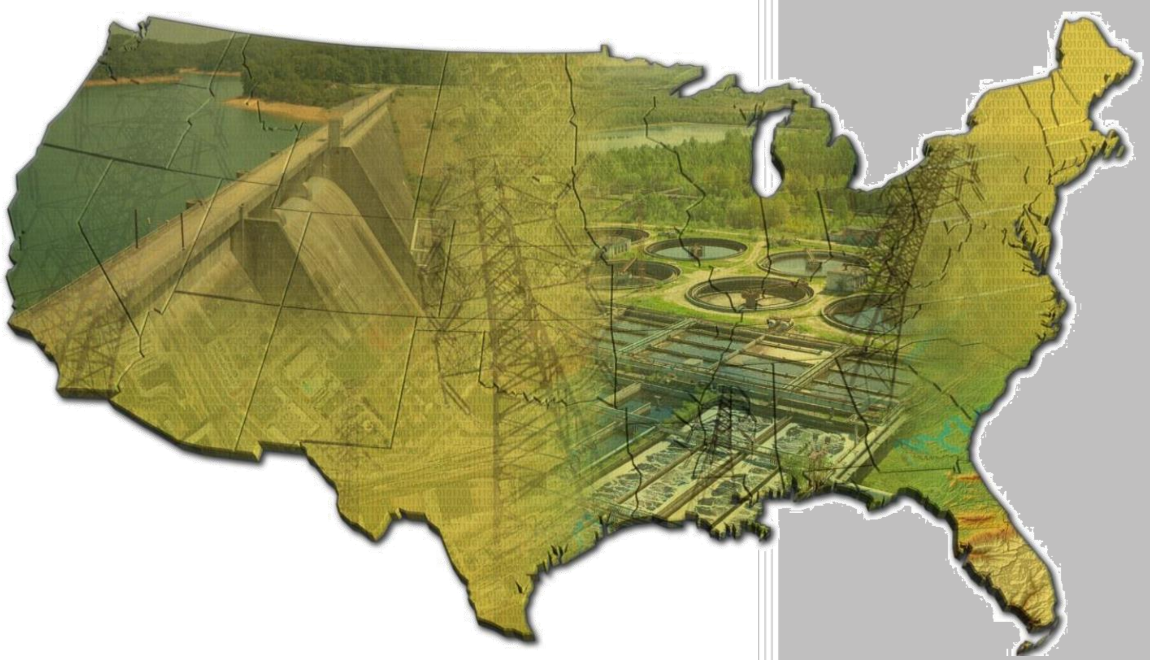
Resilience of the U.S. Electricity System: *A Multi-Hazard Perspective*



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August 18, 2016

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Date Published: August, 2016

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This document was prepared for Greg Singleton and James Bradbury at the Department of Energy's Office of Energy Policy and Systems Analysis (EPSA). The Authors and National Laboratory staff would like to thank a number of participants that donated their time and effort towards informing the results of this report, as well as the support of Mr. Singleton and Mr. Bradbury for their encouragement and support throughout the process.

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ABBREVIATIONS

ARI – Annual return interval

BS – British Standard

CPC – Climate Prediction Center

CSU – Colorado State University

CT – Combustion turbines

DER – Distributed Energy Resource

DCS – Distributed Control System

DHS – Department of Homeland Security

DOE – Department of Energy

EEI – Edison Electric Institute's

ENSO – El Niño-Southern Oscillation

G1 – Minor geomagnetic storm

G2 – Moderate geomagnetic storm

G5 – Extreme geomagnetic storm

GIC – Geomagnetically induced current

GMD – Geomagnetic disturbance

GMI – Grid Modernization Initiative

GMLC – Grid Modernization Laboratory Consortium

EHV – Extra high voltage

EIA – Energy Information Administration

EMP – Electromagnetic pulse

EMI – Electromagnetic interference

EPRI – Electric Power Research Institute

HEMP – High altitude electromagnetic pulse

HILF – High impact, low frequency

HVT – High-voltage transformers

IMT – Incident Management Team

IPCC – Intergovernmental Panel on Climate Change

ISO – International Organization for Standardization

LDC – Local distribution companies

MW – Megawatt

NEMP – Nuclear Electromagnetic Pulse

NERC – North American Electric Reliability Corporation

NIAC – National Infrastructure Advisory Council

NOAA – National Oceanographic and Atmospheric Administration

NWS – National Weather Service

PDSI – Palmer Drought Severity Index

PLC – Programmable logic controllers

PPD – Presidential policy directive

PSHA – Probabilistic seismic hazard analyses

QER – Quadrennial Energy Review

PDO – Pacific Decadal Oscillation

ROI – Return on investment

RPS – Renewable portfolio standard

SAIDI – System average interruption duration index

SAIFI – System average interruption frequency index

SCADA – Supervisory control and data acquisition

SF_6 – sulfur hexafluoride

SQL – Structured Query Language

SREF – Short Range Ensemble Forecast

SWPC – Space Weather Prediction Center

USGS – U.S. Geologic Survey

ABSTRACT

The U.S. electricity system is a critical infrastructure that supports human well-being, economic growth, and national security. Comprised of four core components ‒generation, transmission, distribution, and end use, and, increasingly, dependent on supporting infrastructure such as communication and fuel supply ‒the electricity system has multiple vulnerabilities to both natural and human risks. These risks range from the routine and predictable, such as weather events that disrupt transmission or distribution, to high impact, low frequency risks such as catastrophic hurricanes. In addition to such well-defined, discrete risks, electricity systems can also be challenged by complex risks associated with multiple, interacting threats, and/or indirect effects.

Not all of the various risks to which electricity systems are exposed can be readily quantified, predicted, or even anticipated. Hence, the federal emphasis on resilience reflects the growing awareness of the need for more robust approaches to addressing risks to the nation's critical infrastructure and support systems. The concept of resilience integrates four elements that address risk management needs before, during, and after an event:

- *Robustness* – the ability to absorb shocks and continue operating;
- *Resourcefulness* – the ability to skillfully manage a crisis as it unfolds;
- *Rapid Recovery* – the ability to get services back as quickly as possible; and
- *Adaptability* – the ability to incorporate lessons learned from past events to improve resilience

A resilience approach explicitly recognizes that not all risks to the U.S. electricity system can be avoided. However, response options can be implemented to mitigate damage and recover from damage that is incurred in order to resume normal operations and service delivery as quickly as possible while also learning from experience to shift the system toward an increasingly robust configuration.

Framing risk and resilience of the U.S. electricity system in an integrated way necessitates considering different sources of threats, different components of the electricity system that are exposed, different dimensions of resilience, and the different management practices and technologies that can be deployed and/or implemented. For example, some options to enhance resilience may be specific to certain types of threats and may be deployed to protect one component of the system. Yet others may be threat agnostic, providing system-wide resilience to a broad range of threats including those that cannot be anticipated.

Overall, the U.S. electricity system is among the most robust and resilient in the world. Nevertheless, a number of threat scenarios continue to pose risk management challenges. Adequately anticipating and responding to high impact, low frequency (HILF) risks is inherently difficult because they are, by definition, both rare and significant in scale. Undertaking risk assessment and contingency planning for more complex risks such as combined threats will require improvements in scenario development as well as in coordination and communication among different actors. Climate change poses long-term challenges by changing the frequency, intensity, duration of the weather events that represent the largest source of disruptions to the U.S. electricity grid.

Future efforts toward building resilience should focus on risk assessment and planning for multiple and emerging contingencies, particularly for potentially catastrophic threats. Continuing to invest in new generation technologies and grid modernization while enhancing the capacity for launching coordinated responses across multiple actors will generate significant benefits in terms of maintaining reliability. Such investments will also help enable the system to keep pace with the rapidly changing nature of the U.S. energy sector and emerging threats.

1. INTRODUCTION

Recent assessments conducted under the auspices of the U.S. Department of Energy (DOE), the Department of Homeland Security, and the Global Change Research Program have identified a range of risks to the electricity sector from natural, climatic, and human threats.[1,2,3] Disruptions to the U.S. electricity system are associated with a range of security, health and safety, and economic consequences at an estimated annual cost of $18–70 billion.[1] Often, however, such threats are assessed in isolation, limiting the ability to generate comprehensive insights that can assist in risk prioritization or identify risk management options that are robust to a broad range of threats.

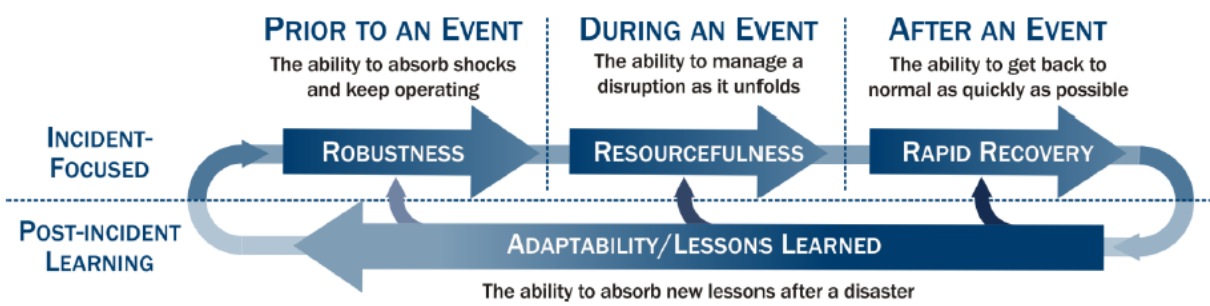
In light of the inevitable risks facing the U.S. electricity system as well as other sectors of the nation, the federal government has emphasized a resilience agenda (Box 1).[1] This has included building national resilience to climate variability and change through the *Climate Action Plan*,[4] the *National Infrastructure Protection Plan*,[5] and the *Quadrennial Energy Review*.[6] The emphasis on resilience has also manifested in the States, particularly in the wake of disasters such as Hurricanes Katrina and Sandy, where enhancing resilience against similar future threats has become a central theme of public and private recovery efforts.[7]

The National Infrastructure Advisory Council defines resilience as having four dimensions (Figure 1):[8]

- *Robustness* – the ability to absorb shocks and continue operating;
- *Resourcefulness* – the ability to skillfully manage a crisis as it unfolds;
- *Rapid Recovery* – the ability to get services back as quickly as possible; and
- *Adaptability* – the ability to incorporate lessons learned from past events to improve resilience

This framing is also consistent with the *Presidential Policy Directive (PPD-21) on Critical Infrastructure Security and Resilience*.[9] Hence, achieving a resilient electricity sector is a multi-objective challenge that is best addressed through proactive, rather than reactive, approaches.[10]

Figure 1. Essential Elements of a Resilient System



Source: NIAC (2010)[8]

The resilience of the electricity system must be viewed in the context of the changing nature of the larger U.S. energy landscape. The first *Quadrennial Energy Review* (QER) identified a range of developments in the energy sector including growing threats from climate change, energy security, transitions from coal to natural gas generation, increased deployment of distributed and renewable generation, and rising investments to modernize the energy grid.[6] These trends are creating new opportunities, but they are also associated with challenges. Continued growth of the U.S. population along with migration and urbanization are changing the geographic distribution of electricity demand and exposure of infrastructure to natural hazards. New energy technologies have to be seamlessly integrated into the electricity grid. Meanwhile, cybersecurity is an emerging priority for U.S. energy infrastructure, while vigilance is still needed against more conventional sabotage and physical attack. Climate change is affecting both energy supply and demand. Supply is affected because it constrains the use of resources such as water, and shifts the likelihood of extreme weather events. Demand is affected because of increased demand for electricity in some regions.

The QER noted that despite ongoing investments in grid modernization, the U.S. electricity system remains vulnerable to a range of threats. While the consequences of extreme weather account for the majority of disruptions, and those disruptions are trending upward,[11] many natural risks can be forecast or at least anticipated (e.g., more intense heat waves). This ability to forecast helps to enable the cost-effective design and deployment of risk management options and technologies to promote grid resilience. A more challenging set of risks are those associated with low probability yet carry high or catastrophic consequences.[3] These include electromagnetic or geomagnetic disruptions, large-scale cyber or physical attack, or combinations of risks evolving simultaneously.

Continuing to make progress on grid modernization and electricity system resilience will therefore necessitate new risk management tools and frameworks that can enable more strategic decision-making. This includes enhancing the capacity to assess risk across a range of spatial and temporal scales through data, modeling, and analysis, but also improving management best practices and mechanisms for their ongoing evaluation.[6] A particular challenge will be enhancing the capacity to monitor, analyze, and respond to systemic, complex risks that propagate over space and time, affect interconnected systems, and are associated with unknown probabilities of occurrence.

Box 1. Federal Initiatives on Electricity System Resilience

- **C*reating the Build America Investment Initiative***. The Administration has created this initiative – an interagency effort led by the Departments of Treasury and Transportation – to promote increased investment in U.S. infrastructure, particularly through public-private partnerships.
- ***Enhancing grid resilience to geomagnetic storms***. In June 2014, the Federal Energy Regulatory Commission adopted a new reliability standard to mitigate the impacts of geomagnetic disturbances on the grid. In November 2014, the Administration established an interagency Space Weather Operations, Research, and Mitigation Task Force to develop a National Space Weather Strategy, to include mitigation of grid vulnerability.
- ***Department of Energy's Grid Modernization Initiative (GMI)***. Includes funding of $220 million per year for three years, for the Grid Modernization Laboratory Consortium (GMLC) – a collaborative research and development program across DOE's national laboratory system.
- ***Partnership for Energy Sector Climate Resilience***. Under this Partnership, owners and operators of energy assets will develop and pursue strategies to reduce climate and weather-related vulnerabilities. Collectively, these Partners and the DOE will develop resources to facilitate risk-based decision making and pursue cost-effective strategies for a more climate-resilient U.S. energy infrastructure.

The objective of this report is to build on the knowledge generated through the first QER by integrating recent literature for a comprehensive analysis of risk and resilience for the U.S. electricity system. The report provides an overview of the current status and trends in the electricity system that are relevant to resilience. This is followed by a synthesis of different natural/environmental and human threats to the electricity system including information on known trends, predictability, and mitigation options. This information on threats is subsequently examined in the context of different general metrics for resilience to assess risk to various system components. This integrated assessment helps to inform the identification of key opportunities and constraints for enhancing resilience. The report concludes with a set of priority recommendations for both research and development activities as well as strategic and operational planning.

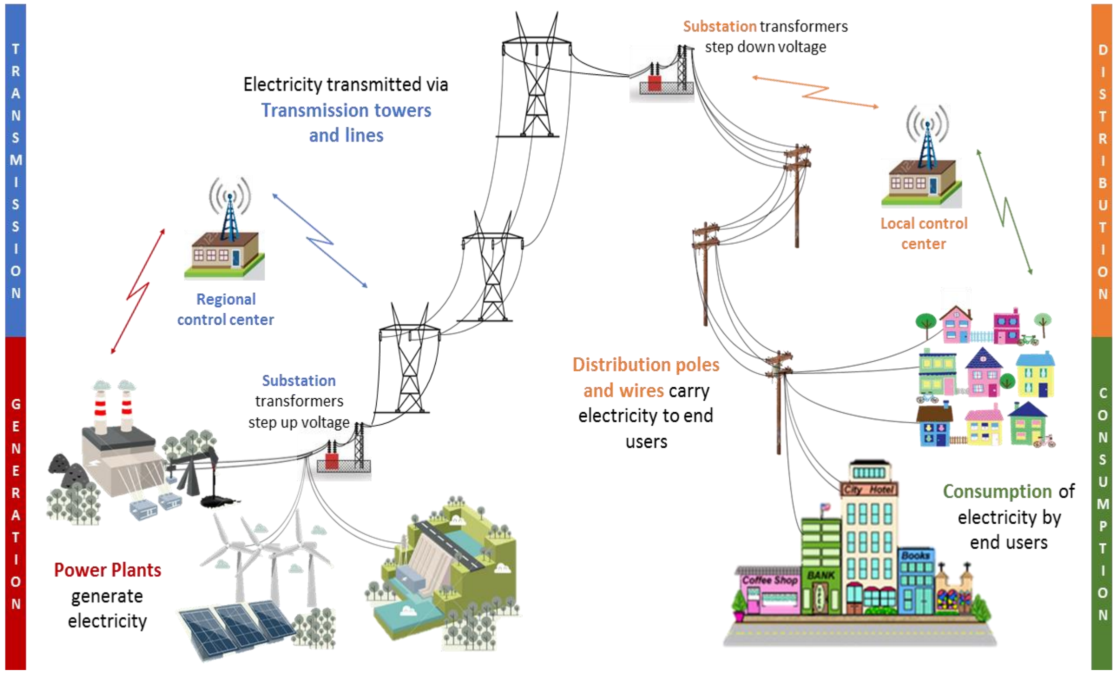
2. OVERVIEW OF U.S. ELECTRICITY SECTOR – STATUS AND TRENDS

The U.S. electricity system is a complex system of systems that include generation, transmission, distribution, and consumption (Figure 2). These different system components can be run and/or maintained by either one entity or multiple entities. There are three primary types of owners and operators for the components of the electricity system:

1) Investor Owned Utilities;
2) Publically Owned Utilities, including Federal, Public Utility Districts and Municipalities; and
3) Cooperatives

The management, investment, and regulatory responsibilities for energy infrastructure vary depending on the type of owner and operator. Changes within the electric sector continue to progress at a quick pace.[6] With the introduction of national policies focusing on the importance of energy security and resilience to a variety of threats, innovation and technology improvements to meet these policies have shifted into a higher gear. Some examples of trending solutions to meet the national call to increase security and resilience are highlighted below. One of the most notable innovations areas is in the types of generation sources that are entering the market. Figure 2 below provides a snapshot of source generation trends from January, 2001–April, 2016. Table 1 below provides a snapshot of how investment and management responsibilities vary by system type owner/operator.

Figure 2. Components of the U.S. Electricity Grid



Caption: The electricity system includes four physical components (generation, transmission, distribution, and end use consumption) as well as the information infrastructure to monitor and coordinate the production and delivery of power and operate the grid. Source: Argonne National Laboratory.

