of assets located over a wide geographic area, from generation to transmission and distribution. In some cases, a utility owns and/or operates or contracts with a generating facility in a state outside its service territory, broadening the geographic scope of its climate change vulnerability. All of these assets are potentially vulnerable to the impacts of climate change, though assessing each individual asset's risk can quickly become a complex task. Figure 1 shows how Partners addressed this issue – some assessed all assets and operations, some focused only on physical assets, and others selected a subset of assets for assessment.

Overall, Partners focused on assessing vulnerabilities for the electric (or gas) infrastructure that they own and operate. Impacts to assets that are owned and operated by others (e.g., a power plant from which a utility purchases electricity during peak demand periods) were not considered in most of the Partner vulnerability assessments. The dependency on the broader grid was not addressed by most Partners. A few Partners identified other vulnerabilities to the supply chain, such as fuel delivery.

Many partners gave special focus to substations because of their importance for reliability (i.e., losing one substation impacts more customers than losing one distribution line). For example, **National Grid** focused on substations in its assessment, mapping FEMA floodplains over their locations to identify priority substations for resilience investments. Similarly, **Dominion Virginia Power** focused its assessment on substation vulnerability to future Category 1-4 tropical cyclones under a high sea level rise scenario.

Several Partners focused on a subset of their assets that are particularly critical to system functioning. **Hoosier** first identified eight critical assets (four generating stations, one building, and three substations), and then assessed the risk from dozens of potential threats (natural, technical, and human). The utility scored the probability, impact magnitude, and availability of resources to respond to each of the threats for each critical asset.

Figure 1: Scope of vulnerability assessment



Who was involved?

To conduct their vulnerability assessments, most Partners used internal personnel and coordinated among multiple internal departments from facilities to generation to emergency preparedness. External stakeholders such as local, state, and federal agencies were also engaged in various assessment processes. In a few cases, Partners collaborated with third parties (i.e., consultants) to develop their vulnerability assessments.

In multiple cases, partners utilized climate data generated by local universities. The direction of this relationship was not always one-way. For example, **Seattle City Light** has established a Climate Research Initiative that funds academic research into areas of interest to the utility. These research areas include the frequency of regional high wind events and convective storms (lightning risk) under future climate scenarios.

Pacific Gas & Electric's (PG&E) focus on collaboration

PG&E engages with various stakeholders on climate change projects, including working with local governments on studies to assess vulnerability and develop resilience strategies. This collaboration "helps PG&E learn more about the climate risks in the communities it serves and identify ways to partner on strategies to address those risks." PG&E also works with regional partners like the Bay Area Council and the Capital Region Climate Readiness Collaborative, which is part of a network of regional climate collaboratives within California. PG&E participated in the Bay Area Council Economic Institute's *Surviving the Storm* report, which looked at the economic impact of a superstorm and associated flooding on the Bay Area.

Timeframes

The timeframes varied among the vulnerability assessments, with some Partners looking more near term (up to 2030), while others considered potential impacts out to the end of the century. Asset lifetimes may impact the timeframes that utilities consider in vulnerability assessments. Some system components may need to be replaced in the near-term (e.g., transmission poles, line undergrounding), while other assets (e.g., substations) could be expected to remain in service longer. The **Sacramento Municipal Utility District (SMUD)** made note of asset longevity in its assessment when it identified that all of its existing thermal generation assets will be decommissioned or repowered by 2050. The utility stated that it would use updated temperature projections in its planning for their replacement. Scenario timeframes can also be influenced by planning cycles. For example, some utilities adopted an approach of matching scenario timeframes to their planning horizons – for example, looking at impacts out to 2050 based on a 30-year planning horizon.

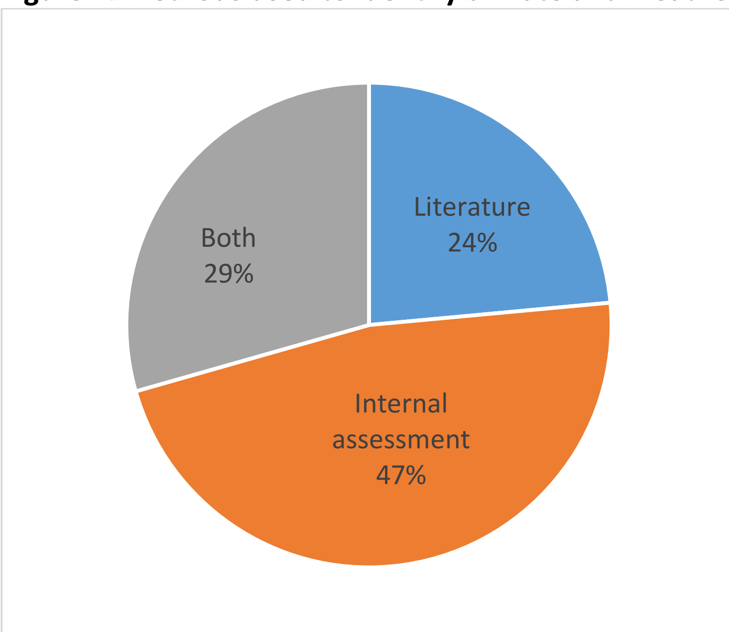
III. Climate Change Threats

Approach to identify climate stressors

As a first step in assessing vulnerability, Partners identified climate and weather stressors (e.g., extreme heat, heavy precipitation events, sea level rise, wildfires) relevant to their systems (e.g., substations, transmission lines, generation, planning and operations) through various sources. This allowed each Partner to focus effort on the stressor(s) most impactful to its assets and operations. In some cases, this step led to a vulnerability assessment focused on a single stressor on a specific system within the utility. This often occurred when a recent event (e.g., a major storm) had triggered a response from either senior management or regulatory bodies. In other cases, direction from senior management or regulatory bodies prompted a utility to select the broadest possible number of climate stressors. This demonstrates the strong influence of leadership and policy in resilience planning.

Of the current DOE Partners, about half used internal consultation to identify stressors. Twenty-four percent of Partners conducted a literature review in order to identify stressors. And about a third of Partners utilized both internal consultation and external literature reviews to identify the particular stressors of concern that could impact the regions in which they operate (see Figure 2). Common sources cited included the National Climate Assessment (2014), DOE's recent reports on energy sector vulnerabilities,[1] National Oceanic and Atmospheric Administration (NOAA) and Federal Emergency Management Agency (FEMA) data, regional studies and guidance, and past events experienced by the utility.

Figure 2: Methods used to identify climate and weather stressors



Types of stressors

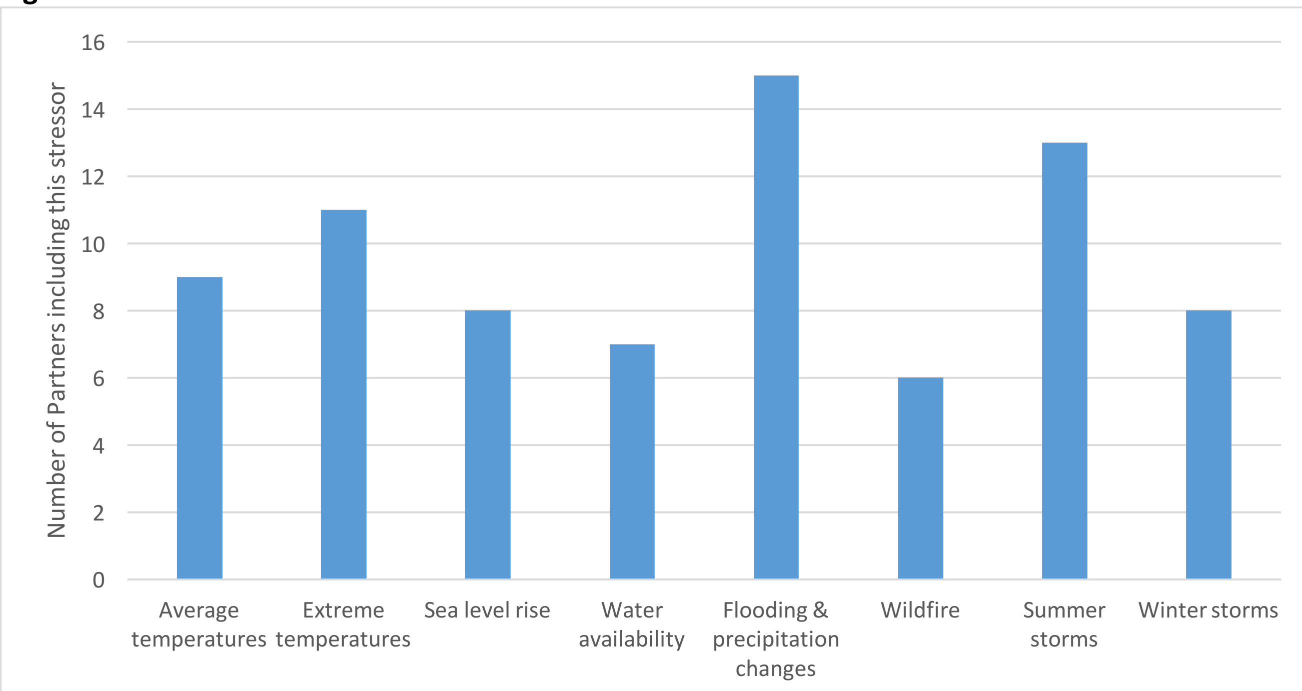
The location of each utility's service territory determines what types of climate stressors it may choose to focus on. For example, utilities in the West highlighted the increased risk of wildfire, while Midwestern utilities are concerned with severe winter storms. Coastal utilities nationwide are concerned about sea level rise and storm surge. Some partners examined their vulnerabilities to a broad number of stressors, while others focused on a single stressor of concern.

