ELECTRIC POWER
RESEARCH INSTITUTE

Electric Power System Resiliency

CHALLENGES AND OPPORTUNITIES

POWER SYSTEM TRANSFORMATION

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INTRODUCTION

In examining the electricity sector and trends related to natural gas prices, load growth, energy policy, and the penetration of distributed generation and demand response, EPRI and its members determined that the power system needs to be more resilient, flexible, and connected [1]. This document addresses the first of these three cornerstones—resiliency—for the power system. Companion white papers address flexibility and connectivity.[1]

In the context of the power system, resiliency includes the ability to harden the system against—and quickly recover from—high-impact, low-frequency events. Recent extreme weather events—including the U.S. Hurricanes Katrina and Sandy and the Tohoku earthquake and tsunami in Japan—have demonstrated the need for resiliency. Other "natural" high-impact, low-frequency events that pose threats to resiliency include tornadoes, wildfires, and severe geomagnetic disturbances (GMDs). Extreme weather has occurred throughout the system's history, although these recent events have raised awareness of the need for enhanced resiliency.

Other trends and events in the past decade—with profound pace and scope—have shaped the need for enhanced resiliency. A 2013 act of vandalism that damaged high-voltage transformers in a west coast substation focused attention on the need for enhanced physical security and resiliency. Wide deployment of communication nodes in the grid raises concerns of cyber-related attacks, while potential coordinated cyber and/or physical attacks are