Figure 3. Monthly Net Generation by Fuel Source[12]

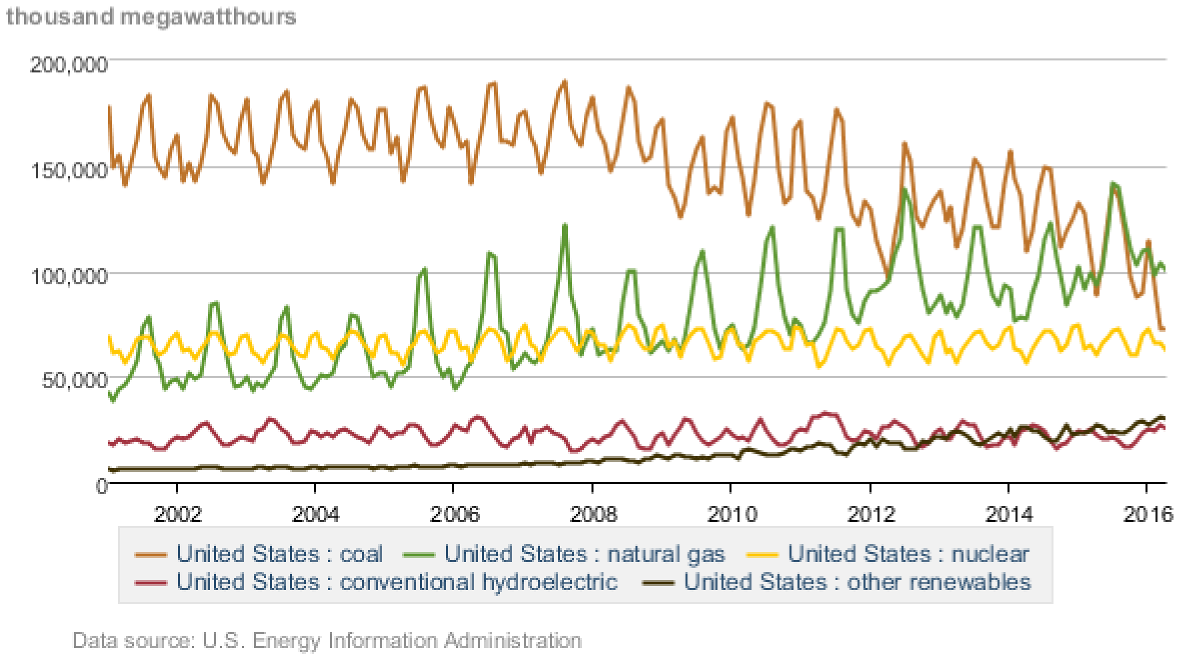


Table 1. Types of Electric Utility Owners and Operators.

Type of Owner/ Operator	Management	Financing	Revenue	Regulation	Infrastructure
Investor Owned Utility[13]	Shareholders /investors not limited to the IOU region of operation	Issued bonds to stakeholders and bank borrowing	Rates are set to recover costs and offer reasonable return on investment to investors	Rates are set and regulated by state public utility commissions/public service commissions	Can own generation, transmission and distribution systems
Publically Owned Utility[13] (including Municipally Owned)	Managed by local entities and public officials	Tax free bonds	Non-profit entities; rates set to recover costs and ensure investment in new facilities	Rates are set by the utility governing board or corresponding city council with public input	Primarily distribution assets
Cooperative[14,15]	Board of directors elected from members	Loans, grants and private financing from members	Not for profit; rates set to recover costs. Any margin is used to pay loans, invest in new infrastructure and/or replace outdated infrastructure	Rates set by board of directors	Typically distribution assets with some generation and transmission

Table 2 below shows the national annual trends in generation by source between April, 2015 and April, 2016 as reported in the most recent release of the EIA's, Electric Power Monthly.

Table 2. Annual Trends in Generation by Source
(April 2015 to April 2016) [Thousand Megawatt hours]

Generation Fuel	April, 2016 Capacity	Change since April, 2015
Coal	278,963	-24.2%
Natural Gas	311,825	6.7%
Nuclear	204,323	1.0%
Hydro	76,950	6.5%
Non-hydro Renewables	87,044	22.9%
Petroleum	3,417	-58.5%

The expansion of the electric generation portfolio can increase the resilience of the system by broadening the sources of available generation as well as transitioning the structure of the market from large, centralized generation to smaller, decentralized generation options. The decentralized model provides for greater flexibility in the event of disruptions as well as potentially reducing the time needed for recovery as disruptions might be more localized. One example of potential distributed generation sources is the influx of renewables.[16]

There are number of other avenues that can be taken to increase the resilience of the electric grid. Recent major disasters have highlighted the need for more opportunities and approaches for resilience such as hardening, smart grid components, capacity growth, and new policies and regulations, especially in market structures. States such as New Jersey and New York, which were severely impacted by Superstorm Sandy, have started initiatives such as "resilience banks." Resilience banks, such as the New Jersey Energy Resilience Bank, will offer low-interest loans in to finance energy resilience enhancements, offsetting the high costs of resilience options for critical energy infrastructure. The remainder of this document will explore not only the types of threats to the infrastructure, but also the key opportunities and technology options that could be used to address one or more of those threats.

3. FRAMING ELECTRICITY SECTOR RISK AND RESILIENCE

The energy sector is accustomed to framing threats to the electricity in the language of risk, which is often expressed as the interaction between the likelihood of an event occurring and the severity of its consequences.[17] A number of criteria influence the assessment of risk:[18]

- Probability of occurrence – *How frequently are threats and/or consequences experienced?*
- Extent of damage – *How critical and/or costly are the consequences?*
- Uncertainty – *How much confidence can be associated with estimates of risk?*
- Geographic extent – *Over how large an area are consequences experienced?*
- Persistence – *Over what duration are consequences experienced?*
- Delay – *What is the latency between the threat and the consequence?*
- Reversibility – *To what extent and/or how quickly can affected systems recover?*
- Social impact – *What is the potential for damage to human and societal well-being?*

Risk assessment and management for the electricity sector often hinge on a number of these dimensions.

For some types of threats, likelihoods are well-established, particularly for common, recurring threats – their frequency enables rigorous statistical analysis of their likelihood of occurrence as well as the return intervals for threats of different intensities. Other types of threats, however, occur with much lower frequency. As such, although their occurrence is plausible (i.e., non-zero probability), estimation of an explicit likelihood is difficult.

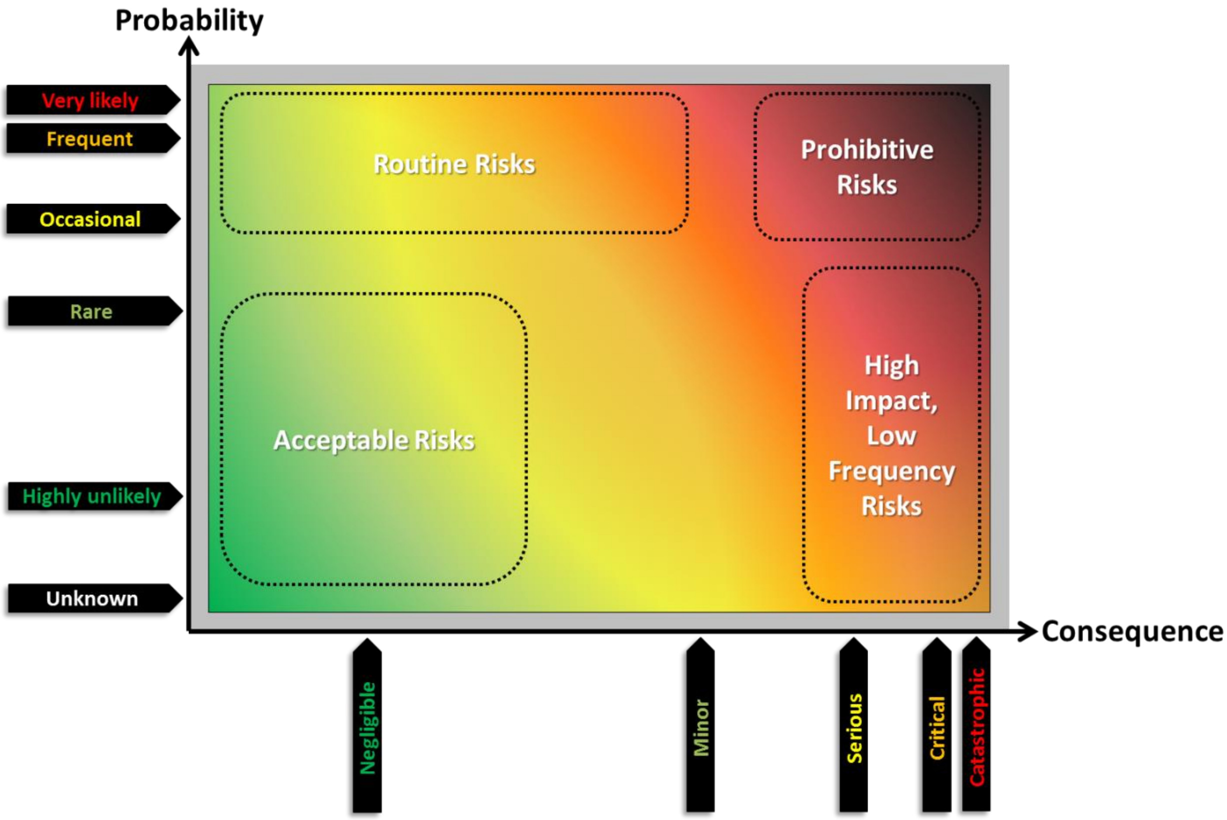
A current challenge is how to assess non-stationary threats – meaning threats that are changing over time or shifting in terms of their geographic location. Climate change is one case-in-point due its projected effects on changing the frequency, intensity, and/or duration of extreme weather events. This means that the ability to estimate the likelihood of such events in the future is reduced, despite ample historical observations. Meanwhile, changing population size and distribution as well as changes in the regional distribution of energy resources (e.g., rapid expansion of hydraulic fracturing to access shale gas resources) and technology are driving changes in energy demand, generation technologies, and the transmission of fuel used in electricity generation.

In addition to the likelihood of various types of threats, the analysis of risk must also give consideration to the consequences that arise from exposure of electricity systems and their components to threats. Such consequences range in severity from negligible to catastrophic depending not only on the geographic extent of the consequences (i.e., local vs. regional vs. national) for electricity systems and the duration over which they persist, but also on the indirect impacts on electricity-dependent systems and, ultimately, human well-being. Often, consequences are contingent on system thresholds that are defined by physical constraints, design criteria, and/or regulatory standards. Consequences may affect different components of the electricity system and therefore different actors or customers. For example, loss of generation capacity can be a significant consequence to an electrical utility, but may not necessarily result in an outage that immediately affects customers. In contrast, damage to local distribution systems can affect customers, even when upstream transmission and distribution are unaffected.

The combination of the likelihood of events and their consequences determines the risk landscape in which electricity systems and their individual components operate (Figure 4). This landscape can be divided into different areas; routine risks, acceptable risks, high impact, low frequency/probability (HILF) risks, and prohibitive risks. For example, some types of risk are accepted, because their likelihoods and consequences are low. Therefore, there is low demand for mitigation interventions. Routine (or recurring) threats are those to which electricity systems are exposed on a relatively frequent basis and thus standard practices have evolved over time to minimize consequences and/or enable rapid recovery. Prohibitive risks are those that the system cannot or is unwilling to bear. For example, electricity systems with very low reliability that result in frequent and/or widespread outages would have unacceptably large and recurring consequences. Hence, significant investments and stringent regulatory standards are used to maintain a robust risk management response to minimize or eliminate such risks. Of particular concern are the HILF risks that lie at the opposite extremes of likelihood and consequences levels.[3] These could include risks with widespread, catastrophic consequences, such as might be anticipated from a geomagnetic or electromagnetic disruption. Therefore, the grid is regulated and managed to provide a baseline level of reliability that is high, with fail safes and redundancies.

The North American Electric Reliability Corporation (NERC) is the key organization that governs the mandatory planning and operational standards associated with the interconnected bulk electricity system (Box 2).[19,20,21] These standards have been designed to cover most reliability events that occur on the system, and provide consistency among grid operators that are required to interoperate to maintain a reliable system. One of the key objectives of such standards is to maintain risks within acceptable or tolerable levels through the implementation of practices and technologies that mitigate risk and/or enable recovery in a timely manner. Meanwhile, reliability standards for the distribution system, to which the majority of outages can be attributed, are established at the state level and overseen by state public utility commissions. Therefore, NERC standards do not apply to equipment on this part of the system.

Figure 4. Conceptual Model of the Risk Landscape



Caption: The risk landscape is formed by the interaction between the probability of threats and their consequences.[18] These axes define different classes of risks that reflect different combinations of probability and consequence.

The persistence of risks experienced by the electricity system is another important consideration. Acute risks are relatively short in spatial and temporal extent, but can be associated with significant consequences. For example, hurricanes often cause damage to electricity systems in a short duration. In contrast, chronic events – those that manifest and persist over long periods of time – may have only modest, short-term impacts, but their cumulative effects can be quite large. For example, drought conditions that affect electricity generation of hydropower facilities can become chronic risks – generation continues, but the loss of generation capacity results in financial losses that continue to accrue until drought subsides.

In the context of a technologically developed society, the presence of power is taken for granted. Society's vulnerability (in terms of possible disruption of established standard of life) is very high, due to the extreme dependence on electricity. From a defense/national security perspective, this dependence constitutes an "asymmetric" vulnerability when looking at possible conflicts with adversaries that are not based in a technologically developed country. With exception of highly secured military system where it is assumed that local generation can be provided as long as needed, the ability to sustain power failures without appreciable damages/consequences is very limited. For domestic households power is preferably restored in hours; for loads with their own uninterruptible power supplies, such as hospitals, the time may stretch to a few days. Failing complete restoration of power, a staggered power dispatch (with controlled blackout) can at least temporarily provide a way to limit consequences.

Box 2. Existing Reliability Performance Requirements for the Bulk Electric System

The North American Electric Reliability Corporation (NERC) has specific requirements that all owners and operators of the bulk electric system must follow. These requirements are based on a set of contingency analyses that evaluate the system response given a range of contingencies associated with loss of specific elements within the system. The planning standards were updated in 2013 to accommodate seven levels of contingencies and the acceptable system response:

0. No contingency, normal system
1. Single contingency, normal system. Loss of a generator, transmission circuit, transformer, etc.
2. Single contingency, normal system. Loss of a line section, bus fault, circuit breaker fault, etc.
3. Multiple contingency, loss of generator unit followed by system adjustments.
4. Multiple contingency, loss of multiple elements caused by a failure to clear the initial fault
5. Multiple contingency, delayed fault clearing due to the failure of non-redundant protection
6. Multiple contingency, two overlapping single contingencies
7. Multiple contingency, common structure (e.g., two adjacent circuits on a common structure)

The standard also specifies penalties for noncompliance with various aspects of the standard.

Consistent with the general definition of resilience (Section 1), a resilient grid system is associated with a number of specific characteristics:

- *Resourcefulness*: in practice this could be applied to the power transmission and distribution system by implementing a constant monitoring and optimized dispatching and/or load shedding to respond to anomalies. For example, if a critical transmission line is lost, power might still be delivered by temporarily overloading parallel/alternative routes and monitoring conductor temperature and time of overload conditions.
- *Redundancy*: over-engineering critical systems to be able to function, at least at a reduced level, in critical conditions.
- *Restoration:* coordination and integration among stakeholders of restoration efforts, plans optimized for a variety of scenarios to avoid the need of improvising a solution during critical conditions. Sharing best practices among different organizations (from local to global, nation-wide) and practicing simulated emergencies should be mandated and coordinated at the national level. This sharing should include mutual assistance programs and their resources (personnel, equipment, parts) during the restoration phase.

Each type of risk is associated with different risk management interventions to maintain or enhance various elements of resilience in the face of different types of threats. The principle value of assessing and characterizing risks to the electricity system is to guide decision-making on the prioritization of risk management options that can enhance resilience. Such options can target the robustness element of resilience, often focusing on specific components of the electricity system (Figure 1). For example, the siting of electricity generation facilities is often informed by understanding of the geographic distribution of natural hazards (e.g., floods, seismic). Infrastructure hardening can make transmission and distributions systems more robust to storm events. Deployable flood defenses can help protect facilities from flood water in the event of a significant flooding event. Such interventions can be cost-effective, particularly for recurring risks that can be anticipated.

Other types of risk management options are "hazard agnostic", in the sense that they can be implemented independent of the threat to which the electricity system is exposed. Much of the investment in grid modernization, for example, has the goal of enhancing overall reliability and flexibility of the system (Figure 1). The effect is often to accommodate emerging technologies, such as distributed, renewable generation, and at the same time to reduce the likelihood of disruption when exposed to threats. For example, flexible load generation and dispatching can automatically adjust to changes in system demand. Programs for automatic under frequency load shedding are used to balance generation and load when a large disruption triggers a drop in frequency. Because such options can provide benefits for a broad range of threats they help provide resilience to threats that are difficult to anticipate.

4. ENVIRONMENTAL AND HUMAN THREATS TO THE ELECTRICITY SECTOR

The U.S. electricity system is exposed to a broad range of threats that manifest over different spatial and temporal scales. Some, like extreme weather events, earthquakes, or geomagnetic disturbances are natural phenomena, the occurrence of which is beyond the control of humans. Such natural threats have been a key focus of planning efforts.[22] The most frequent power outages tend to have localized effects that impact a small number of customers (e.g., resulting from damage to distribution systems caused by trees falling on distribution lines). Damage to the transmission system results in more widespread major power outages that affect large numbers of customers and large total loads. Utilities must report events that affect more than 50,000 customers and 300 MW to NERC.[23]

Table 3 summarizes 2014 bulk power emergencies and disturbances by cause as well as the number of customers affected when known. Severe weather and wildfire events accounted for 90 of the events listed in the disturbance reports. For 67 of those, the number of affected customers is known. By comparison, 76 events were caused by human action such as physical attacks and cyber attacks, but the number of customers affected by these events is unknown.

Although electric utilities have long prepared for specific hazards, they may not be fully prepared to address new and existing hazards that evolve over time. Cyber threats are an example of an evolving threat. New cyber threats may increase the vulnerability of specific components and operations for utilities. As discussed below, climate change also will cause some risks to evolve over time.

This section presents what is known about the various established and emerging threats to the electricity system including historical and future trends as well as the predictability of different threats, which has important implications for threat mitigation and resilience. This information is summarized in Table 4, based on the subsequent discussion in the text.