Changes in precipitation (including flooding, changing precipitation patterns, and extreme precipitation events) was the most frequently identified risk in the Partners' assessments (see Figure 3). It is clear that stressors with defined seasonality (e.g. tropical cyclones or winter ice storms) are of concern to many utilities, as well as long-term changes such as increased

[1] *Climate Change and the U.S. Energy Sector: Regional Vulnerabilities and Resilience Solutions* (2015), *U.S. Energy Sector Vulnerabilities to Climate Change and Extreme Weather* (2013)

temperatures or water availability. For example, the **New York Power Authority (NYPA)** identified extreme winter weather (ice storms), extreme (summer) heat and heat waves, and flooding as stressors of concern on transmission and generation assets.

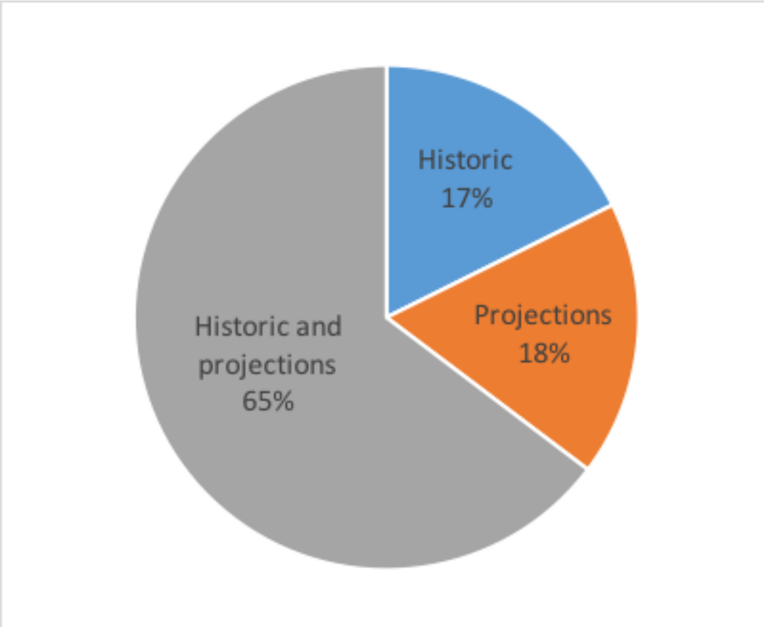
Figure 3: Climate and weather stressors examined



Data sources

In terms of data sources for scenarios, Partners were split in their use of historical data versus future projections (see Figure 4). Three relied only upon historic data to identify areas of vulnerability, while three considered only climate projections. A large majority of Partners used both types of data. Historical data do have many advantages – they are more readily available, and they have the appropriate resolution for utility planning (i.e., hourly/daily resolution, spatial resolution matching the utility's service territory). However, relying solely on historical data puts a utility at risk of underestimating its vulnerability to future climate change impacts.

Figure 4: Type of climate data used



Partners that looked at future climate projections relied upon academic literature to varying degrees, and the International Panel on Climate Change (IPCC) climate scenarios were a commonly-used source. The IPCC develops standardized emissions scenarios that are used as the basis for climate model projections that are utilized by many researchers. So, using this as a source can make comparing between different climate studies more straightforward.

In a few states in which Partners operate, the state itself has commissioned regional climate change studies with scenarios that utilities were able to utilize for their assessments. For example, the state of California has the Cal-Adapt tool, regional analysis, and guidance on sea level rise that **PG&E**, **SMUD**, **San Diego Gas & Electric (SDG&E)**, and **Southern California Edison (SCE)** drew upon for future climate scenarios.

Cal-Adapt is California's resource for visualizing local and regional climate change-related risks. It is a web-based tool, funded by the state, that allows users to identify potential climate change risks in specific geographic areas throughout the state. California's 2009 Climate Adaptation Strategy called for the California Energy Commission to create this tool to "synthesize existing California climate change scenarios and climate impact research and to encourage its use in a way that is beneficial for local decision-makers." The climate data in the tool comes from multiple university, government, and NGO sources. In 2016, Cal-Adapt is undergoing enhancements to align with the IPCC's Fifth Assessment Report, better model spatial distribution (a key determinant of inland flooding) of precipitation in California, capture extreme temperature events (cold snaps and heat waves) with better fidelity, provide more granular local results, and incorporate recent, sophisticated hydrodynamic modeling that represents inundation associated with extreme storm events in concert with various increments of sea level rise. In addition to these major new data developments, Cal-Adapt 2.0 will be dramatically more powerful, supporting aggregation by a number of different criteria (e.g., census tracts, legislative districts), allowing users to upload shape files, and providing an Applications Programming Interface (API) that enables development of third-party tools.

http://cal-adapt.org/

SDG&E was one utility that compared several sources of climate data to find a range of climate change impacts in 2050 and 2100. Figure 5 shows an example of how the utility compiled multiple projections for temperature/heat wave changes, rainfall pattern changes, drought, and sea level rise. SDG&E notes there is considerable uncertainty in planning for sea level rise because of these varying scenarios, particularly looking out to 2100. Because their vulnerability assessment was being presented to internal decision makers, it was important to show the range of possibilities and the considerable uncertainty tied to some of the projected impacts, which becomes a vulnerability in and of itself. In some cases (i.e., for temperature increases), SDG&E found that most sources pointed toward similar outcomes, which makes the planning process a little easier. For those that did not (i.e., sea level rise), they are working to narrow down the range of outcomes, which opens the door for partnerships with climate experts and local agencies to coordinate on data and scenarios.

Figure 5: Example sea level rise scenarios considered by SDG&E

	2050	2100	Comments
Sea Level Rise Projections			
• San Diego Foundation/SCRIPPS	• 5-24 inches	• 6-30 inches	Relative to 2000 sea level
• DOE	• N/A	• 17-66 inches	Relative to 2000 sea level
• EPA	• 10-22 inches	• 30-74 inches	Relative to 1990 sea level
• USGCRP	• N/A	• 7-79 inches	Relative to 1990 sea level
• NRC	• 5-24 inches	• 16-66 inches	Relative to 2000 sea level
• IPCC	• N/A	• 15-28 inches	Relative to 1985-2005 baseline

Table 4. Compilation of sea level rise projections for the Southern California coast from multiple sources for both 2050 and 2100.