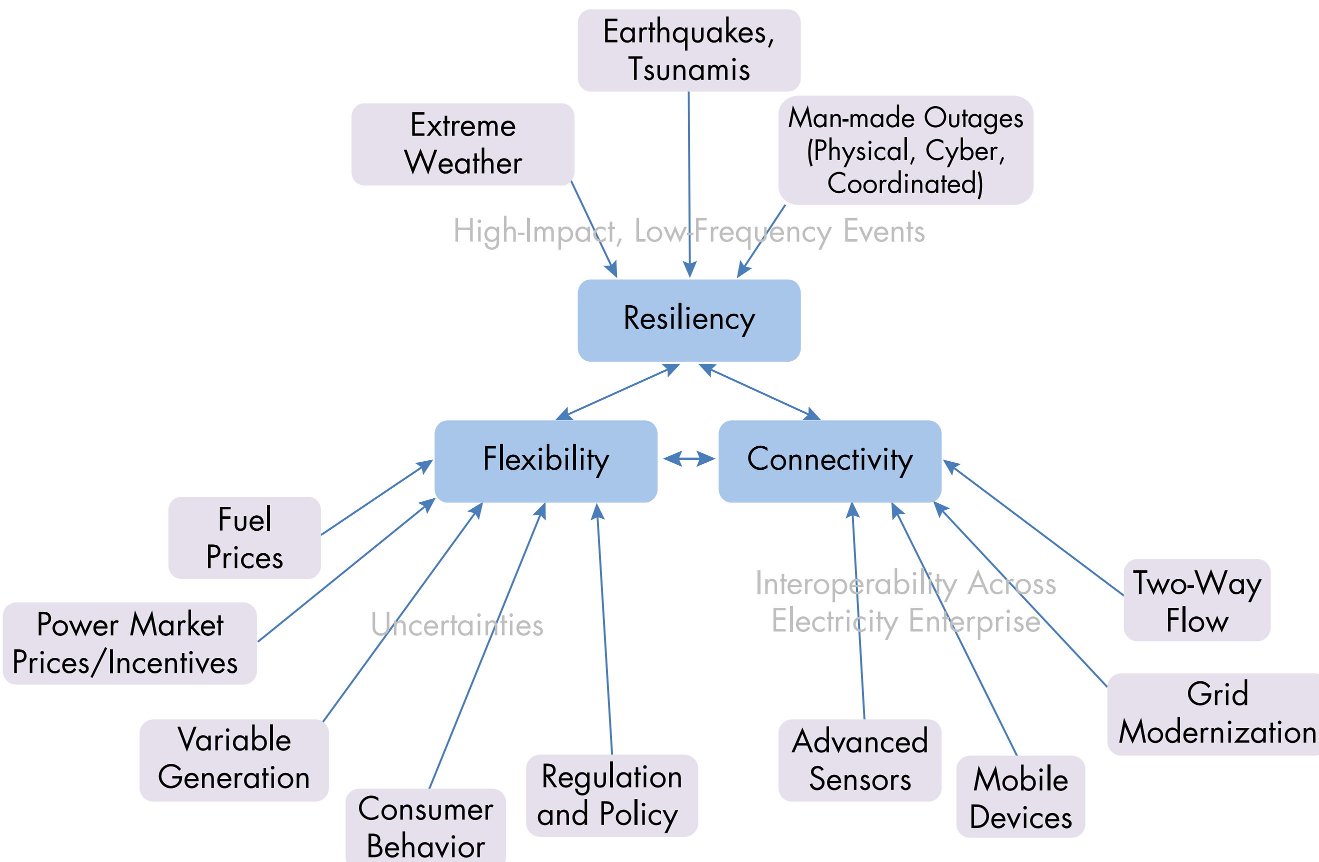

Figure 1. The Three Attributes of the Power System in a "No Regrets" Strategy

[1] *See EPRI white papers on Flexibility and Connectivity.*

INTRODUCTION

also a growing concern. Increasing dependence on natural gas-fired power generation can pose vulnerabilities if a high-impact event disrupts the gas pipeline infrastructure. Similarly, recent increased and continued dependence on wind and solar generation can pose vulnerabilities if disrupted by high-impact events.

Power system outages pose large financial impacts on the community, ranging from residential to small businesses and large corporations. The digitization of society (e.g., smart phones, tablets, and social networking) increases consumer reliance on electricity and reduces customer tolerance for even short outages, increasing pressure on utilities to enhance power system resiliency.

This paper describes innovative technologies, strategies, tools, and systems that EPRI and electricity sector stakeholders are developing and applying to address the challenge of resiliency. Enhanced resiliency of the power system will be based on three elements—damage prevention, system recovery, and survivability—each of which will be discussed in more detail.

This paper is the first step toward developing a more comprehensive EPRI research initiative aimed at increasing power system resiliency. The next step is to identify research gaps, and work with electric utilities, fuel suppliers, government and non-governmental agencies, world-wide research entities, universities, technology providers, and other stakeholders to assemble a roadmap and action plan to accelerate science and technology.

Flexibility

Flexibility refers to the power system's ability to adapt to changing conditions while providing electricity safely, reliably, affordably, and environmentally responsibly. Several factors are driving the requirement for flexibility in both supply and demand, including uncertain fuel prices, power market prices and incentives, variable generation, regulation and policy, and consumer behavior. Flexibility will be critical for owner/operators of the generation, transmission and distribution system, consumers, regulators and policymakers, and market participants. EPRI will engage industry, regulatory, government, research, and other stakeholder groups to develop a roadmap that defines the R&D strategy for key research elements related to flexibility. These include conventional generation, environmental controls, the T&D system, balancing resources, power markets, system operation and planning, and energy utilization. A second EPRI white paper covers flexibility in more depth.

Connectivity

Connectivity of the electric power system refers to the increasingly widespread deployment of advanced communications and monitoring equipment, providing access to data streams and functionality that can help inform decisions and behaviors all along the value chain, from the power plant to the end consumer. Connectivity will enable the grid to become more flexible, more resilient, and better able to capitalize on advanced digital functionality, all while delivering more value to the customer. Several factors are driving the need for, and opportunities associated with, connectivity, including intelligent and connected two-way flow of power and information; grid modernization technologies that depend on and build on increased connectivity; connection of advanced sensors across the network to improve decision making; and ubiquitous interconnected mobile devices across the industry and consumer classes. Connectivity will touch all corners of the power system, from generation to transmission and distribution, and ultimately to the customer. Key areas in which to engage industry, regulatory, government, and other stakeholders in a dialog on connectivity include advanced monitoring technologies, communications infrastructure, data exploitation, and customer value. A third EPRI white paper covers connectivity in more depth.