Table 3. Electric Emergency and Disturbance Events (2014)

Event Type	Number of Events	Events Where Number of Affected Customers is Known	Average Number of Customers Affected
Severe Weather	87	64	149,702
Physical Attack	73	0	-
Fuel Supply Emergency	17	1	140,000
Electrical System Separation (Islanding)	14	4	1,000,092
Public Appeal	8	2	61,400
Cyber Attack	3	0	-
Wildfires	3	3	933,475
Voltage Reduction	3	0	-
Load Shedding	2	2	27,428
Distribution Interruption (Unknown cause)	1	1	75,000
Earthquake	1	1	70,000
Operational Failure	1	1	6,549
Uncontrolled Loss	1	1	1

Source: Energy Information Administration (OE-417)[24]

4.1 NATURAL/ENVIRONMENTAL THREATS

Many of the exogenous threats routinely encountered by the electricity system are natural in origin and can be attributed to weather (both on Earth and in space) or wildlife and vegetation that come in contact with system components. As mentioned above, weather is by far the most common and potentially severe naturally-occurring threat. Analysis of weather-related outages indicates that abnormally high wind conditions are one of the most significant factors driving outages, and overall, weather-related outages are increasing over time. This section therefore starts by discussing what is known about weather-related threats before proceeding to discuss other threats associated with the natural environment.

4.1.1 Hurricanes and Extreme Winds

Experience with U.S. land falling hurricanes over the past decade has revealed the vulnerability of the electric grid to their effects, and the effects of high winds in general. High-speed winds primarily knock over trees, especially when the ground is already saturated with water from rainfall or flooding. Fallen trees can damage or down distribution power lines, resulting in power outages.[25] As the wind speed increases, distribution system asset damage becomes more widespread, system performance is degraded and, eventually, large areas and high percentages of customers may experience power outages. High winds can also damage components at the transmission level of the electric power system, denying service to distribution substations.

Table 4. Summary of Key Threats to the Electricity System

Threats	Threat Characteristics					
	Historical Trend		Projected Trend		Predictability: Near-Term	Predictability: Long-Term
Natural/Environmental Threats						
Hurricanes	↑	Intensity, frequency, and duration of North Atlantic hurricanes have increased since the early 1980s[a]	?	Intensity is projected to increase due to climate change[a]	●	○
Drought	↑	Increasing in the Southwest; declining in other U.S. regions[a]	↑	Increasing due to higher temperatures and evaporation, particularly in the Southwest[a]	●	◐
Winter Storms/ Ice/Snow	↕	Storms have increased; total snowfall has declined; extreme snowfall has increased in the East and North[a]	?	Insufficient information and predictability to assess[a]	●	○
Extreme Heat/ Heat Wave	↑	Increases in heat waves have been observed , particularly in the West[a]	↑	Heat waves are projected t become more frequent, intense, and persistent[a]	●	◐
Flood	↕	Increasing in the Midwest and Northeast, declining in the Southwest[a]	↑	Flood risk is projected to increase due to increases in extreme rainfall events	●	○
Wildfire	↑	Numbers of large wildfires have increased in the western U.S. due to earlier and longer fire seasons. [a]	?	Projected to increase in the Arid West, Southeast, and Pacific coast[a,b]	◐	◐
Sea-level Rise	↑	Global sea level has risen by about 8 inches since reliable record keeping began in 1880[a]	↑	Projected to rise another 1 to 4 feet by 2100[a]	◐	◐
Earthquake	↑	Minor earthquakes have increased in Central and Eastern U.S. in association with underground disposal of waste water from oil and gas production[c]	?	Insufficient information and predictability to assess	○	○
Geomagnetic	↔	No trend has been observed	?	Insufficient information and predictability to assess	◐	◐
Wildlife/ Vegetation	↔	No trend has been observed	↔	No expectation of change in threat frequency	○	○
Human Threats						
Physical attack	↔	No trend has been observed in physical attacks	?	Insufficient information and predictability to assess	○	○
Cyber attack	↑	Attacks have increased markedly in recent years[d,e]	↑	Current trends are projected to continue or increase[d,e]	○	○
Electromagnetic	↔	Although a plausible threat, few events have occurred	?	Insufficient information and predictability to asses	○	○
Equipment failure	↔	No trend has been observed	↔	No expectation of change in threat frequency	○	○
Combined Threats	↔	No trend has been observed	?	Insufficient information and predictability to assess	○	○

Key to Symbols

<u>Assessment of Threat Predictability</u>
- ○ – Poor: Inability to predict general trends or discrete events
- ◐ – Moderate: Some predictability of trends, but not discrete events
- ● – Robust: Skillful predictions of discrete events and trends

<u>Assessment of Threat Trends</u>
- ↑ – Increasing
- ↔ – No change
- ↓ – Decreasing
- ↕ – Trends vary by geography
- ? – Insufficient information

Caption: The table above provides information on observed or projected trends in natural/environmental and human threats to the U.S. electricity system. Notes and references for specific events are listed in Appendix A. The predictability of each threat is also indicated over the short-term (i.e., hours to days) and long-term (months to years).

Other wind events, such as the June 29, 2012 “super derecho” storm that affected the Midwest and mid-Atlantic regions, can create similar impacts and disrupt power to millions of people. Tornadoes generally create a narrow path of destruction and do not cause widespread power outages, but if a tornado passes close to a major transmission substation or transmission corridor, the localized damage to the transmission system could lead to widespread power outages. A number of organizations have presented options for mitigation, preparedness, recovery, and response, including:

- Improving reliability and resilience through efforts such as strengthening distribution poles and wires, improving flood protection, managing vegetation, and burying distribution lines, where feasible. [26,27]
- Increasing system flexibility and robustness through energy storage or creation of microgrids. Grid modernization, smart meters, and synchrophasor technology can enable faster recovery from hurricane damage.[26,27,28]

Seasonal predictions of hurricane activity are based one or more of three basic methods:[29] statistical methods that attempt to correlate seasonal hurricane activity with predictors such as sea surface temperature, analog methods that attempt to find a previous year with similar atmospheric conditions, or dynamical methods that used reduced models of the atmosphere-ocean system to predict the future state of the system and its hurricane activity. NOAA’s Climate Prediction Center (CPC) releases an annual prediction for the severity of the hurricane season that incorporates all three methods.[30] Researchers from Colorado State University (CSU) also release extended range forecasts for the number of Atlantic hurricanes expected and the general hurricane activity in the upcoming season. The CSU model is primarily statistical. It analyzes a variety of different atmosphere and ocean measurements (through May) that are known to have long-period statistical relationships with the upcoming season’s Atlantic tropical cyclone activity to predict the intensity of the hurricane season.[31] SCOR, a global reinsurer, evaluated the forecasts of CPC and CSU and found that, while the forecasts were an improvement over using the long-term average of hurricane activity, each exhibited strong deviations from actual activity limiting the usefulness of these seasonal forecasts.

To predict the track and intensity of an individual local hurricane, NOAA now uses unmanned aircraft to deploy dropsonde sensors to gather data on wind speed, wind direction, and pressure.[32] New technologies, such as the unmanned aircraft and a new Doppler Wind Lidar system, are increasing the accuracy of NOAA forecasting for hurricane landfall and intensity. Forecast errors in track location have decreased significantly since 1970; the 72-hour forecast has an annual average track error of 125 miles. The 24-hour forecast has an annual average track error of 50 miles.[33]

U.S. Tornadoes issues a long-range tornado outlook[34] that extends out several months. At this prediction time scale, the forecast is primarily based on analog methods that focus on large scale weather patterns such as the El Niño-Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and Atlantic Multi-decadal Oscillation. As with long-range hurricane forecasting these methods provide very limited forecast skill and are not very useful for assessing annual risk to the power systems. In contrast with hurricanes, tornadoes form and dissipate rapidly. There is little to no ability to predict the location and intensity of a tornado. Conditions favorable for formation may be seen a day ahead, but actual formation may only be known less than one hour ahead.

It is unlikely that seasonal forecast for hurricanes or tornados will improve significantly in the near future. Research investments in numerical weather forecasting will likely reduce the forecast uncertainties for individual hurricanes, which will enable better response planning and resource prepositioning for the post-hurricane recovery. Uncertainty in hurricane track and intensity will still be present, and power system real-time impact modeling should be improved to incorporate these factors. Finally, forecasting individual tornados is unlikely to provide sufficient lead time to enable any coordinated response planning from electrical utilities.

Climate change may increase the risk of power outages caused by hurricanes from increased intensity, frequency, and duration. Other trends in severe storms, including the intensity and frequency of tornadoes, hail, and damaging winds, are uncertain and understudied.[35]

Preparing for severe weather events requires a balanced process. It is not economical to build transmission and distribution systems that can withstand every extreme, but infrequent, weather event. Developing rapid restoration capabilities can be more appropriate. It is important to balance increased system hardening with provisions for faster restoration.[36]

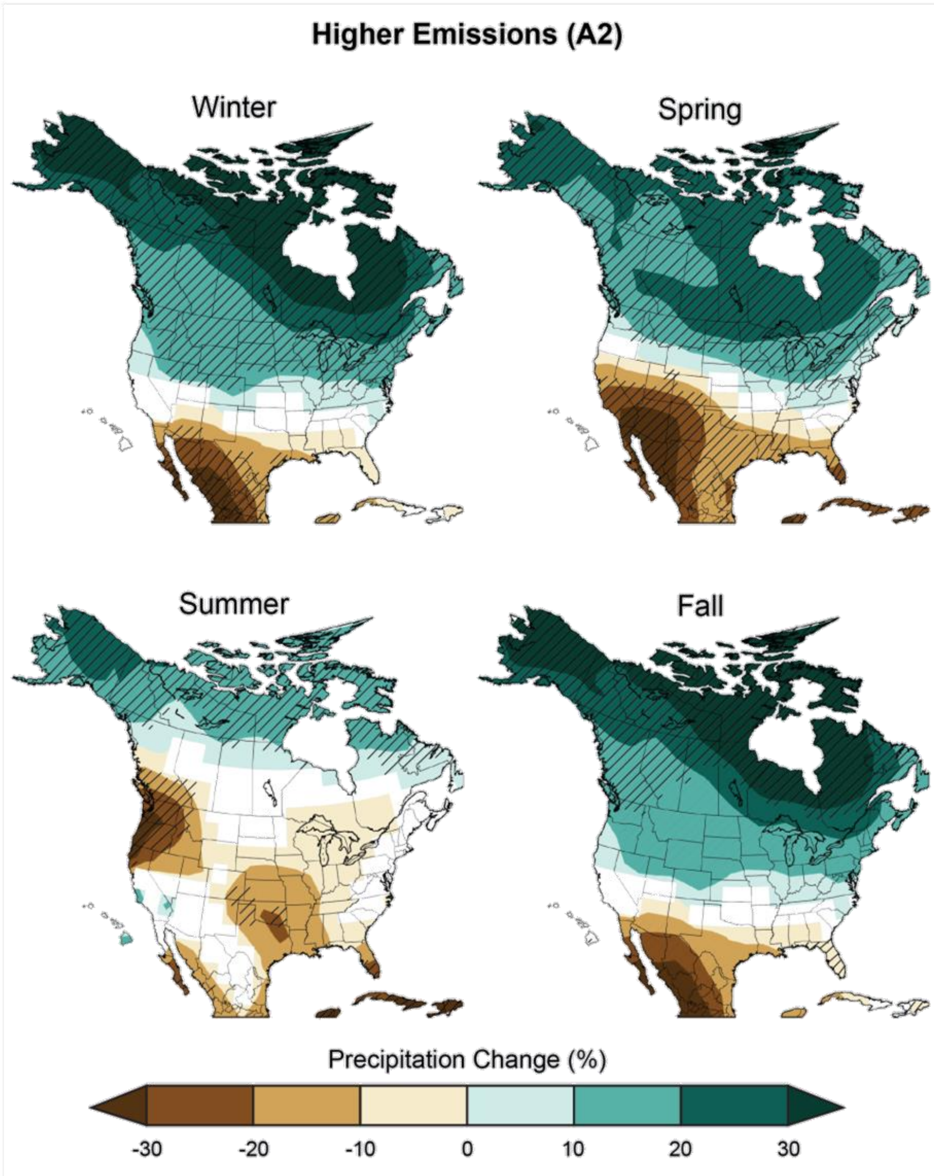
4.1.2 Drought

In 2013, 7% of the electricity generated in the United States was from hydroelectric resources.[37] Low rainfall reduces the availability of hydroelectric resources, particularly in the western United States. For example, in 2014, California experienced its worst drought in 119 years.[38] Consequently, hydroelectric generation for June 2014 was only 58% of the 10-year average.[39] In addition, annual temperature profiles can impact the timing of water availability.[40] A rapid snowpack thaw in the spring can overload reservoir capacity and lead to lost energy normally available later in the year.

Drought decreases the cooling water availability for steam plants and can lead to plant de-rating because of low water levels, low flow rates, or high water temperatures in rivers and reservoirs. Examples include the drought in Texas in 2011, which reduced the cooling water available to power plants by 30%.[41] A recent study[42] simulated the weather experienced during the U.S. Dust Bowl disaster between 1930 and 1934. Generation-capacity losses for California, Arizona, and Texas under such drought conditions would be 17%, 25%, and 30%, respectively. Further, a study of droughts in the southwestern region of the United States over a 1,200-year period indicates that during a 12th century drought, temperatures were higher and precipitation was lower than any drought experienced during the past two centuries.[43] Non-thermoelectric power plants, such as many natural-gas-fired combustion turbines, do not use water for cooling, but they still require water for other purposes, such as improving turbine performance on non-thermoelectric natural gas plants and for housekeeping activities.[44,45]

NOAA and other weather organizations use the ENSO pattern to predict seasonal climate patterns such as an unusually dry season.[46] The U.S. Drought Monitor, run by the University of Nebraska Lincoln, releases weekly estimates of drought severity in the U.S.[47] A major gap relative to drought and it impact on power is the accuracy of long-range predictions of drought and water availability. Climate change is expected to alter the frequency and severity of drought conditions, but the results still carry significant uncertainty. Current projections indicate that the Southwest United States will be impacted by increasing drought conditions.[35] Figure 5 shows how precipitation could change by season by the end of the century. Other power plants in the region will need to increase power production to make up for reduced hydropower generation potentially leading to additional transmission congestion.

Figure 5. Projected Change in North American Seasonal Precipitation for 2071-2099 (compared to 1970-1999)



Caption: Projected changes in seasonal precipitation as simulated by an ensemble of general circulation models for a high emissions scenario (the Special Report on Emission Scenario's A2 scenario). Source: Walsh et al. (2014).[48]

Replacing water-cooled power plants with air-cooled power plants that do not rely on water for cooling can mitigate drought's impacts; other mitigation options include prioritizing low- or no-water cooling options for new generators and setting strong guidelines for power plant water use.[49] (Note: Air-cooled plants may operate a reduced output during periods of high temperatures.) Western Resource Advocates recommends that utilities and regulators consider future water use during planning exercises.[50]

4.1.3 Winter Storms, Ice, Extreme Cold

During an extreme cold weather event, the demand for natural gas increases and puts stress on natural gas pipeline operations. Natural gas-fired electric power generators typically hold interruptible gas transmission contracts. The extreme cold may cause gas pipeline customers with firm transmission rights (e.g. local distribution companies (LDCs)) to require full delivery of the natural gas allowed by their right. If the gas pipeline is physically unable to deliver gas to the interruptible contracts held by electric power generators, these generators are de-rated or shut down. The stress on the electrical grid created by the loss of generation may be compounded by high electrical demand created by the extreme cold. The threat and potential impact of these extreme cold scenarios is being amplified by the increasing reliance on natural gas generation,[51] raising concerns about the ability to maintain electric system reliability during these events.[52]

Electric generation capacity may be lost though other effects of extreme cold. NERC has issued reports on eleven severe cold weather events that have significantly impacted the electric power system since 1983.[53] In addition to natural gas supply issues, generation capacity may be reduced due to generating unit trips, de-rates, or failures to start.[53] Frozen coal piles, fuel oil delivery, and cold temperature impacts on sulfur hexafluoride (SF_6) and air blast circuit breakers have resulted in generator outages and unavailability.[53] Liquefaction of SF_6 occurs between -10°F and -30°F, depending on the density of the SF_6; this liquefaction can cause circuit breakers to mis-operate. In locations where temperatures fall below –10°F, a supplemental means to maintain the SF_6 above -10°F must be provided.

Power outages caused by extreme cold conditions may also cascade through the both electrical and natural gas systems. For example, during a severe cold weather event in New Mexico in February 2011, frozen sensing lines caused many generators to automatically trip offline due to faulty readings from transmitters.[54] The resulting power outages disabled electric-power gas compressors on well gathering lines, which limited the delivery of natural gas to New Mexico.[54]

NOAA and other weather organizations use the ENSO pattern and other atmospheric and oceanic analog conditions to predict seasonal climate patterns, including the likelihood of below normal temperatures.[55] Although these forecasts provide expected general trends, they have limited utility in planning for extreme cold temperature events.

The NOAA Weather Prediction Center (WPC) releases a WPC Probabilistic Winter weather forecast.[56] The maximum duration for the forecast is 72 hours prior to the event. The National Weather Service Storm Prediction Center also releases a 4-to-8 day severe weather outlook that indicates severe and unusual weather conditions that may occur. These forecasts provide electrical grid operators sufficient warning to prepare their systems using the short-term mitigations discussed below.

Extreme cold temperatures are rare and forecasting natural gas and electrical demands are challenging. Even when the forecasts of extreme cold temperatures are accurate, errors in forecasting of natural gas and electrical demand can lead to overly conservative planning or unresolved system risk. Improvements in this type of forecasting can improve coordinated system operations during these extreme events.

Short-term mitigations for extreme cold include winterizing generators, cancelling scheduled generation and transmission outages, reviewing generator fuel procurements, committing additional generator units, demand response to reduce load, coordination with neighboring utilities to maximize the benefit of electricity imports and exports, and operational coordination and information sharing with gas pipeline operators.[57]

Longer-term mitigations for extreme cold weather include encouraging natural gas-fired generators to purchase firm transmission rights to guarantee the availability of fuel. Alternatively, ISO New England has started a Winter Reliability Program to provide incentives to non-gas-fired generators (e.g. fuel oil-fired) to secure fuel and perform maintenance before winter.[58]

Ice accumulation adds weight to power lines and increases the cross sectional area for wind drag on the lines leading to increase mechanical stress and breakage of power lines and support structures. [59] Similar effects are experienced by nearby trees leading to greatly increased occurrence of trees and branches falling on power lines. This type of damage is most prevalent in distribution systems, but may be experienced by transmission lines as well. In many respects, the damage is similar to that caused by high winds during hurricanes and the outcomes are similar (Section 4.1.1).

Similar to extreme cold weather, NOAA and other weather organizations use ENSO and other atmospheric and oceanic analog conditions to predict seasonal climate patterns, including the likelihood of winter precipitation.[55] However, these forecasts do not distinguish between snow and freezing rain and have limited utility in planning for ice storms.