Source: SDG&E

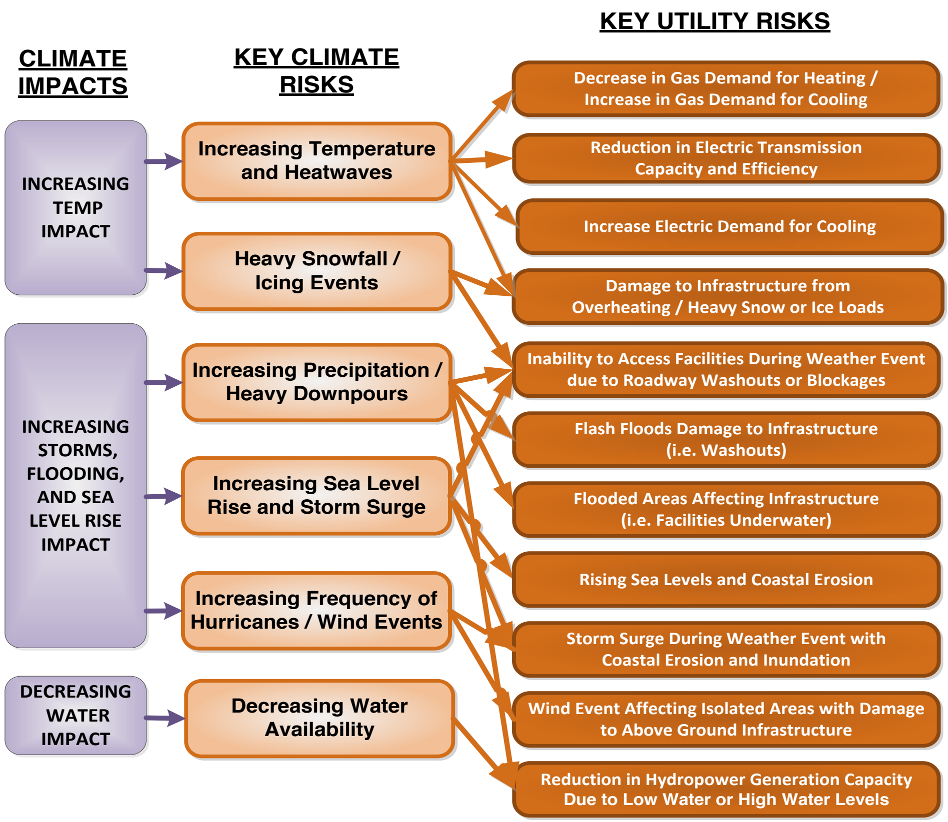
IV. Vulnerability to Climate Change Threats

Approaches for assessing vulnerabilities

Partners used a variety of approaches in conducting their vulnerability assessments. The most common approach was a typical risk assessment whereby threats from climate stressors are identified and applied to existing assets to determine the vulnerability of assets to these threats in a qualitative or quantitative way. Risk assessments were based on: 1) historic events, 2) projections and scenarios of future climate change, or 3) some combination of both. For example, a qualitative risk assessment may examine generally how extreme weather events impacted transmission and distribution systems in the past or how future scenarios of climate change may impact different types of assets. Qualitative risk assessments did not provide details on the number of assets impacted, but rather described the various risks that might threaten the types of assets they own and manage. These qualitative assessments were usually based on internal reviews regarding past events and/or future scenarios. Several Partners used DOE's report *Climate Change and the U.S. Energy Sector: Regional Vulnerabilities and Resilience Solutions* as a source for climate change impacts on their region.

Quantitative risk exposure assessments generally utilized either mapping or a risk matrix approach. Where region-specific climate projection data was available, Partners were able to overlay future stressors (such as flooding, sea level rise, and wildfires) on their mapped assets using GIS. This approach allows a utility to identify the specific facilities that may be at risk under different scenarios. For example, **Iberdrola USA Network (IUSAN)** used this type of approach to identify the percent of different assets at risk to different climate change and extreme weather impacts identified in its vulnerability assessment. IUSAN evaluated climate change and extreme weather-related risks associated with each stressor, based on their scenario analysis of regional climate changes that could affect their assets in the states of New York and Maine. Each of the climate change and extreme weather-related risks is then associated with a series of specific utility risks affecting the electric and gas assets (see Figure 6 below).

Figure 6: IUSAN scenario analysis approach to identifying vulnerabilities in the states of New York and Maine



Source: IUSAN

A risk matrix approach involves scoring the potential likelihood of a risk occurring and the magnitude of impact of that risk. This scoring may be based on internal assessment, past experience, and/or examination of future scenarios. For example, **Public Service Electric and Gas (PSE&G)** identified overall risk scores for different assets by multiplying each risk probability rating by the risk consequence rating (see Figure 7). Probability scores were assigned based on past performance related to the asset and the frequency of the event. For example, in order to achieve a probability score of 4 (defined as once every two years), the event must have happened 5 or more times in the past ten years. Consequence scores were based on the amount of customers affected and length of service interruption. This type of scoring system allows a utility to prioritize and rank risks based on factors that are of importance to their systems.

Figure 7: PSE&G risk probability rating methodology

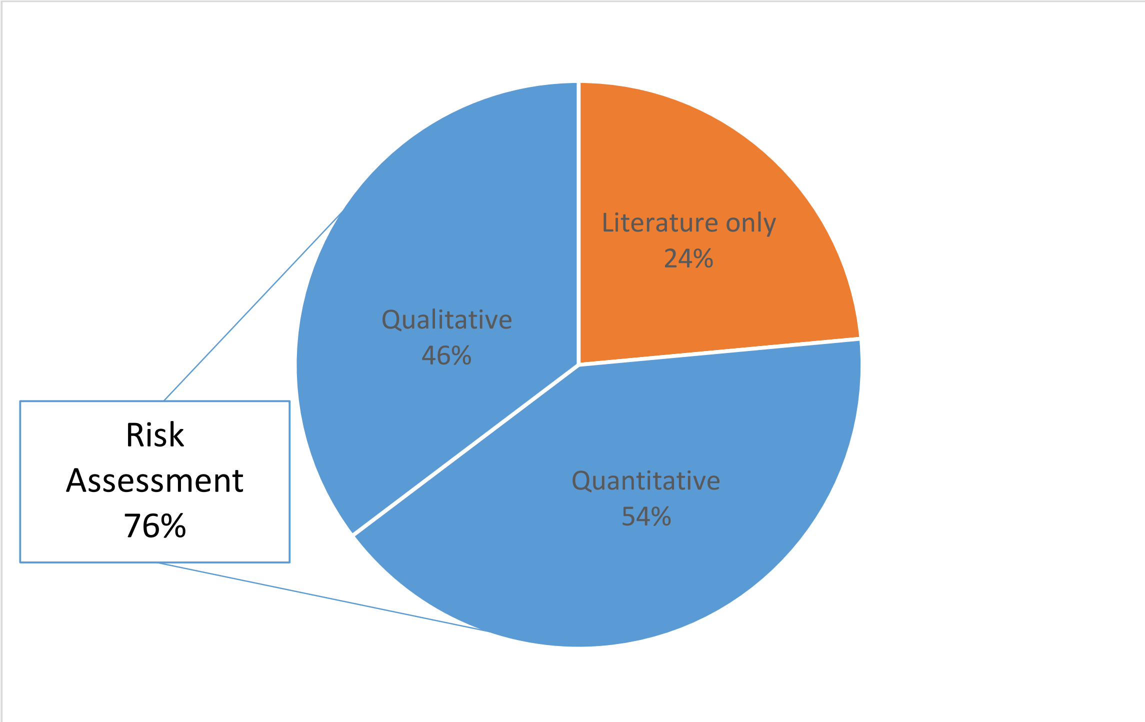
Risk Probability Rating	Risk Consequence Rating Consequence As Defined By Five Levels of Descriptors For Each Domain					
Probability In Any One Year With Likely Frequency of Occurrence	Consequence Basic C = 0 (Inconsequential)	Consequence Basic C = 1 (Minimal)	Consequence Basic C = 2 (Minor)	Consequence Basic C = 3 (Moderate)	Consequence Basic C = 4 (Considerable)	Consequence Basic C = 5 (Severe)
Probability: Basic P = 5 (Expected Once Or More In One Year)	BR = 0 (B)	BR = 5 (B)	BR = 10 (Y)	BR = 15 (O)	BR = 20 (R)	BR = 25 (C)
Probability: Basic P = 4 (Expected Once In Two Years)	BR = 0 (B)	BR = 4 (B)	BR = 8 (G)	BR = 12 (Y)	BR = 16 (O)	BR = 20 (R)
Probability: Basic P = 3 (Expected Once In Four Years)	BR = 0 (B)	BR = 3 (B)	BR = 6 (B)	BR = 9 (G)	BR = 12 (Y)	BR = 15 (O)
Probability: Basic P = 2 (Expected Once In Ten Years)	BR = 0 (B)	BR = 2 (B)	BR = 4 (B)	BR = 6 (B)	BR = 8 (G)	BR = 10 (Y)
Probability: Basic P = 1 (Expected Once In 100 Years)	BR = 0 (B)	BR = 1 (B)	BR = 2 (B)	BR = 3 (B)	BR = 4 (B)	BR = 5 (B)
Probability : Basic P = 0 (Never Expected To Occur)	BR = 0 (B)	BR = 0 (B)	BR = 0 (B)	BR = 0 (B)	BR = 0 (B)	BR = 0 (B)

Source: PSE&G

In a few cases, Partners quantified the costs associated with the risks they identified in their risk assessment, typically to meet a utility-specific need. For example, **Consolidated Edison of New York (Con Edison)** has re-examined its vulnerability to flooding, in light of damage that occurred from Superstorm Sandy, in the context of requesting recovery of its investment in hardening vulnerable infrastructure in its rate case with the New York Public Service Commission.