WHY IS A MORE RESILIENT POWER SYSTEM NEEDED NOW?

Overview

Resiliency includes the ability to harden the power system against—and quickly recover from—HIGH-IMPACT, LOW-FREQUENCY events. Such events can threaten lives, disable communities, and devastate generation, transmission, and distribution systems, as well as interdependent systems such as natural gas pipelines and other fuel transport and telecommunications. Included are:

- Severe weather or natural events
  - Hurricanes and consequent flooding
  - Tornadoes
  - Earthquakes and consequent tsunamis
  - Wildfires
  - Ice storms
- Severe geomagnetic disturbances (GMDs)
- Cyber attacks
- Physical attacks
- Coordinated cyber and/or physical attacks
- Electromagnetic pulse (EMP), high-altitude EMP (HEMP), and intentional EM interference (IEMI) attacks
- Pandemics[2]

Other trends and events in the last decade have further shaped the need for enhanced resiliency, including the following:

- Digitization of society and shifting consumer expectations
- Unanticipated severe shortages of fuel or water for power generation
- Weather impact on growing variable generation
- Growing dependence on natural gas for electric power
- Vulnerability to extreme cold weather

The elements of resiliency—prevention, system recovery, and survivability—align closely with sustainability, a concept that refers to the environmental, social, and economic performance of electric power companies and impacts on their stakeholders. Sustainability has been an area of significant research at EPRI since 2008. Sustainability issues include, but are not limited to, emissions of greenhouse gasses, water availability, employee and public health and safety, and reliability [2]. Although both resiliency and sustainability seek to proactively manage resources in consideration of ever-evolving externalities, they are distinct. Sustainability focuses on a company's performance, the environment, and the communities within which they operate, while resiliency focuses on preparing for and quickly responding when challenged by an external force [3].

Extreme Weather Events

The resiliency of the electric power system is threatened by extreme weather events and natural disasters, including hurricanes and tornadoes, flooding and sea level rise, earthquakes and consequent tsunamis, severe wildfires, drought, or heatwaves, and severe winter storms. Recent extreme weather events inflicted considerable damage on electric infrastructure and left customers without power and often without clean water, food, and fuel for heating or transportation. Cell phone technology failed as well, as cell towers were often powerless and only those with solar cell phone chargers could recharge their phones.

Some data suggests that the frequency of natural disasters may be increasing. According to Munich Re's NatCatSERVICE, the number of geophysical, meteorological, hydrological, and climatological events rose to an all-time high of 247 events in 2010—up from approximately 200 in 2009 and less than 200 in all years from 1980 to 2010 [4].

[2] *In this paper, EPRI defines resiliency as described above but recognizes that it can be defined in several different ways, including for example, in the context of climate preparedness and resiliency. The latter is beyond the scope of this paper.*

WHY IS A MORE RESILIENT POWER SYSTEM NEEDED NOW?

The North American Electric Reliability Corporation (NERC) reported that the number of so-called major disturbances increased dramatically from 1992 to 2009 (see Figure 2) [5].

Drought and heat waves

Extreme events in the form of droughts and heat waves threaten the electricity system by restricting water resource availability for power generation, cooling, and fuel production. Severe droughts in recent years have sharply reduced hydropower capacity in the West and Southeast by 50%. Moreover, diminished surface and groundwater levels required additional energy to pump water. Reliability at thermoelectric facilities is also threatened by drought and heat waves. Elevated ambient air temperatures reduce generation efficiency and also increase energy losses in transmission and distribution systems. Decreased water availability directly affects cooling operations in various ways (e.g., raising the total dissolved solids concentration in the source water). Output from once-through cooling plants is at risk from elevated source water temperatures that may cause discharge limits, leading to derating, emergency variance, temporary curtailment, or financial penalties. Reduced water availability can affect fuel production of oil, gas, and bioenergy. Finally, droughts and heat waves can also exacerbate existing challenges related to water resource allocation, competition with other sectors (e.g., agriculture, municipal, and industrial uses), water quality, and sedimentation in reservoirs.