The NOAA WPC releases a Probabilistic Winter Precipitation Guidance forecast for snow and freezing rain.[56] The maximum duration for the forecast is 72 hours prior to the snow/ice event. NOAA also uses a Short Range Ensemble Forecast (SREF) derived winter weather impact graphics to show forecasted accumulation on roads, surface visibility, and rate (intensity) of winter precipitation.[60] The National Weather Service Storm Prediction Center also releases a 4-to-8 day severe weather outlook that indicates severe and unusual weather conditions that may occur. These forecasts provide sufficient warning for distribution utilities to preposition equipment and crews and to plan for requests for mutual aid to speed post-storm restoration.

Mitigation of ice storms includes two basic utility procedures; tree trimming and system hardening. Aggressive tree trimming, including ground-to-sky approaches, greatly reduce the possibility of ice-laden trees and branches from falling on distribution lines. System hardening may including undergrounding of overhead lines, replacing existing pole and crossbars with stronger components, adding additional guying to dead-end structures and other poles to prevent breakage and cascading mechanical failures, and upgrading conductors with heavier wire.[61]

4.1.4 Extreme Heat and Heatwave

Summers are longer and hotter and extended periods of unusual heat are lasting longer.[35] Most utilities experience peak demand during extended heat waves; these high demands stress the existing electric power infrastructure. On the demand side, a severe heat wave increases air-conditioning load significantly driving up the entire system load curve, with the largest increases during the mid- to late-afternoon peak hours.[62] Cooling degree days have already increased in the U.S. by roughly 20 percent over the last few decades, and this trend is projected to continue in the future.[63,64] On the supply side, high ambient temperature conditions have an impact on combustion turbines (CTs) because of the reduced density of the air at higher temperatures. Unless inlet cooling technologies are used, the output capacity of a CT decreases because the efficiency of converting fuel to power also decreases.[65,66] Extreme heat can lower thermal limits of transmission lines and transformers.[67,68]

NOAA and other weather organizations use the ENSO pattern and other atmospheric and oceanic analog conditions to predict seasonal climate patterns, including the likelihood of above normal temperatures.[55] Although these forecasts provide expected general trends, they have limited utility in planning for extreme high temperature events.

In addition to normal weather and temperature forecasting, the NOAA Climate Prediction Center releases probabilistic outlooks of temperature hazards.[69] The maximum duration for the forecast is 14 days prior to the event. These forecasts provide electrical grid operators sufficient warning to prepare their systems using the near-term mitigations discussed below.

Extreme hot temperatures are rare and forecasting electrical demands are challenging. Even when the forecasts of extreme hot temperatures are accurate, errors in forecasting of electrical demand can lead to overly conservative planning or unresolved system risk. Improvements in this type of forecasting can improve coordinated system operations during these extreme events. Climate change is projected to significantly increase the frequency, intensity, and duration of extreme heat events (Table 4).

Short-term mitigations for extreme hot temperatures include cancelling scheduled generation and transmission outages, committing additional generator units, demand response to reduce load, and coordination with neighboring utilities to maximize the benefit of electricity imports and exports. Longer-term mitigations for extreme hot weather include installation of inlet cooling equipment on gas combustion turbines and combined cycle power plants. There are approximately 90 plants with inlet air cooling across the entire United States, compared to a total of about 1,500 combustion turbines in the Eastern Interconnection alone.[70]

4.1.5 Inland and Coastal Flooding

In the transmission and distribution system, substations are the elements most vulnerable to flooding. Flooding damages ground-level substation control equipment and low-voltage switchgear. High-voltage components, including insulators, circuit breakers, air-break switches, transformers, dead-end towers, lightning arrestors, and metering transformers are situated high aboveground to use air space for insulation from surrounding ground faults; therefore, flooding is less directly threatening to the high voltage power system components.[71] As a rule of thumb, facilities located in areas with more than four feet of floodwater will likely be out of service and could sustain damage to transformers and circuit breakers. (Note: Substations are usually built above grade.)

If floodwaters do not damage the transmission and distribution systems, then crews can restore these systems shortly after the floodwaters recede. The utilities in the area may also reconfigure the distribution networks to bring in power from other unaffected distribution substations. This would be done on a case-by-case basis because of engineering limitations on individual networks (i.e., loading levels and voltage issues). Crews can repair or replace damaged distribution system components as the area becomes accessible. The restoration time for damaged transmission-level components, specifically high-voltage transformers at individual substations, could be months.[72] The repair time for high-voltage equipment depends upon the availability of replacement parts. Specialized transformers would take the longest time to replace, as spare parts are not readily available (see also Section 4.2.1).

The National Weather Service provides Spring Hydrological Outlooks that include the probabilities of a range of flood severities.[73] The National Weather Service (NWS) [73] and the U.S. Geological Survey (USGS) [74] also provide short-term flood monitoring and forecasting. Both monitor the amount of rainfall occurring in conjunction with the rate of change in the affected river stage. The USGS releases a daily map of flood and high flow conditions within the United States. The estimates are measured in percentiles of estimated streamflow. The series of maps also include real-time streamflow gauge data which also forecasts estimate flood stage.

Climate change may increase the risk of flooding, but the results still carry significant uncertainty. Coastal flooding caused by hurricane storm surge may be more severe due to higher sea levels (Table 4). Extreme rainfall events are also becoming more common across most parts of the United States, increasing the risk of flooding. As a result, many areas may experience flooded streets more regularly during high tides and storms.[35]

Flood protection for substations is part of recommended "hardening" investments.[75] Hardening includes elevating or building berms around substations and relocating facilities. Undergrounding of wires to harden them against other threats make them more vulnerable to flooding than overhead wires.[1,76] Many utilities use submersible equipment in flood prone areas to maintain electric power reliability. While system redundancy could prevent power disruptions during a flood, it is possible that flooding could cause partial loss of power that might extend beyond the inundation area. Electric power utilities operating in flood-prone areas have developed planning guidelines based upon experience.

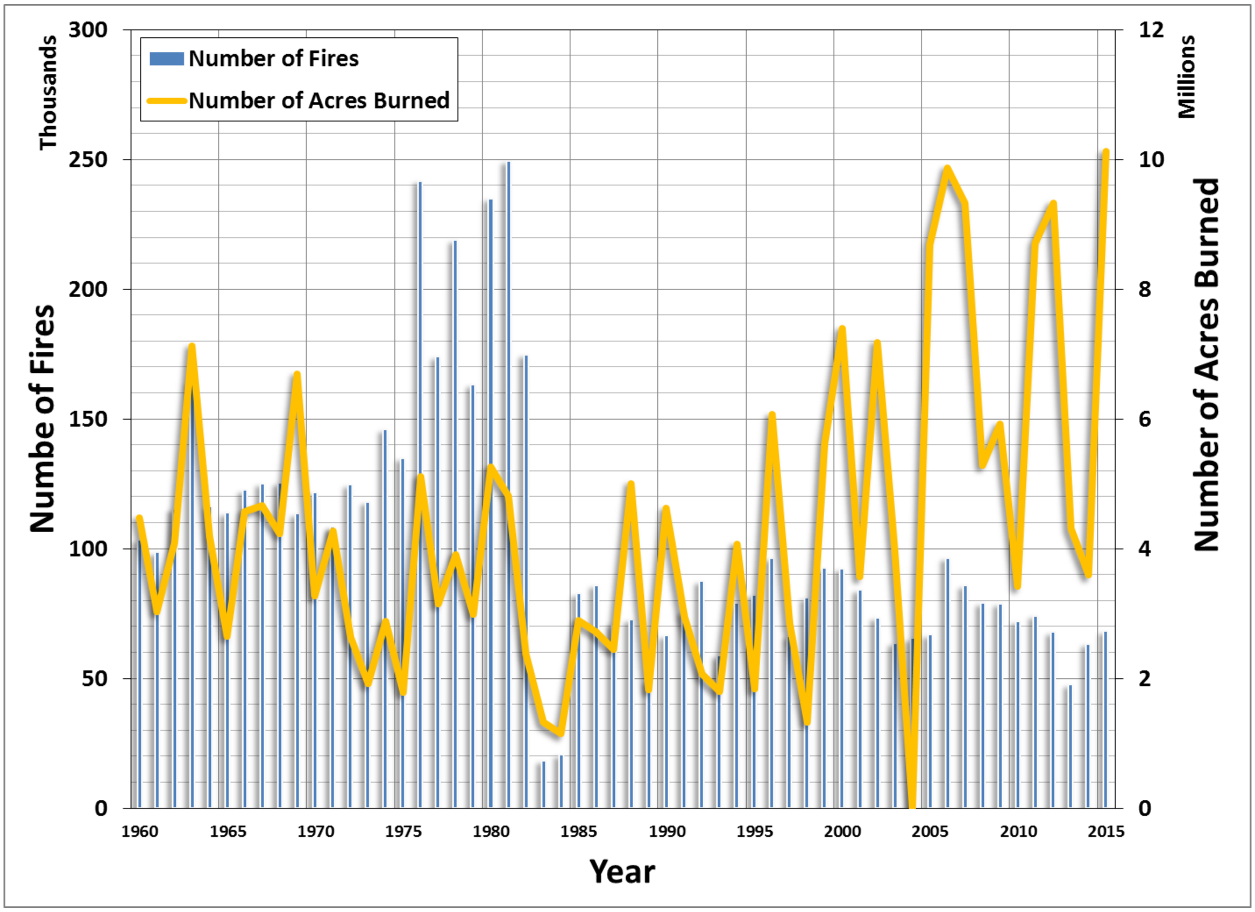
4.1.6 Wildfire

Wildfire events pose a threat to the electricity system, particularly due to the exposure of high voltage transmission lines. Wildfires can trigger emergency line de-rating or shut-downs to prevent line damage. Smoke from wildfires can induce a line fault, resulting in a loss of service.[77] Recent years have witnessed damage and disruption to electricity transmission due to large fires.[2] Alternatively, transmission may be cut to maintain the safety of emergency personnel operating in the area. Penetration of wildfires into residential and/or commercial areas can also expose electricity distribution systems and substations, and wildfires have also disrupted generation facilities. A California wildfire in 2015 damaged five facilities associated Calpine Corporation's The Geysers – the world largest geothermal infrastructure.[78]

Historical fire regimes are undergoing change due to larger patterns of climate change (Table 4). While the absolute number of fires across the U.S. has not increased over the past fifty years, the total area burned has increased markedly (Figure 6). This is associated with a lengthening of the fire season.[48] Climate change is projected to further increase the likelihood of major fires in the future due to continued lengthening of the fire season as well as projected increases in drought conditions (Table 4; see also Section 4.1.2).[48] Predicting wildfires requires understanding sources of ignition, the spatial and temporal distribution of fuel loads, weather conditions, as well as fire management practices. Generally, understanding of the spatial distribution of wildfire hazards is well-documented based on historical events, land use, and U.S. climatology. Furthermore, the various factors that increase the risk of significant wildfire events (e.g., drought, low humidity, high winds, high temperatures) can be monitored and forecast with lead times of days to months.[79] However, due to the stochastic nature of fire ignition, such forecasting tools do not necessarily translate into a reliable forecast of a discrete wildfire event of a specific size in a specific location.

Wildfire risks to electricity systems can be mitigated through wildfire management planning as well as vegetation control planning. Removing vegetation in close proximity to transmission and distribution lines and poles as well as substations and generation infrastructure can reduce the likelihood of direct impacts on electricity assets during wildfire events. This can be facilitated by manual clearing or by prescribed burns. In addition, during wildfire events, fire suppression efforts can target critical infrastructure such as electricity system assets and, in some cases, protective measures such as fire resistant coatings can be applied to power poles to reduce burn risk.

Figure 6. Historical Trend in U.S. Wildfire Frequency and Area (1960-2015)



Data Source: National Interagency Fire Center.[80]

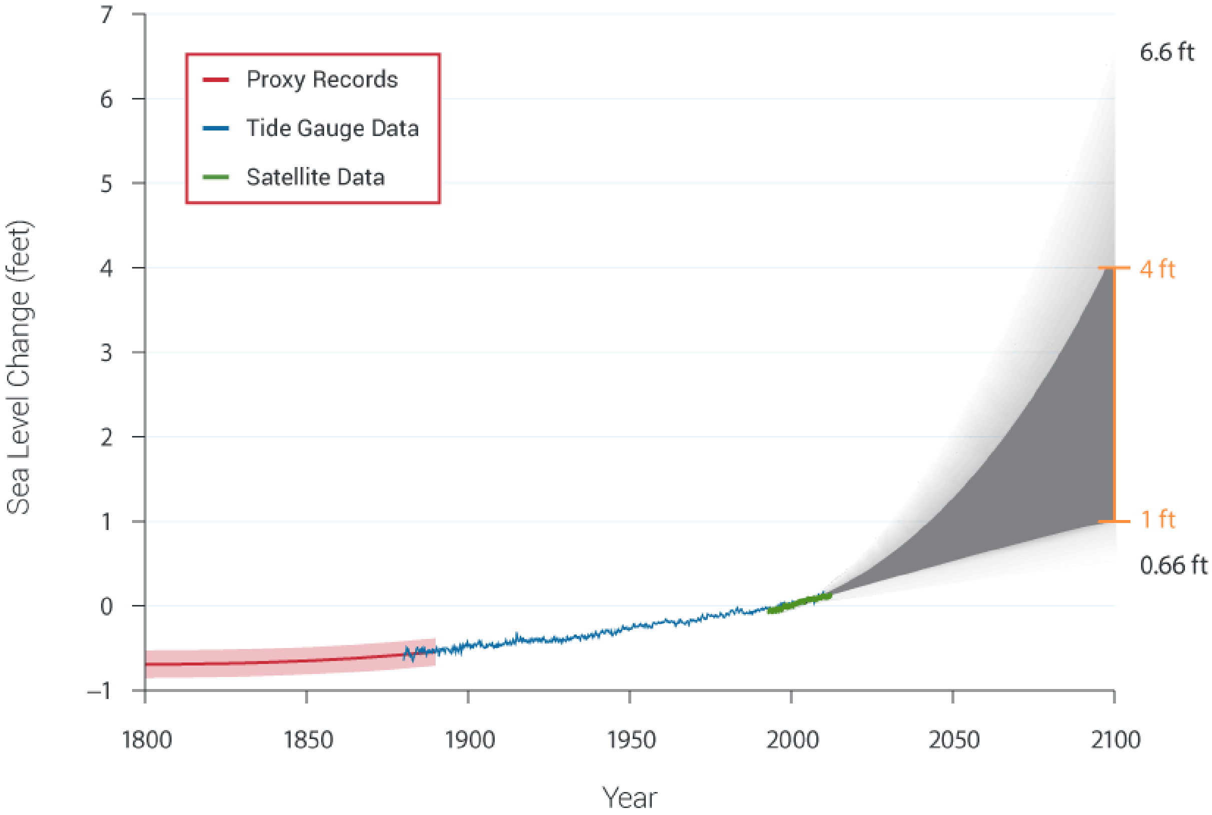
4.1.7 Sea-Level Rise

Climate change and the associated warming of the oceans and melting of glaciers and ice sheets are contributing to a global increase in sea level. Globally, sea levels have increased by approximately 8 inches since records began in the 1880s.[48] This sea-level rise poses a potential threat to energy infrastructure in the coastal zone through two possible pathways. First, the chronic increase in sea level can potentially result in the permanent inundation of coastal land areas, some of which are associated with electricity infrastructure.[81]

Scenarios of future sea-level rise over the 21st century presented in the most recent *National Climate Assessment* reflect the uncertainty in projecting future sea level changes. The different scenarios indicate a range of sea-level rise on the order of 1 to 7 feet by 2100, although model-based projections are more modest, on the order of 1 to 4 feet (Figure 7).

Analysis of sea-level exposure for four metropolitan areas by DOE indicates that power plants and substations are both potentially vulnerable to future sea-level rise. However, energy assets that lie in harm's way are likely to have significantly depreciated to the point of obsolescence by the time they are affected by sea-level rise. Hence, the threat posed by chronic increases in sea level over the long-term may be modest, unless sea-level rise proceeds along the higher range of current scenarios. In this case, the rate of sea-level rise may be sufficiently rapid to threaten existing infrastructure, necessitate premature retirement of the asset or investments in defenses to avoid inundation. That said, reported increases in nuisance flooding in coastal communities are already being attributed to sea-level rise.[82]

Figure 7. Past and Projected Changes in Global Sea Level



Caption: Estimated, observed, and possible future amounts of global sea level rise from 1800 to 2100, relative to the year 2000. Source: Walsh et al. (2014).[48]

The other pathway by which sea-level rise can threaten electricity assets is through its interactions with storm surge events associated with tropical cyclones, hurricanes, and nor'easters. Sea-level rise is projected to increase the depth of inundation associated with storm surges as well as their inland penetration. This may increase the frequency to which electricity assets are exposed to inundation as well as the severity of inundation during storm events. The effects of sea-level rise are most significant for low-intensity hurricanes, due to the change in sea level being relatively large relative to the typical storm surge. For major hurricanes, sea-level rise has comparatively little additional impact on the anticipated inundation of existing infrastructure.[83]

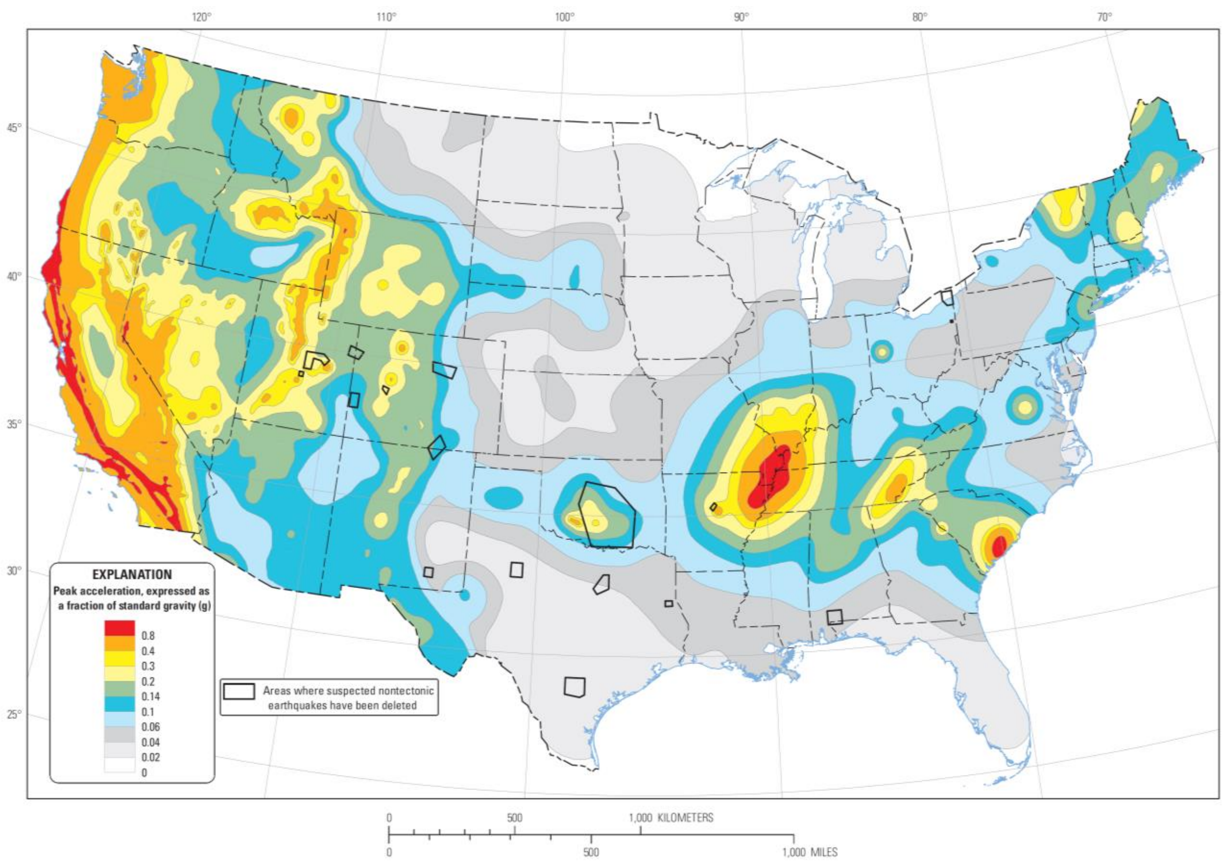
Although future increases in sea level are one of the most robust consequences of global climate change, uncertainty in the specific magnitude of sea-level rise over different time scales remains a challenge for both risk assessment and management. Sea level prediction will likely improve over time, resulting in more constrained estimates of future sea-level rise.