Four Partners relied exclusively upon a literature review for their approach. Here they typically considered their vulnerabilities in a qualitative way based upon the likely impacts on their service territory according to available literature (e.g., local studies, regional assessments, federal research). This could entail a consideration of how longer and more frequent heat waves may impact the utility’s ability to serve peak load in the future, without a full resource planning scenario analysis. Figure 8 shows the breakdown of approach by Partners.

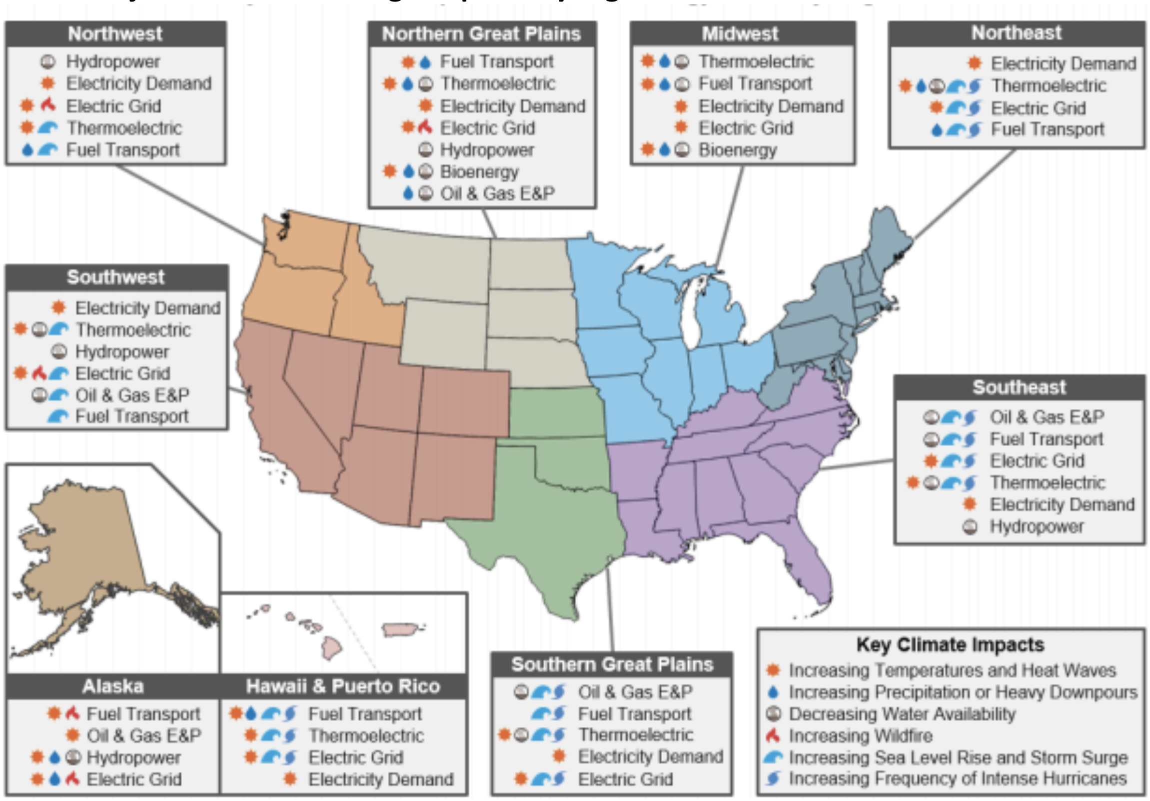
Figure 8: Vulnerability assessment approaches used



Regional vulnerabilities

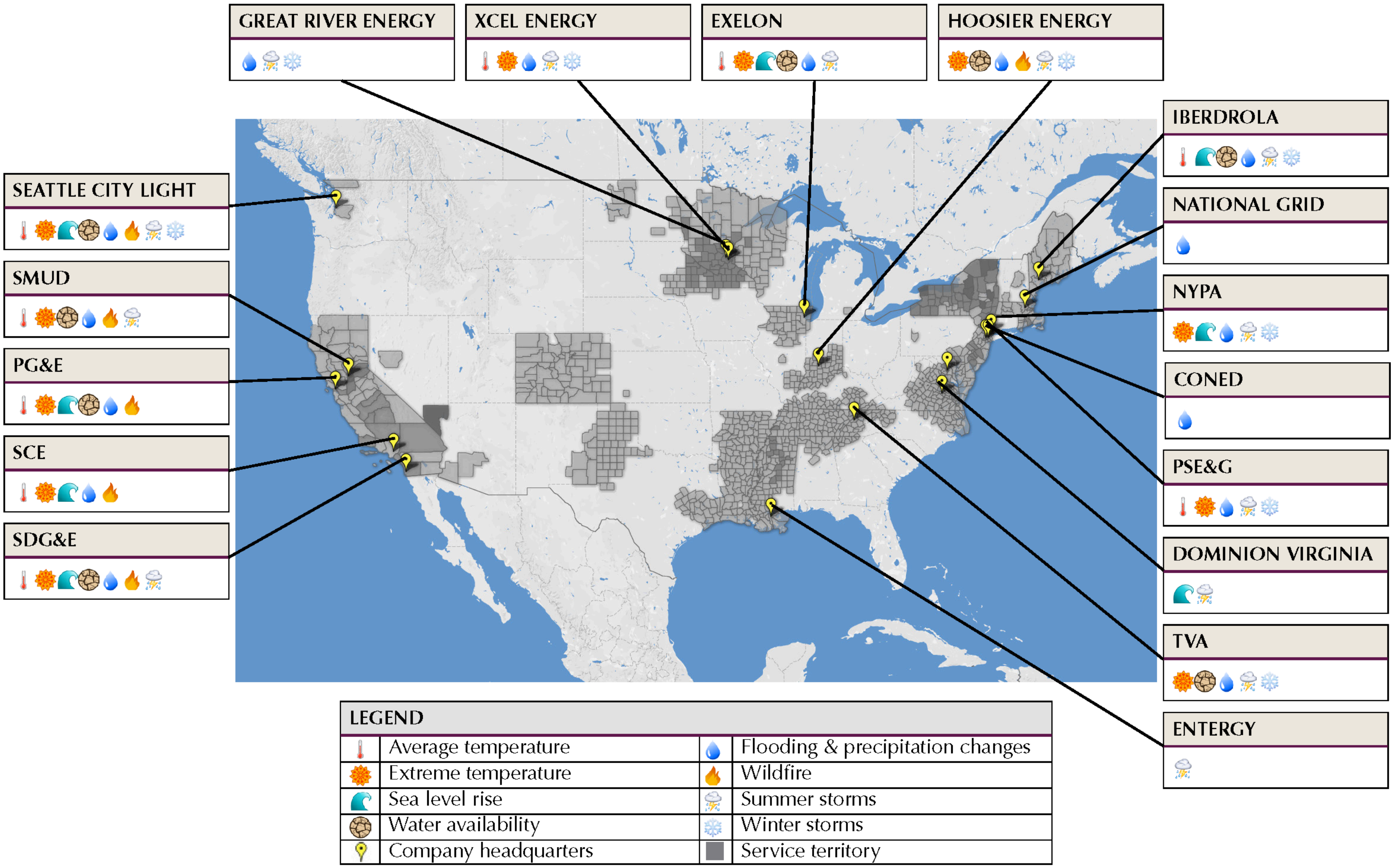
Partners are located across the United States, and by examining their vulnerability assessments, it is possible to identify climate stressors that affect all utilities operating in the same region. This identification can be an important source of information for other utilities operating in those regions who may undertake vulnerability assessments in the future. Climate change vulnerability varies across regions depending upon the nature of the climate impacts, the types and age of energy systems present, and the projected combined impacts on operations, energy demand, and energy supply chains. DOE has examined potential regional climate change impacts on the energy sector (DOE 2015, see Figure 9). The Partners' assessments often focused on a select subset of these potential impacts (see Figure 10).