Flooding and sea level rise

Electric generation and delivery assets, as well as the broader energy system infrastructure, are vulnerable to damage from coastal and inland flooding resulting from extreme events. Recent increases in extreme precipitation have also increased the frequency of inland flooding events, particularly in the Midwest, upper Great Plains, and Northeast. Flooding from storm surge threatens coastal

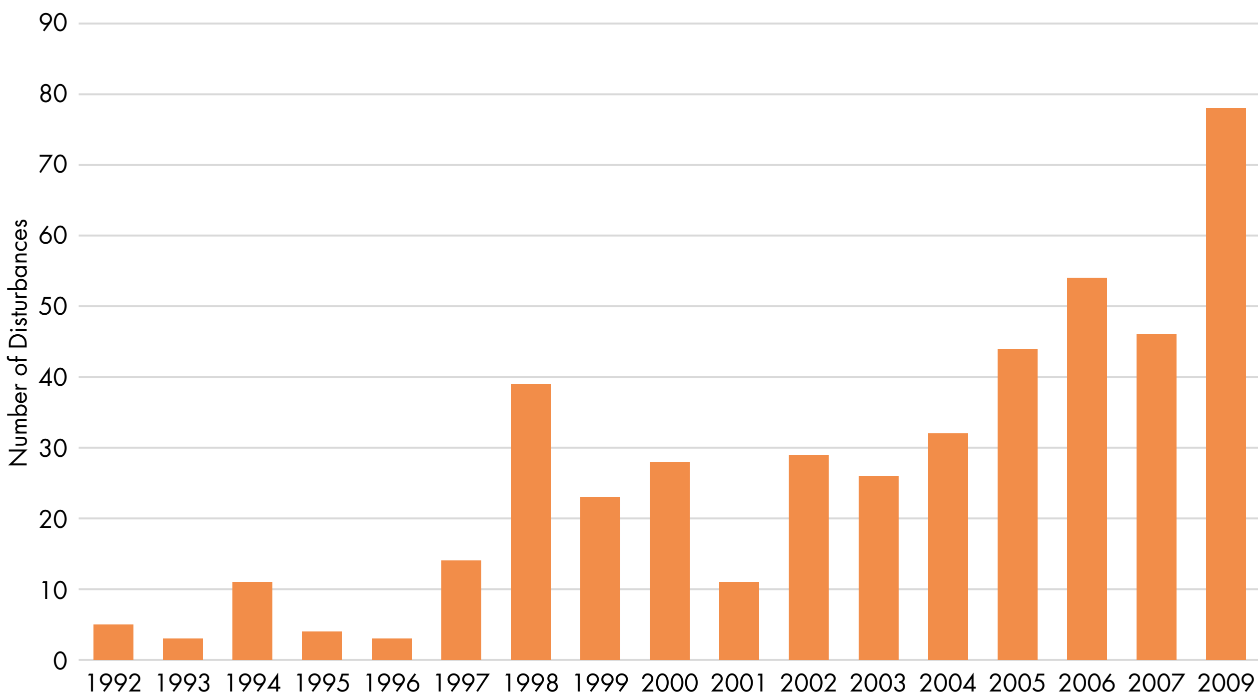

Figure 2. North American Electrical Disturbances Caused by Weather (Source: NERC) [5]

Note: The information is taken from the pdfs found here: http://www.nerc.com/page.php?cid=5166, which is NERC Event Analysis: System Disturbance Reports. The data in the graph displays the number of disturbances recorded in the pdfs that were weather related (if the word "weather" was in the cause of the blackout) sorted by year (data unavailable for 2008). The graph shows number of disturbances caused by weather per year [3].

infrastructure and capital assets that are vital to the electric sector, as well as ports and other transportation networks that could affect fuel distribution or other resources. Current vulnerabilities could be exacerbated in the coming decades by sea level rise. Sea level rise shifts the storm surge distribution in an additive way, which means that even small amounts of rise will affect the frequency of extreme events (e.g., a 100-year flood may occur every few decades), leading to more extensive flooding and inundation when storms make landfall.