Mitigation of the risks associated with sea-level rise is often categorized into one of three strategies: protection, accommodation, and retreat.[84] Protection measures often involve the use of flood defenses (i.e., levies and sea walls) in order to prevent flooding of infrastructure and assets. This can be effective for managing the increases risk of storm surge due to sea-level rise, but may not be suitable for locations that experience permanent inundation in the future. Accommodation measures include elevating infrastructure to reduce the likelihood of inundation. This may be particularly effective for substations, but more challenging for large generating facilities. However, where new construction is occurring, the elevation of sites can be increased to provide additional protection. One of the most robust options for mitigating against the effects of sea-level rise is through retreat measures[84] – siting of infrastructure and assets in locations that will not be affected by sea-level rise. Siting decisions routinely consider exposure to potential hazards in order to avoid vulnerable locations. However, retreat options are not feasible for infrastructure and assets that currently exist, although assets may be allowed to depreciate or be prematurely retired to reduce investment in assets that are increasingly at risk.

4.1.8 Earthquake

Ground shaking can affect the structural integrity of electric power assets through various modes of permanent ground deformation: soil liquefaction, lateral spreading, and/or vertical displacement. Records from past earthquakes indicate that electrical transmission lines are not particularly vulnerable to significant earthquake damage, but distribution systems, transmission towers, and substation components located in areas with unstable soil are at risk of damage. Earthquake related damage includes broken porcelain components, toppled equipment, line failures because of inadequate slack, and leaking gaskets. Distribution lines are not as vulnerable to earthquakes; however, some damage can occur if trees fall into wires or poles, platform-mounted transformers topple, or wires tangle.[85]

Figure 8. The U.S. Geological Survey National Seismic Hazard Map



Caption: The U.S. Geological Survey (USGS) National Seismic Hazard Map of peak ground acceleration exceedance (2% in 50 years) across the United States. Source: USGS (2014).[86]

A damaged electric power asset may continue to operate at a reduced capacity or lose functionality. For example, if a substation is located in an area that is moderately or severely damaged, it will most likely lose complete functionality. Based on the configuration of the electric power network and damage to certain network assets, some areas may experience power outages, because they become disconnected from the grid, even though assets within these regions are undamaged.

There is no advanced notice before an earthquake occurs, and there may be significant transient effects on power systems. If an earthquake causes more customer load than generation to go off-line, the generation surplus will cause the remaining operating generators to spin faster—a situation the system cannot tolerate. By design, the power system, through the control networks, automatically self-corrects by taking units offline within minutes of the earthquake event. If an earthquake occurs when there is less demand on the system, such as in the morning, on the weekend, or in the spring or fall, the reduction in demand would be much less pronounced making it easier for the systems to ride through the event with less risk of cascading failures.[87]

Probabilities for potential future earthquakes can be estimated from historical observational data. The USGS releases National Seismic Hazard Maps that display probability levels for earthquakes across the United States (Figure 8).[86] The USGS also maintains a real-time map of the latest earthquakes.[88] Using the seismic hazard maps, EPRI has performed extensive probabilistic seismic hazard analyses (PSHA) for many power systems and specific components of power systems. One exemplary EPRI study calculates probabilistic seismic hazard at nuclear plant sites using peak ground acceleration and the model of seismicity developed by USGS at each site.[89]

Disposal of hydraulic fracturing (or “fracking”) wastewater in deep injection wells has created nonstationary seismic processes that create a great deal of uncertainty around induced seismicity related to these injections. According to the USGS, this induced seismicity has increased seismic activity in parts of the United States coincident with fracking operations involving injection wells for wastewater disposal. Although most fracking areas are not too close to widespread electrical power infrastructure, risks to specific facilities remain. There is little historical data on induced earthquakes from fracking and, as such, the uncertainty of these events is high. However, the USGS is now producing a 1-year seismic hazard forecast for the Central and Eastern United States from Induced and Natural Earthquakes.[90]

Over the short term, there is no scientifically credible method to predict specific earthquake events. Hence, given only limited long-term predictive capability, the main mitigation mechanism against earthquakes is either to not cite critical electrical infrastructure in active seismic zones or to reinforce facilities or apply strict construction codes within those zones. For known vulnerabilities, utilities should have plans for replacement of permanently or long-term damaged generation or network transformer capacity.

4.1.9 Geomagnetic

During geomagnetic disturbances, the magnetic fields at the Earth’s surface produce geo-electric fields which can drive geomagnetically induced currents (GIC) through grounded transformers and transmission lines. These quasi-DC currents can saturate transformer cores leading to voltage collapse and/or excessive heating and failure of a significant number of high voltage transformers. The type of damage to large transformer could result in long-term, widespread blackouts and also lead to lengthy repairs or replacements that could take on the timescale of weeks to months.[91,92]

A solar storm, named the Carrington Event, occurred in 1859. During this event, a solar coronal mass ejection hit Earth's magnetosphere, creating one of the largest geomagnetic storms on record. This solar storm is widely regarded as the most extreme space weather event on record. This event occurred before the advent of modern electric power grids, but it induced sparks and currents along telegraph lines. In 1989, a solar storm over North America caused a collapse of the Hydro-Quebec power grid and oscillations on the Northeast Power Coordinating Council and the Mid-Atlantic Area Council grids, nearly bringing them down in a cascading collapse. In 2003, a geomagnetic storm caused minor power disturbances in North America but caused over 50,000 customers in northern Europe and Sweden to lose electric power service.[92] Anecdotal reports of significant auroras indicate that the Carrington event was not unprecedented in Earth's history. Historical records of solar events suggest that a reasonable range for the average return period for an extreme geomagnetic storm is 100 to 250 years.

Over relatively short time-scales, the NOAA Space Weather Prediction Center releases a 27-Day Outlook of radio flux and geomagnetic indices.[93] The SWPC also releases a shorter 3-day forecast and a 30 minute forecast.[94] Although such forecasts can provide early warning that a storm is on the way toward Earth, the ultimate impact of the event can vary significantly depending on the latitude and orientation of the charged particles and how they couple with the earth's magnetic field. Such characteristics are nearly impossible to predict with precision. Over longer time-scales, the Sun follows a cycle of magnetic activity reflected by the number of sunspots and the average sunspot area, which waxes and wanes on a time scale of 9 to 14 years. However, major geomagnetic storms have occurred during solar cycle minimums making the solar cycle a poor, long-term predictor of GMD occurrence.

Several strategies and designs can mitigate GIC events. These include 1) identifying high priority facilities and 1) deploying advanced relay technology; 2) installing monitors to measure GIC flow; 3) installing GIC blockers on vulnerable equipment; 4) protecting transmission lines by using a differential element; and 5) implementing back-up precise time sources and back-up communications.[95] However, there are also drawbacks to these solutions. Series capacitor banks, which are used primarily for compensation of transmission lines, can block GIC flow in transmission lines, but they are costly. Another device utilizes a transformer-neutral blocking mitigation scheme. These devices have been installed on a limited basis. A properly designed GIC blocking system should greatly improve system reliability under a GIC event. However, a major concern is the successful operation of a bypass device around the current limiting component during a system fault condition. Mis-operation of a bypass device could cause major system issues and failure of key system components, including insulation failure of the transformer.[96]

A significant amount of work had been done to understand the impact of GMD and GIC on power systems[97] and commercial software packages now exist for performing planning studies.[98] However, a significant gap that remains is our ability to predict the rate of occurrence of very large GMD events and to characterize the spatial distribution of the geo-electric field hazard from these events. Some research has investigated these effects,[99] but both effects are critical inputs into a long-term GMD risk assessment. Also, traditional power system planning models do not including substation grounding or transformer configuration details. These are crucial to being able to model geomagnetic induced currents in the power system. Hence, a significant modeling gap currently exists in modeling, and therefore predicting, GMD risks.

4.1.10 Wildlife and Vegetation

Wildlife and vegetation contact are one of the most common causes of electric system outages reported by utilities. A 2015 survey of energy utilities indicated that wildlife-related outages associated with the distribution system exceeded those associated with severe weather.[100] In 2005, the annual costs of wildlife-caused power outages for California alone were estimated to be $32 million to $317 million.[101] Wildlife can affect transmission, distribution, and substations. However, incursions of animals into substations are particularly problematic as faults in substations can cause outages over larger areas.[102] Vegetation can also pose a threat, particularly to distribution systems. However, the effects of vegetation are often indirect through their association with weather events (e.g., wind or ice) that lead to falling branches, trees, or other debris.

Due to their frequency of occurrence, wildlife and vegetation are well-recognized threats that can be anticipated to routinely impact electricity systems. However, as they tend to be stochastic events, it is not possible to predict the timing and location of specific outages. The link between vegetation threats and weather indicates that increased exposure to vegetation impacts can be anticipated when storm events have been forecast. There is no direct evidence of a future change in the threat of wildlife and vegetation to electricity systems. However, there may be indirect effects through changes in population and electricity demand that increase the extent and number of transmission, distribution, and substation networks. This would effectively increase the exposure of the electricity system to wildlife and vegetation. In addition, changes in the frequency, intensity, and/or duration of extreme weather due to climate change could drive indirect increases in vegetation impacts on the electricity system.

Various measures are commonly used to mitigate the threat of wildlife and vegetation to electricity systems. These include insulation of transmission and distribution lines and connections, using fencing around substations and keeping sites clear of clutter and debris to deter wildlife, as well as tree trimming and vegetation clearing programs to keep transmission and distribution lines free.[102] The latter has the additional benefit of reducing access by wildlife to power lines.[102]

4.2 HUMAN THREATS

4.2.1 Physical Attack

Globally, physical attacks on energy infrastructure have increased significantly in recent years, although the role of improved reporting versus actual increase in the targeting of infrastructure remains an open question. Moreover, in the United States, physical attacks on the U.S. electricity system have historically consisted of small-scale vandalism targeting transmission and distribution systems.[103] Most major transmission substations and lines are located in rural areas and are not staffed. They are often visible from roads, and substations are generally only protected by fences and intrusion alarms (Box 3). In contrast, generation stations are typically staffed with more robust and layered physical protection. Therefore, it is expected that physical attacks will primarily focus on the transmission system components.

To try to reduce the risk of human sabotage and damage, the NERC has developed standards and guidelines to address these issues. The NERC reliability standard CIP-014-1 seeks to protect transmission infrastructure, including substations and control centers, from physical attack.[104] Meanwhile, the 2001 NERC document *An Approach to Action for the Electricity Sector, version 1.0* identifies a four-tiered approach to physical security. An effective program usually encompasses all four of these components:[105]

- **Avoidance**: Ensure electric power system integrity and availability by promoting the development and implementation of security policies, standards, and procedures; by use of outreach programs; and by providing education programs to enhance and maintain appropriate levels of cyber and physical cyber security.
- **Assurance**: Ensure electric power system integrity and availability by promoting the regular evaluation of physical and cyber security measures. A sub-tier component includes the identification of appropriate levels of risk management.
- **Detection**: Protect electric power systems through monitoring, identification, central reporting, and analysis of operational, physical and cyber threats and/or incidents. Promote reporting of threat warnings and threat prevention information back to electricity sector operating regions and utilities.

- **Recovery**: Promote methods for timely investigation of operational, physical or cyber security incidents and rapid recovery/restoration of services supporting the delivery of electric power services. Lessons learned from this layer are incorporated into the other tiers.

Within the electric sector, there is little ability to predict when a physical attack on the power system will occur. However, the rate of physical attack and vandalism in Table 3 indicates that occurrences are not uncommon.

Without the ability to predict, the main mitigation mechanism is to identity highly critical assets in the power system and to protect them from physical attack by assessing the vulnerability to physical attack and hardening transformers and power equipment. Some facilities may warrant security guards to prevent physical attacks. Real-time monitoring of power disruptions, sparing of critical components, and rapid repair will assist in quickly restoring power lost due to a physical attack.[106]

Box 3. High-Voltage Transformers as Key Sources of Vulnerability

High-voltage transformers (HVTs) have been a concern for DOE for three reasons. First, failure of a HVT can cause temporary service interruption and/or cascading failures and damages. Second they are vulnerable to physical attack and sabotage, both from within and from outside the substation where they are located. Third, HVTs are difficult to replace due to their large size and their custom construction, which is largely performed overseas. The NIAC and NERC have highlighted the lack of excess HVT capacity as a priority for enhancing U.S. electricity system resilience. Hence, a robust program of "recovery spares" is one option to address this capacity gap. DOE and DHS are developing a strategy for the utility industry to manage this recognized vulnerability into the future.

4.2.2 Cyber Attack

Recently, the threat of physical attacks has been accompanied by a growing threat from cyber attacks. To date, such cyber attacks have generally been a nuisance – while causing local impacts to infrastructure, they do not necessarily trigger loss of service. Interest in such events is a function of their potential to have more severe consequences and as a metric of potentially increasing risk of severe attacks. This threat does not fall in the category of those that can be well-defined statistically, and it reflects a relatively recent, but growing concern. Its consideration should be part of a more general discussion about physical security and should be based on a classification of the criticality of the different system of the power grid.

As in most cyber physical systems, cyber vulnerabilities exist in the electric grid (Box 4).[107,108,109,110] Cyber threats can be classified as inadvertent (unintentional) or deliberate. An example of an inadvertent threat is a software upgrade or maintenance intervention that may cause unintentional disruptions to the electricity supply. Human errors may also cause inadvertent cyber threats. Deliberate attacks increase in complexity as the actors behind them increase in resources. For example, attacks from individual hacker are less complex than state-sponsored group attacks. Examples of deliberate types of attacks include: cross-site scripting, denial of service, distributed denial of service, logic bombs, phishing, passive wiretapping, Structured Query Language (SQL) injection, Trojan horse, virus, war driving, worm, zero-day exploit, eavesdropping, and coordinated cyber physical attacks.[107,108]

Other factors that increase the vulnerability of the grid to cyber attacks are:

- Lack of password control: personnel do not protect their passwords, or use easy-to-guess, and or easy to social-engineer passwords.

- Bypass of security features: cyber security features are not enabled, default passwords are used, or all personnel use the same password.
- Lack of secure software updates and patches: software patches or updates are not tested to fully meet security standards, or updates to fix security vulnerabilities are not applied.
- Integrity violations: Modifications to data in cyber physical systems are not validated.
- Lack of standardization: Different entities and organization use different cyber security standards.

Box 4. Electricity System Vulnerabilities to Cyber Attack

1. *Supervisory Control and Data Acquisition (SCADA)* were first implemented in the 1970s at a time when cyber security did not need to be addressed. These legacy systems are used today to collect data and send control signals in both the bulk power system (generation and transmission) and at the substation level. They used to rely on dedicated communication links (e.g., phone lines, radio waves) to send information from local area networks within substations to control centers. Today, they rely on modern communication infrastructure such as the internet for that same purpose, but as a consequence are highly vulnerable because they may have hardcoded passwords, backdoors, passwords in clear texts, lack of strong authentication, and firmware vulnerabilities.
2. *Power Plant's Distributed Control Systems (DCSs)* are the systems that perform local control on large power plants. These systems use programmable logic controllers (PLCs) to perform this function. PLCs are microprocessor or computer-based devices, and as such, are susceptible to attacks over the local communication channels to which they are connected, which can cause mis-operation.
3. *Smart Grid* refers to the use of information technologies and communications to increase the reliability, security, and efficiency of the grid while meeting future demand. Because of the increase use of software-based components with communication capabilities, the risk of cyber attacks is also increased since they are susceptible to manipulation over those communication networks, particularly when connected to the internet.
4. *Distributed Energy Resources* (DERs) are usually not under the jurisdiction of utilities, and are highly connected to open networks for communication. Because of this, they are not subject to utilities cyber security standards. They also contain actuators such as smart inverters with advanced sensing and control capabilities that can be access remotely.
5. *Smart Meters* use communication channels to send consumer data to utilities. Fraud can lead to financial risks to utilities and smart meters with disconnect capabilities can be used in a coordinated attack that could cause large drops in demand resulting in blackouts.
6. *Supply Chain* vulnerabilities can be found in legacy systems such as SCADA. For instance, software upgrades may not meet current cyber security requirements, or the system are not updated periodically enabling zero-day exploit attacks.
7. *Corporate Network* communication networks can be a vulnerability, because they provide an entry point to other control networks such as SCADA systems.