Figure 9: Projected climate change impacts by region



Source: U.S. Department of Energy 2015. *Climate Change and the U.S. Energy Sector: Regional Vulnerabilities and Resilience Solutions.* http://energy.gov/epsa/downloads/climate-change-and-us-energy-sector-regional-vulnerabilities-and-resilience-solutions

Figure 10: Specific climate change impacts examined by Partners in their vulnerability assessments



For example, hydroelectricity is an important source of energy generation in the Pacific Northwest and California, and Partner utilities operating in those states all identified hydroelectric generation as a major vulnerability. With reduced snowpack and more frequent and intense droughts, the availability for water in hydroelectric projects will become increasingly scarce. In the same regions, wildfire risk is expected to increase, which can threaten energy infrastructure, particularly wooden transmission line poles. While utilities in this region will have differences in their specific assets and risks, the type and magnitude of these risks will have many similarities. This can make the sharing of data, approaches, and best practices more impactful among utilities in the region. For example, **Seattle City Light's** comprehensive assessment of the vulnerability of its hydroelectric operations to climate change can provide beneficial insight to nearby utilities.

Seattle City Light undertook a system-wide risk assessment, examining the magnitude (high, medium, low) of expected climate impacts in 2030 and 2050. It identified several climate impacts that would impact its hydroelectric operations. Additionally, it evaluated the effect of each climate change impact on the four components of the utility's mission to deliver low-cost, safe, reliable, environmentally-responsible electricity.

			Vulnerability			Potential Magnitude** of Impact to				
Utility Function	Impacts Caused by Climate Change*	Time	Exposure	Sensitivity	Capacity to Adapt	Financial Cost	Safety	Reliability	Environmental Responsibility	Ref. Pages
Hydroelectric Project Operations	Seasonal operations of hydroelectric projects not aligned with streamflow due to reduced snowpack (snow-dominated watersheds)	2030	🟡	🔴	🟡	Low	–	–	Low	59-70
		2050	🔴			High	–	–	Med	
	Seasonal operations of hydroelectric projects not aligned with streamflow due to reduced snowpack (mixed-rain-snow watersheds)	2030	🔴	🔴	🟡	Low	–	–	Med	59-70
		2050	🔴			Med	–	–	Med	
	More frequent spilling at hydroelectric projects due to higher peak streamflows (snow-dominated watersheds)	2030	○	🟡	○	Low	–	–	Med	75-79
		2050	🟡			Low	–	–	Med	
	More frequent spilling at hydroelectric projects due to higher peak streamflows (mixed-rain-and-snow watersheds)	2030	🟡	🟡	🟡	Low	–	–	Med	75-79
		2050	🔴			Med	–	–	Med	
	Increased difficulty balancing objectives for reservoir operations in summer due to lower low flows (snow-dominated watersheds)	2030	🟡	🟡	🟡	Med	–	–	Low	83-87
		2050	🔴			High	–	–	Mod	
	Increased difficulty balancing objectives for reservoir operations in summer due to lower low flows (mixed-rain-and-snow watersheds)	2030	🔴	🔴	🟡	Med	–	–	Med	83-87
		2050	🔴			High	–	–	Med	
Fish Habitat Restoration	Increased difficulty meeting objectives for restoring habitat for fish species due to lower low flows.	2030	🟡	🟡	🟡	Low	–	–	Med	88-90
		2050	🔴			Low	–	–	High	
	Increased difficulty meeting objectives for restoring habitat for fish species due to higher peak flows.	2030	🟡	🟡	🟡	Low	–	–	Med	80-82
		2050	🔴			Low	–	–	High	

*The impacts are those caused by climate change in addition to historical conditions; most existing hazards (such as windstorms) will continue.
**Magnitude refers to the average event or normal condition for the timeframe, not the worst possible year or event that could occur.

Source: Seattle City Light

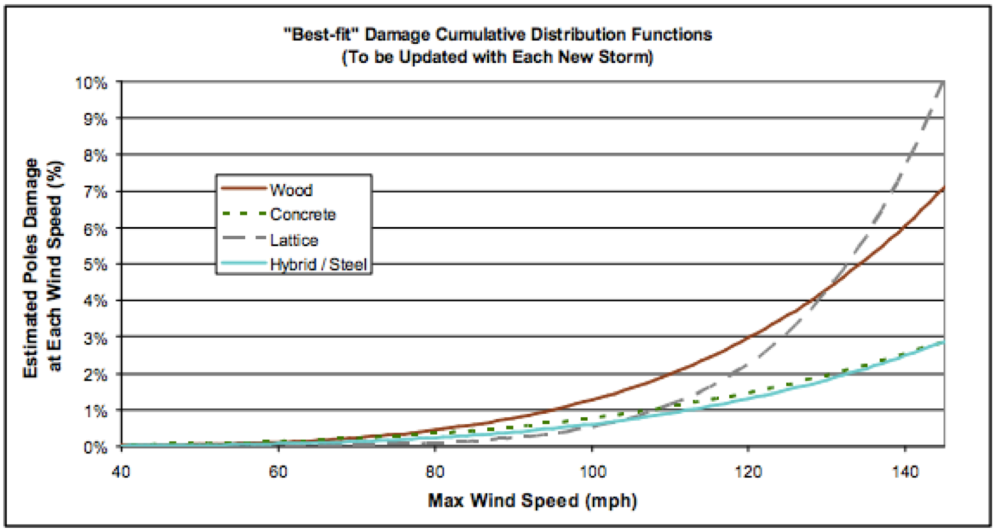
In the South, increasingly intense tropical cyclone activity was recognized as a major vulnerability. Utilities operating in this region have experience with past storms, and can utilize data generated from past events to aid in their resilience planning. For example, **Entergy** combined utility data with a commercially available software tool to estimate the number of transmission poles at risk of failure in a future representative storm.

Infrastructure vulnerabilities

The majority of assessments focused on each utility's infrastructure vulnerabilities – including buildings and facilities, transmission lines, substations, etc. For many utilities, the transmission system is vulnerable to damage from wind (e.g., hurricanes and thunderstorms), ice storms, and storm surge, so the transmission system was an area of particular focus for many utilities. Several Partners noted that technical data concerning the performance of the transmission system under extreme conditions are generally not available. Entergy was able to generate its own empirical performance data using a combination of internal and commercially-available data (see text box and figure, below).

NYPA discussed the importance of their high voltage infrastructure to New York State's energy system, which serves as the backbone of the entire New York State transmission system. NYPA transmission lines provide interconnections to the New York State transmission system, which supplies power from remote NYPA and Canadian hydro generation power projects to major population centers.

Entergy utilized a commercially available software program called Hurrtrack to map wind speeds its system experienced during Hurricane Katrina. It then used GPS data for the transmission poles in its system to estimate the failure rate of its poles for a given wind speed.



Source: Entergy

The company then simulated a representative storm track through its territory, based on past hurricane data that is commercially available, to project the wind speeds its transmission system would experience in possible future storms. This estimate, combined with the empirical failure rate estimate, allowed the utility to conduct a cost-benefit analysis for upgrading components of its transmission system.

Xcel Energy is working with the Electric Power Research Institute (EPRI) to identify best practices for designing transmission (and distribution) systems to better withstand damage from high wind and ice events, which are expected to become more common in its service territory in the future. This includes an original research effort to investigate the behavior of different pole designs in high wind events. **PSE&G** identified its distribution lines being vulnerable to damage to falling trees during more intense summer storms and greater snow loading in winter storms.

Several Partners examined vulnerabilities in their gas distribution systems, though this was not a requirement of the DOE Partnership. The key stressors for these systems were precipitation changes, extreme weather events, and sea level rise – all stressors that make flooding more likely. Floodwater can cause erosion, undermine infrastructure and infiltrate gas pipelines, disrupting service to customers. Salt water corrosion due to sea level rise can do damage as well. **IUSAN**, which operates gas and electric utilities in the Northeast, identified vulnerabilities in both its gas and electricity systems related to increased flood risk.

Planning and operations vulnerabilities

While most of the assessments focused on asset vulnerabilities, about half of the Partners also identified vulnerabilities in planning and operations. While many utility planners point to their ability to successfully manage large fluctuations in temperature today, planning for changes in energy demand will be particularly impacted by extreme heat and cold events. Utilities already integrate temperature data into their planning processes, and several Partners identified the need to incorporate projected temperature changes into their long-term plans. For example, **PSE&G** notes that the operation of gas transmission and distribution facilities will be impacted by extreme cold events, while electric service load capacity can be stressed during extreme heat events. A challenge many utilities face is the disconnect between the granularity of the outputs of climate modeling and the type of temperature projections utility planners need.

In addition, these climate impacts are projected to occur simultaneously with other major changes in energy markets and utility business models which are already underway, including carbon pricing in some locations, increased demand for distributed energy resources and a more interactive grid. These shifts can be expected to offer new opportunities to help manage climate risks but also additional challenges for utility planning and operations overall.