Increasing Digitization of Society and Shifting Consumer Expectations

An important trend that points to the need for resiliency is the increasing digitization of society and shifting consumer expectations. As a result of transmission and distribution outages from major storms, U.S. electricity consumers can expect to lose power for an average of more than 100 minutes annually. As with any average, individual consumers may never see an outage, while others could see outages of several days—despite the sustained, concerted efforts of utilities.

Columnist Bill Federman wrote this in the Albany, N.Y., *Times Union* about post-hurricane life in Connecticut: "Being without heat, hot water, lights, a phone, an internet connection, and retail services of any kind was an adventure that we laughed off—*for about an hour*. (Emphasis added.) Then the seriousness of our predicament began to sink in. Absentmindedly flipping the light switch when we entered a room was no longer amusing" [6].

Beyond the average duration of outages, the other average to be considered is the consumer expectation. Even outages lasting a few hours can frustrate customers, elected officials, and regulators, due in part to the increasing dependence on the "web" of connectivity of digital devices and networks. Disrupted connectivity heightens customers' anxiety and dissatisfaction.

Meeting regulatory standards for restoration is no longer sufficient; consumers want fast restoration. At the same time they expect electricity to be affordable. The investment required to harden the power system to withstand the worst disasters must be regarded by all concerned as prudent and cost-effective.

Extreme Weather Impact on Growing Variable Generation

Federal tax incentives and state renewable portfolio standards have driven significant increases in U.S. renewable resources. Extreme weather can adversely impact this often variable generation.

U.S. wind power generation increased from 8.7 GW in 2005 to 60 GW in 2012—all of it onshore. According to the National Renewable Energy Laboratory (NREL), offshore resources may be as much as four times the total U.S. electricity generating capacity [7]. The U.S. Department of Energy reports that 54 GW of shallow offshore wind turbines (less than 30 meters in depth) would be required to increase wind generation to 20% in the U.S. [8]

Such wind turbines may be vulnerable to severe weather. A Carnegie Mellon study concluded that in vulnerable areas now being considered, nearly one-half of offshore wind turbines would likely be destroyed by severe weather in a 20-year period. Researchers estimated these impacts using a probabilistic model that examined four representative locations along the Atlantic and Gulf coasts. They pointed out that a 2003 typhoon in Okinawa, Japan, destroyed seven wind turbines. With 20 offshore U.S. projects in planning stages (total capacity of 2 GW), the authors recommend that wind turbines be constructed to withstand higher wind loads than currently specified, turbines be able to turn into the wind during extreme storms, and turbines be installed in areas with lowest risk of hurricane damage [9].

To avoid high-wind damage, wind turbine designs include turbine brakes, blade feathering, active yaw systems to turn the turbine into the wind, heavy towers, and strong foundations [10].

Another consideration is that wind and solar generation cannot generate power prior to, during, and immediately after severe storms due to cloud cover. Wind generators may need to be shut down immediately prior to and during severe weather to minimize the risk of damage, and remain offline immediately after the storm while inspectors ensure that turbines are undamaged and can operate safely. This is in contrast to traditional generation, such as coal-fired, natural-gas fired, and nuclear power, which can in most cases continue to generate during severe storms. In the absence of electric energy storage for wind and solar generation, such losses of generation reduce the overall capacity available to system dispatchers. This becomes an increasing challenge as the percentage of renewable generation increases.

Increasing Vulnerability to Cyber Attacks

While weather's potential impacts are included in grid reliability models, the resiliency of the grid to cyber incidents is not well understood. Concerns are heightened by the growing deployment of information and communication technology on the grid.