At present there is no way to predict or forecast cyber-attacks to the grid. Since 2009 there have been at least five instances of cyber vulnerabilities exploited to cause harm on power systems around the world including Stuxnet in July of 2009 and the attack on Ukraine's power grid in December of 2015.[111] Given these trends, it is possible to infer that a sophisticated cyber-attack by a nation-state or large terrorist group on the US critical infrastructure "*is only a matter of when, not if*".[112]

Recently, the University of Cambridge Centre for Risk Studies and Lloyd's published a report where a massive cyber attack is launched in the US.[113] The hypothetical scenario takes out over 50 power plants, affecting 15 states, and the District of Columbia, for a total of 93 million people without power. Though the report clearly disclaims that it is not a prediction, but a hypothetical stress test scenario, it states that the scenario is "*improbable, [but] technologically possible*" and "*within the benchmark return period of 1:200 against which insurers must be resilient*." The report also estimates the economic impact would range between $21.4 billion to $71.1 billion, and it discusses constraints faced by the attackers.[113]

The Department of Homeland Security has been making efforts to mitigate against cyber attacks to critical infrastructure which includes the electric grid. One example is the Industrial Control Systems Cyber Emergency Response Team (ICS-CERT) which conducts cybersecurity and communications assessments on industrial control systems around the country. ICS-CERT conducted 112 in 2015. A summary of their findings from last year for the top six weaknesses in industrial control systems is presented in Table 5. They also offer a cyber security evaluation tool that can be downloaded at no cost to users.

Table 5. Top Six Weaknesses in Industrial Control Systems in 2015

Area of Weakness	Consequence/Risk
Boundary Protection	• Cannot detect unauthorized activity in critical systems • Increased risk to critical assets with weak boundaries between ICS and Enterprise networks
Least Functionality	• Creates vectors for malicious party access to critical systems. • Rouge internal access could be established.
Authenticator Management	• Unsecured password communications can easily be compromised. • Password compromise could allow trusted unauthorized access to systems.
Identification and Authentication	• Results in lack of accountability and traceability for user actions if an account is compromised. • Increases difficulty in securing accounts as personnel leave the organization, especially sensitive for users with administrator access.
Least Privilege	• The more authorized users with elevated privileges, the larger the attack surface for an intruder to steal account credentials with elevated access rights to access and compromise critical systems.
Allocation of Resources	• Understaffing impedes organization cybersecurity monitoring and response capability to a critical system cyber incident increasing the potential impact to the company.

Source: NCCIC/ICS-CERT Industrial Control Systems Assessment Summary Report, FY2015[114]

4.2.3 Electromagnetic

A manmade electromagnetic pulse (EMP) originates from a nuclear detonation or from a directed-energy weapon. Energy fields resulting from a nuclear detonation at altitudes above 40 kilometers (km) are referred to as high-altitude EMP (HEMP). A single, high-altitude nuclear burst could subject a large spatial region that spans much of the continental United States to an electric field with peak amplitude on the order of a few tens of kilovolts per meter. This is the early-time, E1, component with a decay of 1 microsecond or less.

From the same burst, and following the E1 environment, a more slowly varying and less intense electromagnetic field is observed on the ground. This is the intermediate-time E2 environment, which has an electric field strength of several hundreds of volts per meter and a typical duration time of several hundred microseconds. The E1 and E2 waveform components are followed by E3, a low-amplitude, late-time signal on the order of tens of volts per kilometer. This late-time E3 signal results from geomagnetic perturbations caused by the high-altitude nuclear detonation and has a response time up to several hundreds of seconds. It is often referred to as magnetohydrodynamic EMP.

The early-time E1 effects appear as flashovers and voltage-stress damage to power delivery equipment and to communications electronics. Although present in the HEMP environment, the intermediate-time E2 component was not found to be important in assessing the behavior of the electric power system. Instead, E2 effects fall within the normal criteria for frequently occurring natural incidents and expected manmade incidents, such as switching transients (an exception would be the case in which the E1 pulse has destroyed some surge protection devices, thus making systems more vulnerable to E2 as well). As stated previously, E3 manifests on long power lines as a quasi-direct current that flows through transformers and shunt reactors. E1 and E2 could affect communications for control systems used throughout the electric power system, depending upon the methods used to perform the communications. Power companies are moving away from wave traps toward fiber-optic communications, wherein the fibers are embedded into the core of the static overhead ground wire of the transmission lines. This shift represents an improvement in that, although the transmitter and receiver electronics of the fiber-optic communications will still be sensitive to E1 and possibly, to E2, the fiber itself is immune to EMP effects. Because the two primary EMP threats from manmade incidents, E1 and E3, manifest on the electric power system in such dissimilar ways, they must be evaluated separately. As noted previously, E3 affects a system after it has already been affected by E1.

The loss of power generation capability arises from either damage or disruptions in power plant electrical instrumentation systems, including switchyard power, control systems, combustion turbine generator packages, and the control rooms themselves. Operation of the power generation plant is dependent upon proper functioning of all these subsystems, especially their major components. Within power plants, the percentage of generation lost is a measure of functional degradation. The assessments made in the late 1980s and early 1990s (neglecting the losses in generation capacity due to the plant's control room circuitry) resulted in estimates of 4.4 percent generation loss.[115] This effect would result from switchyard E3 pulse leakage, affecting operation of step-up transformers by electrically isolating them from the grid.

Much like a physical attack (Section 4.2.1), it is impossible to predict an EMP attack. Early warning systems may be able to provide 10-20 minutes of warning if the attack utilizes a ballistic missile for delivery.

A significant knowledge gap in modeling the impacts of an EMP attack is the likelihood of equipment failure, the state of the failed equipment and the time sequence of the failure events. In the event of control equipment losses at the substation, the effect upon the substation cannot be predicted. It is not known whether the substation would remain functional or isolate itself. The loss-mode of the control equipment would determine the state of the substation. For example, loss of circuit breaker control equipment may send a signal to open the circuit breaker, or it may not. If the signal is sent, the circuit breaker opens and the EHV transformer is isolated from its source, its load, or both.

If the probability of loss for every component level of the load circuit is calculated, the total system effect can be estimated. Each component level depends on its upstream component. If an upstream component is out of service, downstream component-level flashovers and failures will not affect substation circuit breakers or the EHV transformer. The protection philosophy of each component level on the load circuit must also be considered. For example, a flashover on a sub-lateral component may blow a fuse, cause a circuit breaker to disconnect, or otherwise remove it from the rest of the circuit. The sub-lateral will remain out of service until manual operator intervention occurs. If the flashover occurs during E1, that sub-lateral will not be included in the system when E3 arrives.

Protection from E1 EMP is primarily through grounding and shielding of critical components, for example, by utilizing shielded substation control houses; the elimination of conductive paths that can couple E1 into sensitive equipment (e.g. switching from wave traps and copper signal wires to fiber optics); and installing equipment constructed to sufficiently rigorous standards to ensure survivability in E1 environments.

4.2.4 Spontaneous Equipment Failure

The failure of equipment may not qualify precisely as a "threat" because it typically refers to a condition of deterioration that could be the result of design limitation and/or operations of the equipment near of past design specifications. However, such factors need to be considered in risk management, particularly when the equipment has high criticality for power grid operations and/or its replacement or repair may require a period of time that is not compatible with the maintenance of an acceptable electric service for the users (see Box 3).

Spontaneous failures of equipment used in the generation, transmission, distribution, or storage of electricity pose a threat to the reliability the U.S. electricity system, both in isolation and through their potential to trigger cascading failures across multiple system components. Equipment failures can arise from a number of sources. For example, for generators, failures appear to be more prevalent for distributed rather than centralized systems. Statistics on equipment failures from wind generators, indicate differential rates of failure for small vs. large generator units as well as differences in how failure rates change as the devices age.[116] Similarly, photovoltaic modules experience failures due to faulty manufacturing, damage during transportation, or faulty installation. The most common failures of PV modules are associated with delamination of the module, cell part isolation due to cell cracks, and laminate discoloring.[117] In contrast, centralized generation systems, whether thermal (fossil and nuclear) or hydroelectric, have lower risk tolerances for faults that would take the facility offline, and thus spontaneous faults resulting in outages are rare.

Spontaneous equipment failures are, by definition, stochastic events that cannot be predicted, although equipment and materials can be expected to depreciate and degrade over time, which can increase the probability of failure.

Faults in transmission and distribution lines are often transient – power may be lost or disconnected for a short period of time. Such faults are then isolated by power system protection technologies, after which the fault clears and service can be restored. Such faults can rise from contact between the lines and other objects (such as trees, other objects, or animals), or lightning strikes (see Section 4.1). In contrast, persistent faults cannot be resolved by disconnecting power and are often associated with physical damage to transmission and distribution lines.

4.2.5 Combined threats

The occurrence of truly random events, such as hurricanes and earthquakes, is expected to be independent making the probability of two closely spaced, collocated events exceedingly low. However, an intelligent attacker may plan to use occurrence of one naturally-occurring HILF event to amplify the impact of a physical, cyber, or EMP attack (Table 6). Electric systems are generally not designed to withstand or quickly recover from damage inflicted simultaneously on multiple components.[103]

Table 6. Potential Interactions between Natural and Human Risks to the Electricity System

Natural Disaster	Combined With	Discussion
Hurricane	Physical or Cyber	Hurricanes typically result in a large loss of load. A physical attack during or immediately following a hurricane is not expected to yield significant amplification.
GMD	EMP	Periods of significant, very high GMD can be predicted approximately 30 minutes ahead of time, although the exact locations and intensity are still relatively uncertain. However, a well-timed EMP attack could be used to significantly amplify the hazard and impact of an naturally occurring GMD event.
Ice Storm	Physical or Cyber	Ice storms typically result in a large loss of load. A physical attack during or immediately following an ice storm is not expected to yield significant amplification.
Drought	Physical or Cyber	Droughts are chronic events that last an extended period of time making coordination with a physical or cyber attack possible. Droughts also place power systems in stressed conditions with low levels of hydro or thermal generation (due to lack of water in storage or for cooling). This may be amplified by high loads due to high temperatures. A well placed physical or cyber attack that compromised the remaining generation assets could significantly amplify the impact of the two combined events.
Flood	Physical or Cyber	A flood of sufficient severity to affect generation could constrain generation capacity within a utility or region. Physical or cyber attacks coordinated to coincide with generation shortfalls could overstretch capacity or slow recovery efforts.
Extreme Cold	Physical or Cyber	Extreme cold events are forecasted far enough in advance to enable coordination with a physical or cyber attack possible. Extreme cold places power systems in stressed conditions with potentially low levels of thermal generation capacity amplified by the increased electrical load. A well placed physical or cyber attack that compromised the remaining generation assets (or the natural gas pipeline system) could significantly amplify the impact of the two combined events
Extreme Heat	Physical or Cyber	Extreme hot events are forecasted far enough in advance to enable coordination with a physical or cyber attack possible. Extreme cold places power systems in stressed conditions with potentially low levels of thermal generation capacity amplified by the increased electrical load. A well placed physical or cyber attack that compromised the remaining generation assets (or the natural gas pipeline system) could significantly amplify the impact of the two combined events
Earthquake	Physical or Cyber	The timing or location of major earthquakes are not predictable making coordination with a physical or cyber attack difficult.

5. INTEGRATED ASSESSMENT OF ELECTRICITY SECTOR RESILIENCE

Placing the various threats discussed in Section 4 in a context useful for prioritizing risks and mitigation options for decision-making requires the systematic integration of information on threats with that on their likelihood of occurrence and their consequences as well as risk management options that can enhance resilience. This section presents such integrated information by using published literature and expert judgment to systematically assess risk and resilience for different components of the electricity system. First, the section outlines the metrics of risk and resilience used in the assessment while acknowledging the nascent state of resilience metrics for U.S. power systems. Second, those metrics are then applied in a comprehensive assessment in order to identify key threats and/or system components that should be priority targets for future investments in resilience.

5.1 ASSESSING ELECTRICITY SECTOR RESILIENCE

The variety of threats that may affect the resilience of the energy system are profoundly different in nature with respect to their likelihood of occurrence, the severity of the consequences, their predictability, and the availability of technologies and practices to avoid impacts or quickly recover. Meanwhile, electricity infrastructure and assets are typically functionally divided among generation, transmission, and distribution systems (Section 2), each of which have differential exposure and vulnerability to threats as well as different governance regimes in terms of ownership and responsibility for management.

In the past, this complexity has often led to resilience of the electricity system being framed around discrete threats and/or system components. This has encouraged reductionist thinking toward identifying the risk that individual components will fail when challenged by a specific threat. Although this facilitates risk assessment, it makes it difficult to generate a comprehensive picture of resilience for the sector or to prioritize risks. The identification of a more systemic framing of resilience as well as specific metrics that can be used for the monitoring and evaluation of resilience in the electricity system is a rapidly evolving area of inquiry. Hence, this report does not attempt to define the specific metrics of resilience that should be used. However, continuing to develop a community consensus around such metrics is an important task for enhancing future resilience of the electricity sector.[118,119]

Figure 9. Metrics of Electricity System Resilience Used in the Current Report

System Components	Threats	Dimensions of Risk	Adequacy of RIsk Management
•Generation •Transmission •Substations •Distribution (above and below ground) •Storage	•Environmental •*Weather/climate* •*Seismic* •*Wildlife* •Human •*Physical attack* •*Cyber attack* •*Electromagnetic*	•Threat probability •Vulnerability •Impact	•Robustness •Resourcefulness •Recovery •Adaptability

Here, resilience is explored generally through four dimensions that collectively define resilience across the electricity system for the range of threats to which the system is exposed:

- First, **system components** reflect the elements of the electricity system that are exposed to risk (*i.e.*, *resilience of what*);
- Second, **threats** reflect the hazards that can trigger adverse impacts (i.e., *resilience to what*);
- Third, **dimensions of risk** reflect the factors that determine to what extent a system component is susceptible to harm and the potential severity of the impacts; and

- Fourth, the **adequacy of risk management practices** reflects the maturity of current threat mitigation technologies, policies, and practices to maintain risks within acceptable limits.

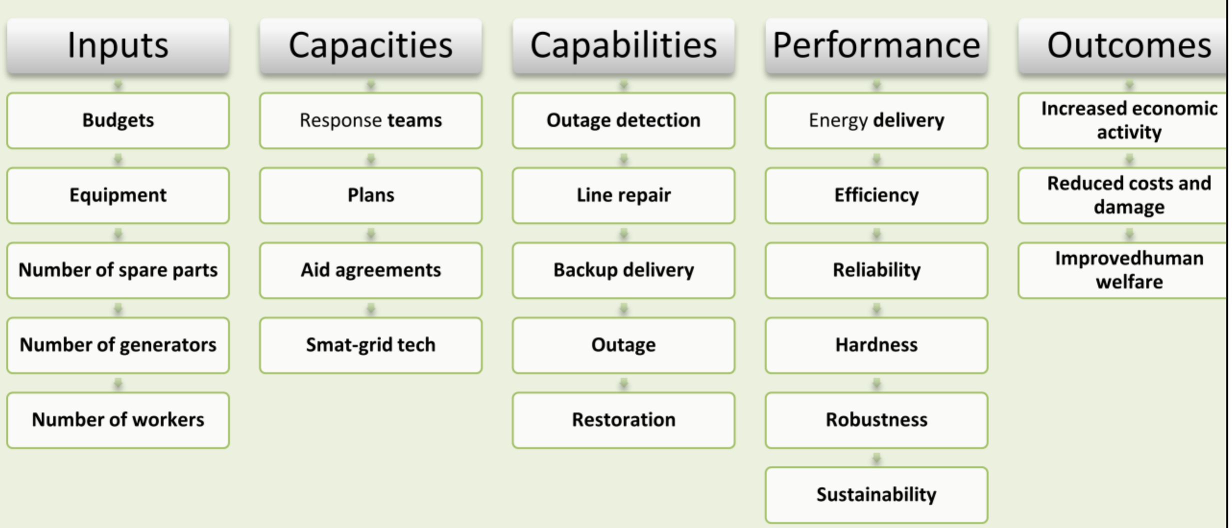
Box 5. Toward Industry Resilience Metrics for the Electricity Sector

The ability to track resilience, evaluate progress, and prioritize challenges is a critical aspect of enhancing the overall resilience of the U.S. electricity system. Resilience metrics can be used by regulators and electricity system planners for developing, implementing, and monitoring general policies, emergency management efforts, contingency planning, and investment planning. While such metrics invariably reduce the complexity of the electricity system to a small number of parameters, such simplification can be an effective mechanism to gauge and monitor progress towards the improvement of resilience plans.

However, existing metrics are applied inconsistently, neglect important concepts of resilience, and/or are not robust to the range of contingencies for which industry decision-makers should plan. Therefore, a key recommendation emerging from the *First Quadrennial Review* was *"Develop comprehensive data, metrics, and an analytical framework for energy infrastructure resilience, reliability, and asset security."*[6]

A review undertaken by RAND Corporation in 2015 provided not only a logic framework for structuring resilience metrics (see below),[118] but also a list of metrics that have either been proposed or are currently in use at the facility or regional level. Those examples provide an entry point for further development, refinement, and integration of metrics so that they can be robustly applied across geographic scales, system components, and threats.

Figure 10. A Logic Framework for Resilience Indicators for the Energy System



Caption: The above logic framework for resilience indicators identifies different classes of metrics as well as general examples of types of metrics associated with each class.[118]

5.2 ASSESSMENT OF ELECTRICITY SECTOR RISK AND RESLIENCE

Applying the various general metrics to the U.S. electricity system results in a comprehensive perspective of the key points of risk to various system components as well as the extent to which current management practices convey sufficient resilience to those risks (Table 7; Appendix B). Using this approach, this study considers the range of threats discussed in Section 4, including information on the likelihood of threat events of different intensities, the impacts to system components that are often associated with those threats, and the available options for mitigating impacts or recovering from their effects.

To illustrate the importance of threat intensity on risk, contrasts are drawn between low intensity and high intensity threats. For example, major hurricanes are associated with different levels of risk than minor hurricanes and tropical storms, although the probability of a land falling major hurricane in any given year is lower. However, for some types of threats, the likelihood of their occurrence is unknown, either because they happen to infrequently to generate useful statistics, or because they are only plausible scenarios that have yet to be observed.

The risk posed by a given threat to a system component is a function not only of the likelihood of the threat, but also the vulnerability and potential impact associated with threat exposure. System components vary in the extent to which they are exposed to different types of threats. For example, locating distribution lines below ground significantly reduces their exposure to weather, which reduces the risk of adverse impacts during severe weather events. Meanwhile, some components have a greater vulnerability to threats based upon the design standard. Transmission lines tend to be built to a higher standard than distribution lines, and thus the latter has a greater vulnerability to many types of threats, particularly weather. That said, outages associated with distribution systems are often localized and therefore the impacts in terms of customers affected can be relatively limited. Some types of risks remain difficult to assess, in part because of uncertainty in the likelihood the threat.