Links to other sectors

The energy sector is intertwined with many other sectors, including transportation, forestry, emergency management, water, and public health. A few Partners noted important links to other sectors in their vulnerability assessments. **PG&E** works with local fire and emergency management agencies to monitor, plan for, and respond to wildfire risks. They also work with water management agencies to address water risks and reduce consumption (both within the organization and by customers).

A few Partners identified vulnerabilities to their operations due to impacts on other energy sectors. For example, **Great River Energy's** assessment noted that coal delivery was vulnerable to increased flooding events along regional rail lines. A climate change impact on the rail transportation system could disrupt its ability to operate its coal-fired power plant, potentially disrupting service to customers.

Tools

In some cases, Partners worked in collaboration with researchers to utilize modeling and analytical tools to examine climate change impacts at a local level. **Exelon** funded a study in 2012 assessing future hydrologic changes in a particular watershed using Aqueduct mapping tool in order to better understand the potential changes in water availability for its generating assets within that region. While the modeling capabilities were found lacking at the time, advances are being made in this particular area of climate science, and with further refinements this tool could prove useful to utilities in the near future.

Private sector data and tools are also available. Partner utilities have used water risk tools such as Aqueduct and Water Prism,[2] outage and damage prediction tools, and GIS for mapping risks. A number of Partners have also developed their own tools. For example, **PG&E** developed the Storm Outage Prediction Project (SOPP) model to predict the number and timing of sustained outages that each region within the service area can expect during adverse weather conditions. This model was initially built for winter wind storms, but can also forecast outages that arise from other weather events such as low elevation snowfall and heat waves. Leveraging data from Cal-Adapt and other sources, **SCE** created an Adaptation Planning tool that layers climate impact maps over SCE's energy infrastructure to identify vulnerabilities.

V. Lessons Learned

In aggregate, the Partners undertook a comprehensive assessment of climate change vulnerabilities, providing many examples of best practices that can inform future work in the sector. Future assessments could benefit from these best practices and lessons learned. Key lessons learned include:

- *Downscaled climate projections are difficult to find or not adequate, making it hard to accurately assess local-level vulnerabilities*
  Many Partners used regional projections, which do not provide the specificity that is required to assess risks down to the facility level. Some utilities worked with universities to develop more localized climate information, but these efforts can require significant resources, are done without the benefit of accepted standardized methodologies, and still result in significant ranges in outcomes. To inform quantitative risk assessments, it is particularly useful if localized data on climate and extreme weather can be provided probabilistically (e.g., likelihood of heat waves of a given intensity and duration); however, such information is rarely available for most climate threats.

- *Assessments based only upon historic data may underestimate future exposure risks*
  For example, planning to the historic experience and understanding of a 100- or 500-year flood event may put a utility at risk, considering these types of events are projected to occur more frequently in many regions. When quality climate modeling projections are available, using these data instead might prove more cost effective because the projected frequency of specific impacts can be estimated and used in utility cost-benefit analysis.

- *The physical risks to assets are easier to evaluate than risks to operations*

[2] Aqueduct, developed by the World Resources Institute, is a global water risk mapping tool (http://www.wri.org/our-work/project/aqueduct). Water Prism, developed by EPRI, is a decision support system that evaluates water resource risks at the regional, watershed, or local levels (http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002002120).

In terms of scope, the assessments focused more on vulnerabilities of assets than vulnerabilities of operations. While these are clearly related – if an asset becomes inoperable, utility operations are impacted – the focus on assets may miss a crucial opportunity for resilience planning. A focus on operations can, for example, identify areas where the utility's generation portfolio should be modified to account for lower output in the future from hydroelectric resources or water-cooled generating units in drought-prone areas. It can also mean identifying what type of backup equipment and response personnel will be required in coming years. The health and safety of utility personnel, of which a significant percentage work outdoors exposed to the elements and in extreme conditions, can be affected by climate change as well. The National Climate Assessment[3] and more recently the USGCRP (USGCRP, 2016) has identified a wide range of negative health impacts due to increased air pollution, allergens, wildfires, heavy precipitation and heat wave events, and changes to disease vectors like mosquitos and ticks.

- *Regulatory processes can impact the implementation of resilience solutions*
  Regulated utilities must have the approval of their regulators before investing in resilience solutions, suggesting that the regulatory policy arena may be an area of future work to promote these efforts. The regulatory approval process is complicated, in part, by the lack of established and broadly accepted data sources or assessment methodologies, impact metrics, and solution strategies.

- *The impacts of climate change on other sectors may be important for utilities to consider*
  Few Partners considered the impact of climate change on other sectors, though some of these may have direct impact on utilities. Generating assets, in particular, are vulnerable to disruptions in the transportation of fuel that could be caused by extreme weather events or sea level rise/storm surge. Utilities may at times rely on electricity produced by assets owned and operated by other companies or rely on the timely availability of replacement equipment to repair or replace damaged equipment, and will need to understand those vulnerabilities.

- *Collaboration between utilities and other stakeholders can help facilitate awareness and action*
  Awareness of the expected impacts of climate change is growing but is still inconsistent across the public and private sectors within communities. Collaboration among utilities can help spread best practices and raise awareness of available datasets and tools as well as the importance of devoting attention to long-term climate-related planning. Moreover, collaboration between utilities and their local and regional stakeholders and communities can broaden the resources available to utilities and improve the overall "readiness" of a region. This type of cooperation can have the added benefit of ensuring that a utility's customers are equally resilient to the impacts of extreme conditions and

[3] *National Climate Assessment* (2014)

events, and therefore able to continue (or quickly resume) purchasing power without extensive interruption.

Needs identified by Partners

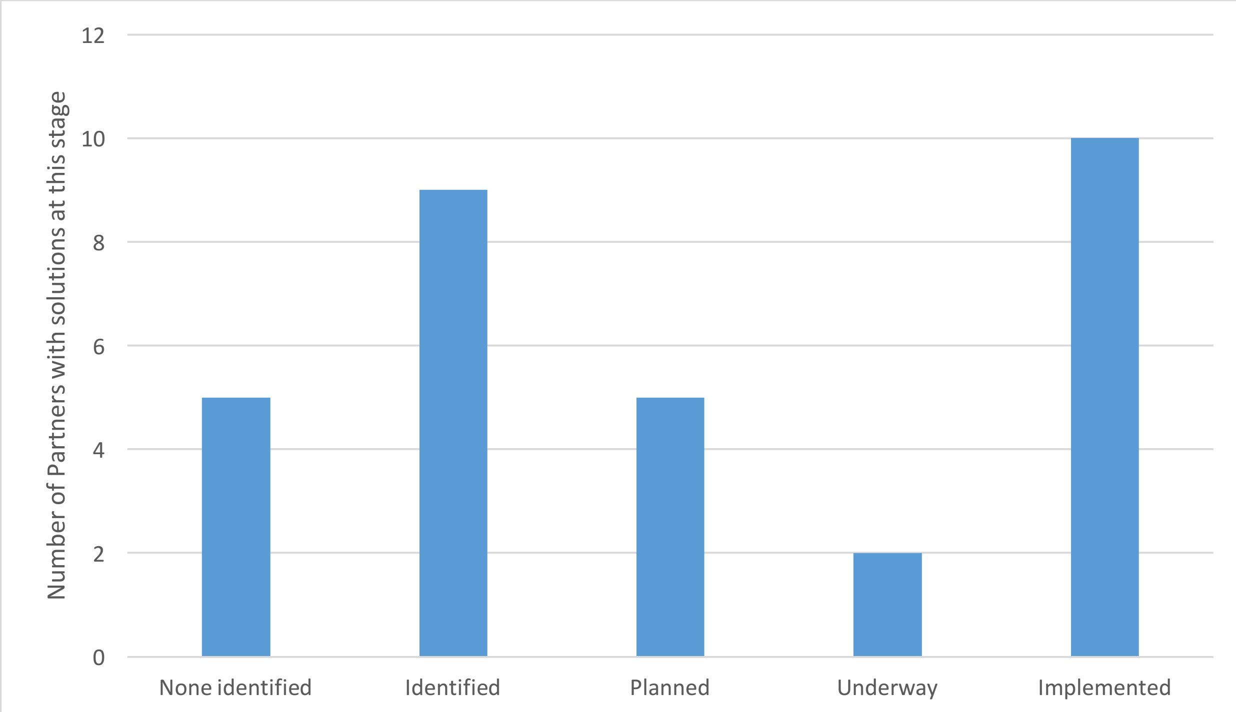
In their assessment reports, Partners identified multiple data that are necessary for effective resilience planning but currently unavailable. The data gaps were of two sorts – first was down-scaled climate model data for projected changes in future climate. The other was technical data and information for assessing the performance of utility assets and the broader energy system under a wide range of climate conditions. In general, Partners found the spatial and temporal resolution of current climate models lacking. Some of the identified data shortcomings were a lack of hourly temperature projections (including peak temperatures in future scenarios), projections of future wind patterns, and resolution at the watershed or smaller scale. Partners also identified as a critical need enhanced research to understand the performance of assets, like transmission lines or transformers, under changing environmental conditions. Tools are also lacking for readily estimating the performance of the grid in response to events that damage or disable assets, particularly on the distribution system. As improved data and analytical tools become available, Partners plan to incorporate it in future vulnerability assessments.