Cyber attacks could incorporate, but not be limited to, combinations of the following:

- Distributed denial-of-service attack in which attackers flood network resources to render physical systems unavailable or less responsive
- Rogue devices to access and manipulate the system or provide incorrect data to system operators
- Reconnaissance attacks that probe a system to provide attackers with information on system capabilities, vulnerabilities, and operation
- Eavesdropping that violates confidentiality of network communication
- Collateral damage as unplanned side effects of cyber attacks
- Unauthorized access attacks in which the attacker obtains some control over the system, and accesses and manipulates assets without authorization
- Unauthorized use of assets, resources, or information that would feed incorrect information to system operators
- Malicious code or malware through viruses, worms, and Trojan horses [11]

The distributed nature and diversity of the system also presents security challenges. Limited on-site supplies and the challenges of securing replacement system components would hinder recovery. Vulnerability has increased as the industry relies more on automation and remote monitoring and control [11].

Cyber attacks can be dormant, widely distributed, and executed at a time preset by attackers. Once executed, adverse impacts may be difficult to detect. In contrast to physical attacks, cyber attacks lead to unseen damage in operation, information, and control systems. Inventorying damage from cyber attacks may take much longer and require more resources than corresponding efforts from physical attacks. Evaluations may need to cover large infrastructure, requiring specialized diagnostic and repair crews that may not be available at all sites. This may lead to new ways for utilities to design systems and workforce training [11].

Because preventing all possible cyber incidents is not cost effective or feasible, designing the electric grid for resiliency to potential incidents is vital. This requires having in place the tools, processes, and technology to detect incidents when they occur, respond in ways that continue to provide the highest possible level of electric service, and support quick recovery. The grid's complexity also necessitates close cooperation of power system and information technology experts.

Enhanced Awareness of Physical Security Risks

A 2013 act of vandalism that damaged high-voltage transformers in a west coast substation, along with other post-9/11 events, have focused attention on the need for enhanced physical security and resiliency against such attacks at substations and transmission facilities. Remote transmission power lines, substations, communications facilities, or natural gas transmission supplies are susceptible to attack with little or no risk of detection. Selecting points of attack and estimating the consequences are within the capability of technically trained saboteurs.

High-value choke points—facilities that, if destroyed, could significantly degrade power system capability—are easily located either on the ground or from system maps. Detailed maps of U.S. power systems were once readily available in the public domain and can still be obtained on the Internet.

Deliberate attacks can cause more focused damage to facilities and equipment in substations than natural events, but prior to 9/11, deliberate attacks were viewed as unlikely, warranting limited precautions. However, society's dependence on the power grid may be exploited by a variety of adversaries with ideological or political motives. Substations, in particular, present many targets, and the power system's growing reliance on natural gas pipelines and supervisory control and data acquisition (SCADA) communication systems, point to attacks on these as equally disruptive.

Physical security concerns have also stimulated regulatory activity. NERC developed CIP-014-1 to address Physical Security in November 2014. This was in response to a FERC order in March 2014 directing the development of a standard to account for physical security threats and vulnerabilities. The standard went into effect in October 2015 [12].

Increased Vulnerability to Geomagnetic Disturbances

Solar storms or GMDs have demonstrated their ability to disrupt the power grid. In March 1989, a GMD led to the collapse of the Hydro-Québec TransÉnergie Interconnection, leaving more than six million people without power for nine hours. Solar storms and their coronal mass ejections can disturb the Earth's geomagnetic field over wide regions and as global phenomena can adversely impact systems on multiple continents. The disturbance in Earth's geomagnetic field can cause geomagnetically induced currents (GICs) in the ground and electric network. Once introduced into the bulk power system's transmission and generation facilities, these currents can saturate (or quasi-saturate) and may damage equipment, much of which can be difficult to replace immediately. High-voltage transformers require long lead times to construct and are predominantly manufactured outside North America.