The maturity of risk management practice for different types of risk is a function of industry's experience, the perceived severity of the risk, and the availability of effective risk management measures. Industry is well-equipped to manage risks that occur frequently, in part because they can be anticipated and, in some instances, even forecast. Federal and state standards for infrastructure design, planning, and operations assist in making infrastructure more robust or enabling rapid recovery. Technological innovations enhance system reliability and efficiency, while improvements in control systems accelerate situational awareness, fault detection, and facilitate load balancing. However, some risks occur so rarely and/or with such intensity that complete mitigation of the risk is unfeasible. Hence, resilience efforts should focus on ensuring the system can recover as rapidly as possible.

Assessing the current state of the U.S. electricity system against these different metrics reveals a broad range of risks that span a gradient from negligible to potentially catastrophic (Table 7). Fortunately, the majority of these risks are relatively minor. The electricity system is robust to a broad range of routine risks that arise with relatively high frequencies, but with negligible to modest consequences (e.g., from safety, operational, financial standpoints). For example, the electricity system has evolved to cope with storms, winter and summer temperature extremes, minor drought events, and even minor earthquakes (Table 7).

Table 7. Integrated Assessment of Risk and Resilience to the Electricity Sector

Threat	Intensity	Electricity Transmission	Electricity Generation	Electricity Substations	Electricity Distribution (above)	Electricity Distribution (below)	Storage
		Assessment of Risk & Resilience					
Natural/Environmental Threats							
Hurricane	Low (<Category 3)	● Moderate	● Low	● Moderate	● High	● Low	◐ Moderate
Hurricane	High (>Category 3)	◐ High	● Moderate	● Moderate	◐ High	● Moderate	◐ Moderate
Drought	Low (PDSI> -3)	● Low	● Low	● Low	● Low	● Low	● Low
Drought	High (PDSI<-3)	● Low	◐ Moderate	● Low	● Low	● Low	◐ Moderate
Winter Storms/ Ice/Snow	Low (Minor icing/ snow)	● Moderate	● Low	● Low	● Moderate	● Low	● Low
Winter Storms/ Ice/Snow	High (Major icing/ snow)	● High	● Low	● Moderate	● High	● Low	● Low
Extreme Heat/Heat Wave		● Low	◐ Moderate	● Moderate	● Low	● Low	● Low
Flood	Low (<1:10 year ARI)	● Low	● Low	● Low	● Low	● Moderate	● Low
Flood	High (>1:100 year ARI)	● Moderate	◐ Moderate	◐ Moderate	◐ Moderate	● Moderate	● Moderate
Wildfire	Low (>Type III IMT)	● Low	● Moderate	● Low	● Low	● Low	● Low
Wildfire	High (Type I IMT)	● Moderate	● Low	● Moderate	● Moderate	● Low	● Moderate
Sea-level rise		● Low	● Moderate	● Low	● Low	● Low	● Low
Earthquake	Low (<5.0)	● Low	● Moderate	● Moderate	● Moderate	● Moderate	● Moderate
Earthquake	High (>7.0)	● Moderate	● High	● High	● Moderate	● High	● High
Geomagnetic	Low (G1-G2)	● Low	● Low	● Low	● Low	● Low	● Low
Geomagnetic	High (G5)	○ Low	◐ Moderate	○ High	◐ Low	○ Low	◐ Moderate
Wildlife/Vegetation		● Low	● Low	● Low	● Low	● Low	● Low
Human Threats							
Physical	Low	● Low	● Low	● Low	● Low	● Low	● Low
Physical	High	◐ Unknown	◐ Unknown	◐ Unknown	● Unknown	● Unknown	◐ Unknown
Cyber	Low	◐ Low	◐ Low	◐ High	○ Moderate	○ Moderate	Low
Cyber	High	○ Unknown	○ Unknown	○ Unknown	○ Unknown	○ Unknown	○ Unknown
Electromagnetic	Low (Ambient EMI)	● Low	● Low	● Low	● Low	● Low	● Low
Electromagnetic	High (NEMP & HEMP)	● Low	○ Unknown	○ Unknown	● Low	● Low	○ Unknown
Equipment Failures		● Low	● Moderate	● Low	● Low	● Low	● Moderate
Combined Threats		○ Unknown	○ Unknown	○ Unknown	○ Unknown	○ Unknown	○ Unknown

Key to Symbols

Level of Risk: Low; Moderate; High; Unknown

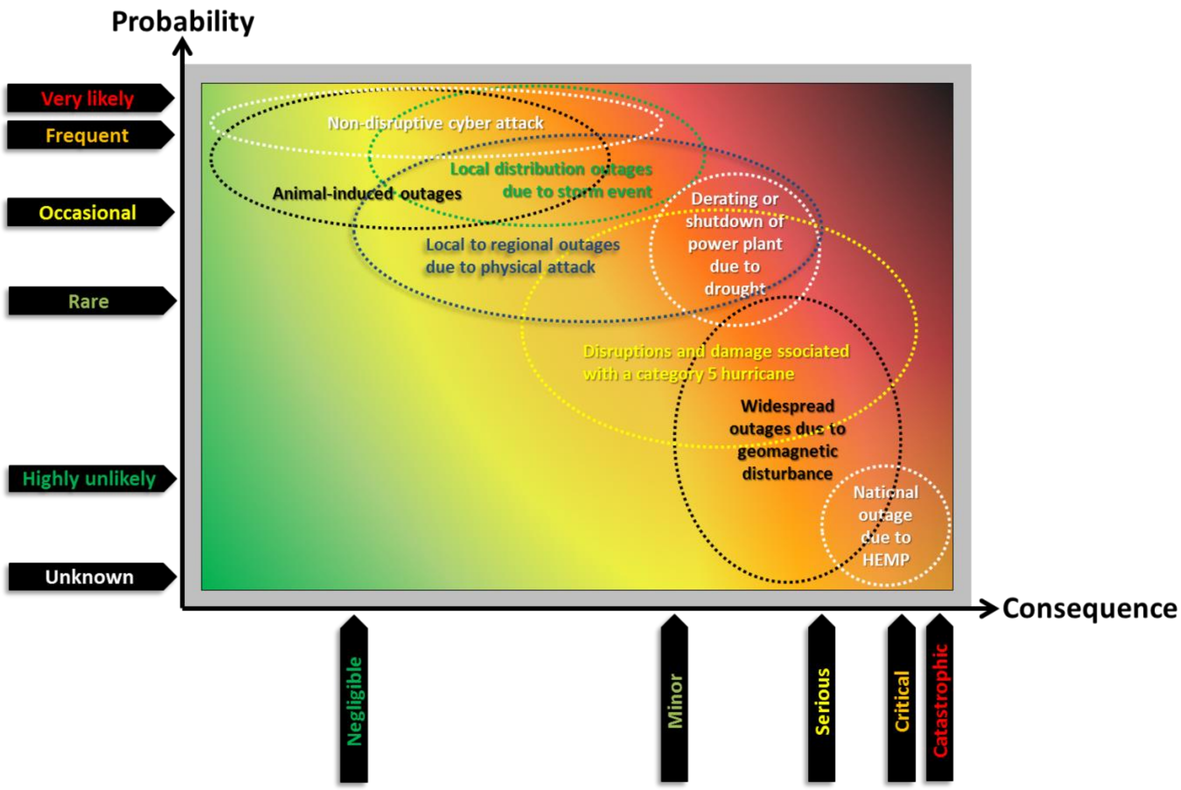
Status of Risk Management Practices for Current Threats

- ○ – Nascent: critical vulnerabilities exist
- ◐ – Established, but opportunities for improvement remain
- ● – Well-established and robust

Caption: Assessments of risk and status of risk management practice are based on information in Section 4, published literature, and expert judgment (for statistically unknown threats). Table cells represent a qualitative assessment of risk by electric system component and threat. Some threats are divided into low or high intensity threats. Estimates of individual sub-components of risk (probability, vulnerability, and impact) are presented for each system component in Appendix B.

The more significant risks to the system are those that are rare (or have never occurred), but that have potentially catastrophic consequences – HILF events (see Section 3).[3] Examples include a High Altitude Electromagnetic Pulse (HEMP) from a nuclear weapon (or NEMP), severe geomagnetic disturbances (GMDs) from a solar coronal mass ejection, a large-scale cyber-attack (or coordinated, combined cyber and physical attack occurring simultaneously in multiple selected critical locations), or a natural disaster of historic intensity (Table 7; Figure 11). Included within HILF risks are those with probabilities that are completely unknown, with consequences that span multiple interconnected systems, and/or are changing over time due to dependencies on other driving forces. Often, even generating scenarios of such threat events is challenging – either because they manifest in ways that are difficult to anticipate or because their plausibility is perceived to be so low that they are dismissed. Such events are sometimes referred to as "black swans". The absence of foresight for such events poses obvious challenges for risk management, but also highlights the importance of resilience. Given efforts to prevent or mitigate damages may be stymied by lack of foresight, pursuing options that enhance the capacity of systems to manage during an event and bounce back afterwards become important elements of the risk management toolkit. Nevertheless, significant gaps persist in preparedness and resilience for HILF events, making them a priority for future assessment and investment.

Figure 11. Risks to the Electricity Sector Mapped to the Risk Landscape



Caption: The risk landscape (as in Figure 4) with specific examples of types of threats. Each threat is associated with a different range of probability and consequence and therefore risk.

An apparent challenge that emerges for the electricity system is the expansion and growth of human threats to the electricity system. The risks associated with those threats can be severe and they have the potential to affect a broad range of system components. Because human threats are a function of human choice and agency rather than the environment, it is difficult to assess the likelihood of their occurrence or the potential extent of their consequences (Table 7). For example, while physical attacks on the electricity grid are common, impacts to date have been modest to negligible. Hence, stakeholders have limited experience with more extreme attacks. As demonstrated by the rise of cyber attacks on the U.S. energy system, emerging technologies have the potential to generate new threats to which the electricity sector must remain vigilant. Severe human threats are also those for which risk management strategies are in a nascent state, creating gaps in resilience.

The other insight that emerges from a comprehensive assessment of the electricity system's resilience is the differential risks associated with different system components (Table 7). There are clear contrasts, for example, with respect to the risks to which above ground distribution systems are exposed compared with below ground systems. Meanwhile, energy storage systems are associated with relatively fewer risks, in part due to the limited storage infrastructure that currently exists across the United States. However, storage is likely to expand in the years ahead, becoming more integrated into the national grid. This may increase its importance as well as the vulnerability of the energy grid to potential disruptions to storage capacity. Although differential risks can be identified, it is also important to note that not all components of the system have the same criticality for system reliability. Disruptions of the bulk power system and generation have the most impact – that is where the largest capital investment resides and where replacement/repairs (or lack thereof) are costlier and may affect the largest segment of the population.

In assessing the resilience of the current electricity system, it is important to be aware that the system is undergoing rapid change as are the risks to which it is exposed. As a case-in-point, climate change is an emerging risk that has been a particular focus of U.S. national resilience efforts. Given severe weather events are the major source of both routine and HILF threats to the U.S. electricity system, future changes in the U.S. climate have implications for the frequency, intensity, and duration of weather and climate threats. This includes conventional weather-related threats like floods, extreme heat events, hurricanes (addressed above), but also includes challenges such as sea-level rise (Section 4.1.7), which is anticipated to interact with hurricanes and other coastal storms to increase the risks to coastal electricity infrastructure.

6. TOWARD ENHANCED RESILIENCE OF THE ELECTRICITY SECTOR

6.1 OPPORTUNITIES FOR ENHANCING RESILIENCE

The assessment of the current state of resilience across the U.S. electricity system identifies a number of opportunities that should be the focus of future research and development and utility planning. First and foremost, the sector should seek to maintain its current level of robustness and reliability to the range of high frequency, routine risks to which it is exposed and, where possible, continue to make incremental improvements in their mitigation. However, the most significant gains in resilience will likely come from addressing those challenges that the sector is not currently well-equipped to manage. In particular, HILF risks stand out as priorities for resilience. There is a need to better understand the likelihood and consequences associated with various types of HILF events and a need to enhance risk management options, technologies, and planning to address a broader range of contingencies (Box 6). To this end, developing the capacity for viewing, modeling, assessing, and managing the electricity system as an integrated infrastructure network, rather than a collection of discrete components, will aid in enhancing overall system resilience.

An important management tool for infrastructure operators are the prescribed reliability planning standards that outline in detail the performance requirements of the system following the failure or loss of specific combinations of components. The NERC Standard TPL-001-4 *Transmission System Planning Performance Requirements* specifies these requirements for transmission system owners and operators.[19] While this serves as a useful basis for planning and operating the system, and provides consistency among system owners and operators that depend on each other in operating an interconnected grid, it fails to capture several elements of system resilience that we are addressing in this report.

Areas that the existing industry planning standards do not capture as it relates to system resilience:

- **Severe events**. The industry standards do a good job of capturing likely events that could have an impact on reliability, like the failure of single components or components that relate to each other, for instance multiple circuits in a common right of way. However, many of the high impact events postulated in this report would not be captured through a component failure analysis as prescribed in the industry reliability planning standards.
- **System analysis**. The planning standards address system impact based on component failure analysis. However, vulnerabilities to the system that might compromise the entire operation of the system are not addressed. These could include widespread physical consequences or cyber vulnerabilities that simultaneously disable or degrade the system.
- **Time to recover**. Because an essential element of resilience is the recovery from an off-normal event, considering time to recovery, from full onset of the event through partial recovery to fully recovered. Based on the nature of the event, the damage incurred, and the ability of the system to quickly recover will dramatically impact the resilience of the system. This factor is not included in the traditional reliability requirements.

In addition, NERC's operational standards such as FAC-011-2, *System Operating Limits Methodology for the Operations Horizon*, consider an even narrow range of contingencies and response scenarios. Therefore, increasing the capacity of the bulk power system to accommodate HILF events in planning and operations while maintaining robustness, survivability, adaptability, response, and recovery is key opportunity for enhancing resilience.[19]

6.1 CONSTRAINTS AND LIMITS ASSOCIATED WITH ENHANCING RESILIENCE

Although there are clear opportunities for enhancing the resilience of the U.S. electricity system, there are also a number of constraints associated with capitalizing on those opportunities. Resilience investments can be expensive and require significant capital and time to implement. This necessitates the need for utilities to prepare a rate case that includes sufficient justification, which can be a challenge when investments involve preparation and planning for events that have not yet happened. Uncertainties in global climate change, economic development, and changes in State and local policies and regulations regarding electric infrastructure resilience create additional difficulties, as does incomplete understanding of the interactions between energy infrastructure and other systems of critical infrastructure. Discussions with subject matter experts and industry partners as well as open source research have identified the following as the most common constraints associated with enhancing resilience:

6.1.1 Predictability of Threats and System Responses to Climate Change

The development of predictive models has always been of interest to the electric power industry. The development of adequate models allows utilities to understand potential consequences of an event and plan for mitigating those consequences before an event happens. Historically, past events (i.e., natural hazards) have been used to help formulate parameters of the model in an attempt to minimize error. However, the growing need to incorporate future threats that are changing over time is posing new challenges. For example, uncertainty in the future frequency, intensity, and duration of extreme weather events is now multiplied because of climate change. Hence, risk management efforts are moving into unmapped territory. The climatic changes forecasted to manifest over the next 50–100 years should also impact upgrades to existing and development of new technologies and infrastructure. The uncertainties associated with the accepted climate change models, in addition to human behavioral responses to those climate changes (i.e., shifting of population centers), exacerbate the ability to plan for future infrastructure needs.

Box 6. Technology Options for Enhancing Grid Resilience

Distributed Energy Resources (DERs)

Positive impacts: DERs can help mitigate the negative consequences of natural hazards if they are correctly configured to supply energy during interruptions. Because of their widespread locations and generally low power, they are more resilient (or much less attractive as a target) to physical attacks than larger plants located at centralized physical locations.

Positive and negative impacts: DERs can have either a positive or negative effect on capacity constraints. For instance, some resources such as energy storage and demand response provide additional flexibility to the system. Other resources such as PV can create additional stress on existing generation because their integration generally requires additional reserves and their capacity value decreases as a function of their penetration level. Additionally, accurately valuing these resources (regardless of type – solar, demand response, storage) is a challenge for utilities and system operators, so they tend to be overly conservative when assigning capacity values. If their capacity value is overestimated at large penetration levels, they could create long term generation capacity shortages for the system.

Negative impacts: On the flip side, they increase the points of entry for a cyber attacks. Though a single resource can be considered a low value target, a more sophisticated coordinated attack could have a significant impact on the grid. The increased complexity of communications and controls necessary to run this type of devices increases the interdependencies with the communications infrastructure.

Microgrids

Microgrids can be thought of as a collection of distributed resources that can be reconfigured an islanded at any moment to supply a larger portion of the grid than a single household or building. Because of their similarity to DERs, microgrids have similar positive effects to distributed energy resources.

Positive impacts: Microgrids have a positive impact on natural hazards because they can be used to supply critical loads and services during grid interruptions.

Negative impacts: There is a possibility that recovery times might increase due to increase difficulty to identify damaged equipment. This is particularly true for distribution systems where utilities generally rely on customers phone calls to pinpoint problems and send crews out.

Renewable Energy Sources

Here we refer to utility-size renewable energy power plants.

Positive impacts: renewable resources have a positive impact on dependencies and supply chain interruptions because, unlike fossil fuel power plants, they do not depend on other infrastructure to provide their fuel.

Positive and negative impacts: Some renewable energy resources increase the resilience of electric power systems to the long-term effects of climate change. For instance, periods of longer drought are seen in parts of the world because of changing weather patterns and in these cases, resources such as wind and solar have a positive impact on grid resilience because they are not water-intensive. However, resources such as hydro and geo-thermal can have a negative impact because of the water consumption required for either cooling (geo-thermal) or through evaporation and leakage in reservoirs. When considering hurricanes, wind plants that are within close proximity of the affected load centers or offshore can have a negative impact because they will most likely stop producing power due to cutoff speeds being reached during the event, at the time when it is most needed. Similarly during snow storms, solar power plants can be affected due to the potential accumulation of snow on top of the solar panels. In both of these cases, having geographic diversity in wind and solar portfolios can help mitigate these potential negative impacts.

Advanced Interdiction Analysis

Interdiction analysis provides information about the potential impact that different vulnerabilities pose to a system. In power systems, interdiction analysis can be used for analyzing physical, cyber and supply chain and interdependency threats. The objective is to identify which parts of the system, if attacked, would result in larger consequences from such attacks in order to prioritize investments (e.g., hardening, spares) in order to increase resilience to those threats.

Positive impacts: As mentioned above, interdiction analysis helps prioritize investments to increase resilience to physical, cyber and supply chain threats.

Negative impacts: Interdiction analysis relies on accurate threat modeling in order to be effective. It is important to understand and create awareness about the limitations and assumptions made in the models employed for this type of analyses.