VI. Conclusion

In accordance with their participation in DOE's Partnership for Energy Sector Climate Resilience, a number of utilities across the country have completed climate change vulnerability assessments. Partners used a variety of approaches to examine vulnerabilities affecting different categories of utility assets and operations. The stressors of concern varied by region and by utility. These vulnerability assessments offer some important lessons learned for future assessments that these utilities may undertake and for other utilities that may prepare vulnerability assessments in the future.

Since most vulnerability assessments included all assets and multiple climate stressors, Partners commonly identified more than one solution to improve their resilience. Some of the identified solutions involved current investment, like upgrading a certain portion of transmission poles. Others identified solutions including changing internal planning processes, for example by planning to build all new substations at a higher elevation.

Figure 11: Stage of implementation of resilience solutions



As Figure 11 shows, Partners are in various stages of implementing the solutions they identified for themselves. This was not a requirement for this phase of the Partnership, but serves to show the level of activity that the Partners have undertaken to minimize their exposure to climate change.

Though not required at the vulnerability assessment stage, most Partners identified specific solutions to lower the risk from the vulnerabilities they identified. The next stage will be for each Partner to develop a separate resilience strategy (within 18 months of joining the Partnership). The Partnership Guidance states that each strategy should include milestones and identify the actions that are being pursued. Many of the Partners already have taken a first step toward developing their resilience strategy by examining potential response actions in their vulnerability assessments.

Finally, the vulnerability assessments reviewed in this summary represent a variety of approaches and best practices. Additional details for each of the vulnerability assessments is provided in the appendix along with links to the assessments, where available. As noted in the introduction, the Partnership assessment activity is envisioned to be an “iterative-continuous improvement” process, and this summary analysis can serve to provide a framework for future vulnerability assessments by describing the approaches used, climate risks analyzed, specific data sources that were utilized by utilities, best practices and opportunities for improvement to inform areas of future research and investment that can help the nation prepare for future climate change impacts.

References

Melillo, J.M., T.C. Richmond, and G.W. Yohe, Eds. 2014. *Climate Change Impacts in the United States: The Third National Climate Assessment*. Washington, DC: U.S. Global Change Research Program. http://nca2014.globalchange.gov/

DOE, 2013. U.S. *Energy Sector Vulnerabilities to Climate Change and Extreme Weather*. Washington, DC: U.S. Department of Energy. http://energy.gov/downloads/us-energy-sector-vulnerabilities-climate-change-and-extreme-weather

DOE, 2015. *Climate Change and the U.S. Energy Sector: Regional Vulnerabilities and Resilience Solutions*. Washington, DC: U.S. Department of Energy. http://energy.gov/epsa/downloads/climate-change-and-us-energy-sector-regional-vulnerabilities-and-resilience-solutions

USGCRP, 2016: *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. Crimmins, A., J. Balbus, J.L. Gamble, C.B. Beard, J.E. Bell, D. Dodgen, R.J. Eisen, N. Fann, M.D. Hawkins, S.C. Herring, L. Jantarasami, D.M. Mills, S. Saha, M.C. Sarofim, J. Trtanj, and L. Ziska, Eds. U.S. Global Change Research Program, Washington, DC, https://health2016.globalchange.gov/

Appendix A – Summary of Partner Vulnerability Assessments

This appendix provides a high level summary of each of the vulnerability assessments completed as part of phase one of DOE's Partnership for Energy Sector Climate Resilience.

Consolidated Edison of New York (Con Edison)
Con Edison's vulnerability assessment addressed the impact of climate change on its system, particularly those components that were damaged by Superstorm Sandy. Through the assessment, the utility sought to quantify the risks of climate change impacts and develop a risk mitigation plan. The assessment focused on the increased likelihood of the events observed during Sandy – flooding and extreme precipitation – but also related stressors like sea level rise, changes in wind patterns, days below freezing, and heat waves. Con Edison partnered with a Collaborative to assess its vulnerabilities and plan a hardening investment strategy. The Collaborative was comprised of state regulators, local governments, universities, and advocacy groups that all provided input on Con Edison's approach through a series of stakeholder meetings.

The assessment used a variety of climate data as input, both historic and climate scenario projections. Historic observations formed the basis of Monte Carlo simulations that gave probabilistic data on future impacts, and the climate projections further refined the identified impacts. The utility identified a number of specific assets that were at increased risk of flooding or other damage based on this assessment. Con Edison requests that funds for hardening projects – like installing submersible substation components that would be resilient to flooding – be incorporated in rate cases.

Dominion Virginia Power
Dominion examined vulnerabilities to its system due to sea level rise by 2100, which is projected to be 12 inches in Dominion service territory. The utility added this level of sea level rise to scenarios of storm surge associated with various tropical cyclone strengths and tide heights. These projections were mapped onto locations of substations to identify those at which existing flood mitigation strategies may be insufficient. The vulnerability assessment identified a number of substations that remain vulnerable to inundation during Category 3 and 4 storms. Category 5 storms were not explicitly examined because it is already known that existing substations and transmission lines are not rated for storms of this strength.

Entergy Corporation
Entergy conducted an infrastructure exposure assessment, with support of its regulators and senior management, to inform a cost-benefit analysis of various hardening improvements to its system, particularly its transmission system. First, the utility evaluated its transmission pole performance at varying wind speeds, using data collected following Hurricanes Katrina and Rita. The utility also constructed representative storm tracks of varying storm strengths using historical data and a commercially available software package. By applying its observed pole

performance rates to assets in the path of the simulated storm track, Entergy was able to quantify likely costs of replacing poles after a future storm. It could then conduct a cost-benefit analysis to identify cost-effective system upgrades in its system.

Exelon Corporation
Exelon based its assessment on key climate change impacts that it identified as being material to its transmission and distribution and generation operations. These identified climate stressors included increased frequency and severity of storms (including floods), droughts and other changes in precipitation patterns, increasing variability in temperature patterns, and changing public expectations. This last stressor encapsulates increased customer demand for renewables and distributed generation and regulatory uncertainty around climate change policies, both of which impact the utility's planning processes.

Exelon reviewed the climate literature to identify likely future ranges for the climate system stressors identified above (vulnerabilities to changing public expectations were not included in this vulnerability assessment) across different geographic regions. It then examined vulnerabilities to different parts of its business (e.g., utilities, generation companies, etc.) from these impacts, and identified currently planned investments that would alter its vulnerability. Exelon also conducted a region-specific assessment focused on water availability.

The vulnerability assessment also includes a discussion of how the multiple Public Service Commissions regulating Exelon's utilities consider the funding and approval issues around resilience strategies.

Great River Energy (GRE)
GRE's member cooperatives and baseload generation facilities are located in different regions of the country (Midwest and Northern Great Plains, respectively), so it examined climate change scenarios for those two regions. GRE focused its vulnerability assessment on changes in temperature and precipitation patterns, including more extreme weather events. It undertook a comprehensive assessment of its critical infrastructure, mostly its transmission and generation assets. For each of these assets, GRE identified vulnerabilities from the expected impacts due to climate change.

Hoosier Energy
Hoosier assessed the vulnerability of its critical assets to various hazards. This risk assessment considered the probability of various natural events occurring (e.g., blizzard, high winds, or ice storm), the impacts of each event, and the internal resources available to respond. This resulted in a ranking order of vulnerabilities to each event for each critical asset. The vulnerability assessment also included a qualitative risk assessment for critical business activity. Hoosier utilized a methodology suggested in Rural Utilities Service Bulletin 1730B-2, Exhibit C.

Iberdrola USA Network (IUSAN)
AVANGRID, on behalf of a select number of its operating companies in IUSAN, conducted a vulnerability assessment to identify the threats to its assets and operations from climate

change, identify risk mitigation strategies to improve resilience, and identify the resilience parameters of those mitigation strategies. The company used various government sources for climate change projection data for several stressors (temperature changes, increased frequency of extreme weather events, sea level rise), up to the year 2050.

By mapping its assets onto climate scenario projections, AVANGRID was able to identify specific vulnerabilities to sea level rise and flooding. The company further identified vulnerabilities of its assets to increases in average temperatures and extreme weather events. In parallel, it examined its operations and identified vulnerability of its restoration efforts in climate change scenarios. For all identified vulnerabilities, AVANGRID also proposed resilience solutions which will be examined for cost-effectiveness in a future report.

National Grid

National Grid noted a number of climate change impacts that could impact its system - increased flooding, higher wind speeds, sea level rise and coastal erosion, increased temperatures, increased vegetation, and more frequent ice storms. It used observed impacts from historic events to qualitatively assess the likely vulnerabilities from these climate changes. The utility then ranked the magnitude of vulnerability ("low," "medium," or "high) for individual assets in its system.

National Grid identified flooding as the most probable near-term climate change impact, so it focused its quantitative assessment on flooding risk at its substations. It used FEMA data to identify specific substations at risk of flooding. Based upon a literature review of likely sea level rise in its region, National Grid determined it did not have assets at low enough elevation to need to account for sea level rise in addition to the FEMA floodmaps. The utility used this analysis to identify a priority list of substations for which resilience strategies have been identified.

New York Power Authority (NYPA)

NYPA completed its vulnerability assessment in order to examine the vulnerabilities of its transmission and generation infrastructure to changes in wind patterns, ice storms, flooding risk, and extreme temperatures. Specifically, the assessment used data for individual transmission line segments to estimate the impact that extreme winter weather, particularly icing, would have on loading capabilities of the transmission system. The report also examined the vulnerability of generation facilities to extreme winter weather, extreme heat, and flood damage, and presented flood mitigation strategies.

Pacific Gas & Electric (PG&E)

PG&E undertook a comprehensive risk exposure assessment to identify the critical assets that are at risk from a variety of climate change scenarios. Their vulnerability assessment notes that this report is a first step, and the next phases will be to assess asset performance under risk scenarios, then will develop resilience responses. PG&E completed their assessment internally, utilizing their climate science team and various other departments, as well as external stakeholders (state, local, and federal agencies). Their assessment examines the entire PG&E service area, including electric and gas assets, as well as planning and operations.

PG&E's climate science team developed future climate scenarios based on various sources: FEMA flood maps (100- and 500-year), California Coastal Commission sea level rise guidance, NOAA data on inundation and subsidence, and resources like the California Climate Assessment and Cal-Adapt. Key stressors of concern included flooding, sea level rise, subsidence, heat waves and temperature, drought, and wildfires. PG&E utilized mapping of scenarios to determine the number and percent of facilities, as well as specific facilities at risk to these different stressors, primarily focusing on the 2050 timeframe. Future assessments will examine how critical assets fail under scenarios and will also examine additional sea level rise scenarios. PG&E included many implemented, planned, and needed resilience options as part of this report as well.

Link to vulnerability assessment: http://www.pgecurrents.com/wp-content/uploads/2016/02/PGE_climate_resilience.pdf

Public Service Electric and Gas (PSE&G)

PSE&G leveraged its observations of system damage from recent severe storms (e.g., Superstorm Sandy, Hurricane Irene) to assess its vulnerabilities to climate change impacts. The regional impacts it focused on were identified in the *Regional Climate Vulnerabilities and Resilience Strategies* report. Specifically, the utility examined its vulnerabilities to flooding due to more severe tropical cyclones and sea level rise, higher winds due to more severe tropical cyclones, and more extreme temperatures. For each of the identified climate stressors, PSE&G considered the magnitude of changes due to climate change. It then assessed whether or not its current infrastructure was resilient to this change.

Sacramento Municipal Utility District (SMUD)

SMUD's vulnerability assessment was completed as part of the utility's broader climate change preparations. The assessment reviewed the literature to identify the expected magnitude of climate change impacts in the service territory and in locations in which purchased power is generated and transmitted for key stressors: increased temperatures and heat events, increased wildfire risk, changes in wind patterns, changes in precipitation and regional hydrology and increased flood risk.

For each of the climate stressors identified from the literature, SMUD examined how its physical assets would be affected. For example, for the expected temperature changes for California that it identified from multiple academic studies, SMUD noted that it would have increased summer cooling demand, reduced generation efficiency, and lower transmission capabilities. An initial Climate Readiness Strategy was approved by SMUD's board and is guiding regular revisions of the vulnerability assessment, incorporation of findings into long-term planning efforts and more detailed action plans where needed.

San Diego Gas & Electric (SDG&E)
SDG&E relied upon a number of climate change projections in order to assemble the likely magnitude of impacts in its region. From this literature review, the utility identified increasing temperatures, increased risk of drought, increased severity of storms, greater wildfire risk, and sea level rise as the key stressors affecting it. SDG&E quantified the uncertainty and range of these climate change impacts, and then used this data to assess vulnerabilities in its system. The vulnerability assessment identified the general types of infrastructure (i.e., transmission poles or coastal substations) that would be vulnerable under different climate change scenarios. It also identified vulnerabilities to its operations, including maintenance, repairs, and planning.

Seattle City Light
Seattle City Light identified eight climate stressors impacting the Pacific Northwest and examined how each of those stressors would impact various components of the utility's system. The vulnerability assessment focused on the utility's shoreline infrastructure, electricity demand, transmission and distribution, hydroelectric operations, and fish habitat restoration. Some of the identified climate stressors impact more than one component, so Seattle City Light found 13 impact pathways in total.

For each impact pathway, Seattle City Light reviewed the literature to identify likely future values for the eight climate stressors under different climate change scenarios. It then conducted either quantitative or qualitative risk assessments to determine the magnitude of vulnerability to its assets and operations in 2030 and 2050. It also examined its internal sensitivity to the expected impacts and its existing capacity to respond. This analysis was also coupled with an assessment of potential adaptation actions the utility can take to reduce its vulnerabilities.

Link to vulnerability assessment:
http://www.seattle.gov/light/enviro/docs/Seattle_City_Light_Climate_Change_Vulnerability_Assessment_and_Adaptation_Plan.pdf

Southern California Edison (SCE)
SCE's vulnerability assessment is based upon output from the Adaptation Planning tool it developed using climate change data from the literature and the California Energy Commission. This tool can examine maps of climate scenario data and the utility's assets to quantitatively identify how many assets are vulnerable under different climate change scenarios. The utility identified a number of assets vulnerable to warming temperatures, increased extreme heat events, increased wildfire risk, sea level rise, and changes in precipitation. In addition, the utility examined how climate change will impact future load and utility operations.

SCE has created a workplan to use the results of its vulnerability assessment in the coming months to identify and implement cost-effective adaptation strategies targeting the identified vulnerabilities.

Tennessee Valley Authority (TVA)

TVA's vulnerability assessment uses regional climate data from various government sources as well as climate projections from the 2014 National Climate Assessment. Additionally, it relied upon a 2009 EPRI study called *Potential Impact of Climate Change on Natural Resources in the Tennessee Valley Authority Region*. Using these sources of projected climate changes for Tennessee and the surrounding region, TVA identified the following high-level vulnerabilities on its mission to provide energy, manage natural resources, and promote economic development: changing heating and cooling demand, changing precipitation patterns and increased evaporative losses affecting hydroelectric project operations, temperature-related system efficiency losses, decreasing water quality (due to lower dissolved oxygen levels associated with higher temperatures), loss of biodiversity and habitat, and changes in natural resource-based recreation.

TVA is incorporating climate change risks into all its planning processes, and its vulnerability assessment includes a consideration of various approaches to risk management. This includes factors to consider when identifying and prioritizing vulnerabilities, identifying impacts, and valuing resilience strategies.

Xcel Energy

Xcel's vulnerability assessment is broken down by business unit: generation, transmission, and distribution. For each business unit, Xcel identified the climate stressors that would be most impactful. It then examined its current policies and practices in light of the conditions expected in a changing climate. Key stressors across business units included increasing intensity and frequency of extreme weather events, increasing seasonal demand, and changes in water availability and temperature.

In its vulnerability assessment, Xcel notes the uncertainty around extreme weather events; consequently, it identifies programs and processes that improve communication, restoration capabilities, and safety as the most effective resilience strategies.