Optimal Spare Acquisition and Positioning

Optimal spare positioning is intended to reduce vulnerabilities in the supply chain. Strategically positioning acquiring and locating spares around the system may significantly reduce recovery times.

Positive impacts: resilience to supply chain threats is increased, and recovery times for other types of threats such as natural disasters are reduced.

Negative impacts: Similarly to advanced interdiction models, optimal spare acquisition and positioning is highly dependent on threat models. It is important to understand and create awareness about the limitations and assumptions made in the models employed for this type of analyses.

6.1.2 Cost Recovery and Stranded Investments

Electric energy infrastructure (including both bulk power and local distribution) is primarily privately owned. Due to deregulation, customers can receive power from separate generation, transmission, and distribution companies. Those complexities are further compounded by the rates that local utilities charge, which are generally regulated by State agencies.[120]

In the midst of these complexities, electric power customers expect power to be delivered consistently with minimal disruptions. Keeping the lights on is an equally important imperative to the utilities, as disruptions can result in a significant loss of revenue. Customer expectations and minimizing revenue loss are sufficient motivators for power companies to invest in processes and solutions that minimize downtime, both on blue sky days and on days when an adverse event shuts down the power.[121]

Federal and State regulators have jurisdiction over the bulk power system, while State or local regulations typically drive local distribution rates.[120] This business model can lead to tensions between the regulators and industry to implement resilience-enhancing options. The utilities must build rate cases to justify the installations of any new measures and/or cover the cost of current costs of operation, which may have changed. Part of this rate case is providing justification that these costs are reasonable and prudent and can include showing estimates for return on investment (ROI). This may be difficult to justify in front of a public utility commission and the end use customers. Some important trade-offs must be considered.

The Edison Electric Institute's (EEI) comments on the QER[122] recommended that the industry be allowed to develop "*innovative alternative utility rate design models*." The increased prevalence of distributed generation (e.g., microgrids, solar, wind, and smart vehicles) and the challenges with incorporating those typically intermittent power resources into the grid, almost necessitates a new model. New design models will allow costs to be allocated to the proper customers while maintaining the need to keep the grid reliable and resilient. The EEI also suggested developing additional Federal programs or tax provisions designed to generate consistent funding to implement changes before and after extreme events. These types of programs will allow Federal assistance in preparing for the changing environment for energy infrastructure and promote proactive investments in resilience-enhancing activities.

6.1.3 Communication and Workforce

The continuum of resilience-related activities spans from complicated to simplistic, expensive to inexpensive, and time consuming to instantaneous in implementation. Many discussions involving resilience of the electric grid center on changes to the actual infrastructure, for example, upgrading existing infrastructures or installing new components. In fact, a number of measures can be taken to enhance resilience that utility management, employees, and State and local entities can employ that are not as costly or time consuming. Several references (i.e., ISO 22301,[123] BS 25999-2,[124] and ANSI/ASIS SPC.1[125]) are available that focus on the creation of robust plans, whether they look at business continuity, emergency preparedness, or disaster response. Some components are common to all plans, regardless of the type. Examples include establishing key points of contact; coordinating interactions with outside responders; and training, exercising, and regularly maintaining the plan.[126]

6.1.4 Coordination and Collaboration

Maintaining electric power during and post emergency touches almost every component of a community in some way. A community's dependence on electric power necessitates collaboration among a disparate set of entities to include State and local governments, the utility providers, and owners of other critical infrastructure. The dependence on electric infrastructure for operations should require a shared responsibility among the entities for keeping it operational; doing so will increase resilience across the entire community. [121]

Enhancing coordination and collaboration among these entities depends on two items: (1) awareness of connections and impacts of these connections and (2) the information available and the ability to share that information. Exchanging information that could be considered business sensitive has always been problematic, even during an emergency or in the recovery phase.

The education of the consumer population, specifically the individual residential consumers, is important in communication and collaboration. Resilience efforts can cost a significant amount of money; the utilities will seek to recover these costs, typically via the customers. The customers, especially individual residential customers, however, have a difficult time understanding improvements that are not immediately or only incrementally felt. Situational awareness and education are as important at the individual end user level as they are for State, local, and private sector critical infrastructure owners and operators. [121]

Barrett et al. (2013) summarized the need for enhanced communication, collaboration, and understanding for all entities involved in understanding the risk to a community, the importance of energy infrastructure in that risk picture, and the preparation for disruptions to the system, as shown below:

> *As a nation, we will need to find better ways to manage these areas of shared responsibility stemming from current and future evolutions of the aggregate and shared risk picture. This requires finding solutions that blend broader risk management needs for a more resilient electrical grid with the private sector's ability to invest in ways that meet challenges effectively and efficiently. It also requires an open dialogue about the full costs and potential benefits of a more interactive and modernized smart grid that allows consumers to help by reducing demand during peak periods and provides deeper insights into the otherwise opaque real-world operating conditions of the grid itself.*[121]

6.1.5 Governance Gaps

Infrastructure resilience is a whole-of-community issue. As such, the utilities and the private sector can work towards resilience in complementary ways. For example, the utilities can work on the process, procedures, and construction, while the private sector can prepare for the loss of electricity during a disaster and assist in community preparation in resilience. Although utilities are making investments to increase resilience, long-term solutions rely on the identification and management of shared risks and identification of governance gaps. Governance gaps in this context are defined as areas of shared risk where there is no clear identification or responsibility assigned to one or more entity. This lack of clarity can lead to an increase in consequences or impacts of an event because these areas are often overlooked. [121]

One common governance gap is realized during HILF events such as Superstorm Sandy. The magnitude of the disruptions caused by this type of event highlights, even further, the need for coordinated efforts among State, local, and private sector entities. However, the identification of the shared risks and assignment of who is responsible for what is often not considered or is considered but never discussed in detail. Lessons on the importance of the identification of the shared risks and the identification of the entities responsible to address those risks often occur after a major event. Multi-entity exercises can help shed light on these governance gaps and assist in preparing for these disastrous events before they happen.

While consumers often absorb the recovery costs associated with resilience improvements, private investment in electricity infrastructure is an important component to consider from a governance perspective. Governance actions, such as public policies, regulations, and process, play a role in the nature and magnitude of private investment in electricity infrastructure.[120] Policies and legislation implemented through State and local governments, developed in concert with other members of the community as well as the utilities, can help secure funds as well as remove barriers to implementing resilience measures.

6.1.6 Future Risk

While utilities, State and local governments, and other private sector entities struggle to make improvements to address the existing landscape of hazards, they also face another significant hurdle—addressing the notion of future risks that may not be in the typical time frame for planning or amenable to traditional methods of planning. Utilities typically base their planning assumptions on historic data;

however, the effects of climate change can lead to ever-changing surroundings and uncertainty in the future. Global climate has already started to deviate from historic averages. According to the Intergovernmental Panel on Climate Change (IPCC) *Special Report on Extreme Events*,[127] in the haste to rebuild infrastructure as quickly as possible after a disaster, utilities could miss an opportunity to improve their infrastructure rather than rebuild it to the previous standard. With the advent of deviations in those patterns due to climate change, historic trends could be misleading, as frequency, magnitude, or new events manifest themselves over the next half century, thus leading to infrastructure that is unable to perform as efficiently or at all.[121]

In addition to the uncertain and shifting landscape of natural disasters, other occurrences of man-made threats are increasingly ambiguous due to the unpredictability of terrorist actions, the prediction of and protection against cyber-attacks, as well as more traditional man-made threats (e.g., worker errors or insider threats using knowledge of the system). Another type of risk is the interdependency among the electric grid and other systems of critical infrastructure, especially telecommunications. As with electricity, telecommunications (phones as well as internet) are critical to the operations of modern times. Most, if not all, critical infrastructure relies on telecommunications in some way. Electric power requires telecommunications to maintain information and responsiveness across the grid, especially as the grid starts to get "smarter."[121] SCADA systems are a common telecommunications component of utmost importance to the operations of the grid. This risk can build upon itself, leading to increasing consequences that depend on how interconnected the systems are and how quickly the system can recover. For example, a disruption in the grid can impact telecommunications systems that support the function and operation or other portions of the grid, which can in turn cause further disruptions in the grid.

7. CONCLUSIONS AND RECOMMENDATIONS

The resilience of the U.S. electricity system continues to evolve in response to changes in both the system itself (e.g., scale, design, technology, and planning standards) as well as changes in the human and environmental threats to which it is exposed. Electric power systems are currently well-equipped to effectively manage a broad range of threats in order to mitigate risk or successfully recover from disruption and damage. This is why the U.S. has one of the most reliability energy grids in the world. Nevertheless, some types of risks remain challenging – either because their scale is so great, because they have only recently emerged, or because the risk is difficult to define. As such, resilience efforts should shift toward these more complex risk management challenges. Key risks identified within this report include the following:

- *HILF threats associated with natural hazards (particularly weather or space weather) of historic intensity or large-scale physical, cyber, or electromagnetic attacks*. The lack of industry and regulatory experience with such rare events, the difficulty of predicting or forecasting their occurrence, and the potential scale of the consequences have collectively limited the development of robust resilience strategies.
- *Combined or blended threats associated with simultaneous exposure of the electric grid to one or more natural threats in combination with a physical or cyber attack*. Such threats are plausible, but could manifest in ways that are unprecedented. This poses significant challenges to the development of contingencies that can be incorporated into planning and operational standards.
- *Threats that affect vulnerable components of the electricity system or that exceed critical thresholds*. Distribution networks are a weak link in the electric grid, but disruptions and outages associated with distribution are often localized. Generation, transmission, and substation assets are often more robust to both human and natural threats. However, these assets are still

vulnerable to single point-of-failure risks, such as the loss of large power transformers. Furthermore, once design, planning, and/or operational limits for such assets are exceeded, significant and potentially catastrophic consequences can occur.

In response to these vulnerabilities, a number of recommendations can be made to guide future decision-making to enhance resilience of the U.S. electricity system:

- Building a greater understanding of HILF events and capability to incorporate HILF threats into risk assessments and cost/benefit analyses of possible interventions or management strategies will be an important component of resilience efforts. In addition, scenario-based planning to explore multiple contingencies can be used to stress test the system and identify gaps in resilience.
- Recent efforts to develop a robust and scalable system of resilience metrics for the electricity system should continue. Resilience metrics have an important role to play in tracking progress toward risk management and resilience objectives and for providing early warning of potential weaknesses in the system.
- Planning and operational standards are needed that extend beyond the classic reliability requirements into resilient design principles. This will provide a common basis for electricity infrastructure owners and operators to ensure that their system will interoperate with other adjacent infrastructure associated with the interconnected power system.
- Utilities and regulators should increase their capacity to assess and manage non-stationary risks and their uncertainties. Future changes in not only the climate, but also population, technology, and societal preferences have important implications for resilience. It is important to understand whether risks are increasing or decreasing and whether those trends vary over different geographic areas.
- Despite a general consensus across the industry regarding the value of enhancing resilience of the electricity system, a number of constraints act to slow or prevent action. Uncertainty regarding different types of risks is one factor. However, concerns regarding the financing of investments in resilience as well as the coordination of action across a diverse group of actors – utilities, regulators, and consumers – at different scales make decision-making a complex task. Policies and practices that can help to streamline assessment and decision-making while enhancing coordination and communication can be just as important to resilience as the development of robust infrastructure and assets.

APPENDIX A. REFERENCES FOR TABLE 4. SUMMARY OF KEY THREATS TO THE ELECTRICITY SYSTEM

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APPENDIX B. DETAILED ANALYSIS OF RISK AND RESILIENCE OF THE U.S. ELECTRICITY SYSTEM

Table 8. Detailed Integrated Assessment of Risk and Resilience to the Electricity Sector

Threat	Intensity	System Components	Electricity Transmission			Electricity Generation			Electricity Substations			Electricity Distribution (above)			Electricity Distribution (below)			Storage		
		Dimensions of Risk: P	V	I	R	V	I	R	V	I	R	V	I	R	V	I	R	V	I	R
Natural/Environmental Threats																				
Hurricane	Low (<Category 3)	High	Low	Moderate	Moderate ●	Moderate	Low	Low ●	Moderate	Moderate	Moderate ●	High	Moderate	High ●	Low	Low	Low ●	Moderate	Moderate	Moderate ◐
Hurricane	High (>Category 3)	Moderate	Moderate	High	High ◐	Moderate	Moderate	Moderate ●	High	Moderate	Moderate ●	High	High	High ◐	Low	Moderate	Moderate ●	Moderate	Moderate	Moderate ◐
Drought	Low (PDSI> -3)	High	Low	Low	Low ●	Low	Low	Low ●	Low	Low	Low ●	Low	Low	Low ●	Low	Low	Low ●	Low	Low	Low ●
Drought	High (PDSI<-3)	Moderate	Low	Low	Low ●	Moderate	Moderate	Moderate ◐	Low	Low	Low ●	Low	Low	Low ●	Low	Low	Low ●	Moderate	Moderate	Moderate ◐
Winter Storms/ Ice/Snow	Low (Minor icing/ snow)	High	Moderate	Moderate	Moderate ●	Low	Low	Low ●	Low	Low	Low ●	Moderate	Moderate	Moderate ●	Low	Low	Low ●	Low	Low	Low ●
Winter Storms/ Ice/Snow	High (Major icing/ snow)	Moderate	High	High	High ●	Low	Low	Low ●	Moderate	Moderate	Moderate ●	High	High	High ●	Low	Low	Low ●	Low	Low	Low ●
Extreme Heat/Heat Wave		High	Moderate	Low	Low ●	Moderate	Moderate	Moderate ◐	Moderate	Moderate	Moderate ●	Low	Low	Low ●	Low	Low	Low ●	Low	Low	Low ●
Flood	Low (<1:10 year ARI)	High	Low	Low	Low ●	Low	Low	Low ●	Low	Low	Low ●	Low	Low	Low ●	Moderate	Moderate	Moderate ●	Low	Low	Low ●
Flood	High (>1:100 year ARI)	Low	Moderate	Moderate	Moderate ●	Moderate	Moderate	Moderate ◐	Moderate	Moderate	Moderate ◐	Moderate	Moderate	Moderate ◐	High	Moderate	Moderate ●	Moderate	Moderate	Moderate ●
Wildfire	Low (>Type III IMT)	High	Low	Low	Low ●	Moderate	Moderate	Moderate ●	Low	Low	Low ●	Low	Low	Low ●	Low	Low	Low ●	Low	Low	Low ●
Wildfire	High (Type I IMT)	Moderate	Moderate	Moderate	Moderate ●	Low	Low	Low ●	Moderate	Moderate	Moderate ●	Moderate	Moderate	Moderate ●	Low	Low	Low ●	Moderate	Moderate	Moderate ●
Sea-level rise		High	Low	Low	Low ●	Moderate	Moderate	Moderate ●	Low	Low	Low ●	Low	Low	Low ●	Low	Low	Low ●	Low	Low	Low ●
Earthquake	Low (<5.0)	High	Low	Low	Low ●	Moderate	Moderate	Moderate ●	Moderate	Low	Moderate ●	Moderate	Low	Moderate ●	Moderate	Low	Moderate ●	Moderate	Low	Moderate ●
Earthquake	High (>7.0)	Low	High	Moderate	Moderate ●	High	Moderate	High ●	High	High	High ●	High	Moderate	Moderate ●	High	High	High ●	High	High	High ●
Geomagnetic	Low (G1-G2)	High	Low	Low	Low ●	Low	Low	Low ●	Moderate	Low	Low ●	Low	Low	Low ●	Low	Low	Low ●	Low	Low	Low ●
Geomagnetic	High (G5)	Moderate	Low	Low	Low ○	Moderate	Moderate	Moderate ◐	High	High	High ○	Moderate	Low	Low ◐	Low	Low	Low ○	Moderate	Moderate	Moderate ◐
Wildlife/Vegetation		High	Moderate	Low	Low ●	Low	Low	Low ●	Low	Low	Low ●	Low	Low	Low ●	Low	Low	Low ●	Low	Low	Low ●
Human Threats																				
Physical	Low	High	Low	Low	Low ●	Low	Low	Low ●	Low	Low	Low ●	Low	Low	Low ●	Low	Low	Low ●	Low	Low	Low ●
Physical	High	Unknown	High	High	Unknown ◐	High	High	Unknown ◐	High	High	Unknown ◐	High	High	Unknown ●	Moderate	Moderate	Unknown ●	High	High	Unknown ◐
Cyber	Low	High	Moderate	Low	Low ◐	Low	Low	Low ◐	Moderate	Moderate	High ◐	Moderate	Moderate	Moderate ○	Moderate	Moderate	Moderate ○	Low	Low	Low
Cyber	High	Unknown	High	High	Unknown ○	Moderate	Moderate	Unknown ○	High	Moderate	Unknown ○	Moderate	Moderate	Unknown ○	Moderate	Moderate	Unknown ○	Moderate	Moderate	Unknown ○
Electromagnetic	Low (Ambient EMI)	High	Low	Low	Low ●	Low	Low	Low ●	Moderate	Low	Low ●	Low	Low	Low ●	Low	Low	Low ●	Low	Low	Low ●
Electromagnetic	High (NEMP & HEMP)	Unknown	Low	Low	Low ●	Moderate	Moderate	Unknown ○	High	High	Unknown ○	Low	Low	Low ●	Low	Low	Low ●	Moderate	Moderate	Unknown ○
Equipment Failures		Moderate	Low	Low	Low ●	Moderate	Moderate	Moderate ●	Low	Low	Low ●	Moderate	Low	Low ●	Moderate	Low	Low ●	Moderate	Moderate	Moderate ●
Combined Threats		Unknown	High	High	Unknown ○	Moderate	Moderate	Unknown ○	High	High	Unknown ○	High	High	Unknown ○	High	High	Unknown ○	Moderate	Moderate	Unknown ○

Key to Symbols

Level of Risk	Dimensions of Risk	Status of Risk Management Practices for Current Threats
Low	Ⓟ – Probability	○ – Nascent: critical vulnerabilities exist
Moderate	Ⓥ – Vulnerability	◐ – Established, but opportunities for improvement remain
High	Ⓘ – Impact	● – Well-established and robust
Unknown	Ⓡ – Risk	

Caption: Assessments of risk and status of risk management practice are based on information in Section 4, published literature, and expert judgment (for statistically unknown threats). Table cells represent a qualitative assessment of risk by electric system component and threat. Some threats are divided into low or high intensity threats. Estimates of individual sub-components of risk are presented for each system component and threat: probability refers to the frequency or likelihood of a threat occurring; vulnerability refers to the sensitivity of a system component to harm or damage; impact refers to the potential severity of damage in terms of financial costs, affected customers, and/or health and safety. This table forms the basis for Table 7 in Section 5.2.

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