Power systems today may be more vulnerable to the effects of a severe GMD than they were only a few decades ago. Since the 1950s, the number of miles of high-voltage transmission lines has increased by about a factor of ten [13]. Hence, the number of assets that provide a conductive path for GICs has increased dramatically over the past five solar cycles, which average about 11 years. During the same period, transmission line and transformer designs have increased in voltage from 100-200 kV to 345-765 kV, which has lowered their resistance by a factor of ten and further increased their susceptibility to GMDs [14]. The conducting paths are lengthening as transmission lines become interconnected (e.g., across national borders). In the past two decades, construction of new transmission lines has slowed, forcing some systems to operate the high-voltage power system closer to operating limits more often. These assets are more susceptible to overloads because the equipment may be operating closer to its nameplate thermal rating when the GIC initiates additional heating.

In the last two years, a major step was taken by approving two new reliability standards designed to address the risks of severe GMD events. In April 2015, the Stage 1 Operating Procedures Standard took effect requiring transmission operators and reliability coordinators to have operating procedures for GMDs. Even more significantly, the industry has also approved the Stage 2 Reliability Standards for GMD vulnerability assessment and mitigation planning, which NERC filed with the Federal Energy Regulatory Commission (FERC) in January 2015. The latter standard represents a major milestone because those entities involved in reliability planning in North America will have to include GIC and GMD effects in their planning studies and assess their systems to a severe benchmark GMD event that occurs an average of once every 100 years. If these entities determine that there may be issues resulting from such a GMD, they must take actions to address those risks. These GMD standards were initiated in response to FERC Order No. 779 [15, 16].

Vulnerability Due to Increased Dependence on Natural Gas for Electric Power

Shifts in the generation mix also contribute to the need for enhanced resiliency. Increased dependence on natural gas for power generation makes the power system vulnerable to disruptions in the gas industry by high impact events, such as hurricanes. Electric power generation is increasingly dependent on natural gas. This trend has been driven by increased supply (including shale gas), reduced natural gas prices, and efficient generation technology. In the past decade, power generation (GWh) fueled by natural gas increased from 17% to 25% in the United States. Natural gas now accounts for the largest percentage of generating capacity (GW) in the United States (39%), surpassing coal (30%). NERC projects further increases in both absolute and percentage share of natural gas-fired generation and capacity [17].

This brings several positive impacts. Natural-gas-fired combustion turbines (CTs) and combined-cycle units offer the lowest investment requirements of any commercially-available central station plant, high efficiency, and a small plant footprint. These units can be more readily sited than coal plants and can be constructed in a much shorter time than other large-scale options. When burning natural gas, most CTs today are capable of near-zero emissions of nitrogen oxides (NO_X), sulfur oxides (SO_X), carbon monoxide (CO), particulates, and hazardous air pollutants (HAPs) through the use of ultra-low NO_X combustion with exhaust scrubbing systems. Their efficiency reduces emissions of carbon dioxide (CO_2) compared to some coal generation, and peaking natural gas generation can help offset variable generation such as solar and wind power generation.

However, because natural gas is not easily stored on site (in contrast to coal and fuel oil), electric generators rely on real-time supply of natural gas through pipelines. High current demand (and further projected increases) for natural gas for uses other than generation (currently space heating and increasingly transportation, exports, and manufacturing) impacts reliable delivery [17].

As a result, power generation and natural gas industries are increasingly interdependent. NERC reported in 2013 that this interdependence "has made the power sector more vulnerable to adverse events that may occur within the natural gas industry" and "can amplify the exposure of the bulk power system to disruptions in fuel supply, fuel transportation, and delivery" [17]. Dependence on natural gas-fired power generation can pose vulnerabilities if a high-impact event disrupts gas pipelines.

With its 300,000 miles of interstate and intrastate gas transmission pipelines, the United States has experienced disruptions. According to the Energy Information Administration (EIA), as a result of the September 2008 Hurricanes Gustav and Ike, "almost all of the natural gas production and processing capacity in the [Gulf coast] area was shut in, with continued shut-ins affecting production into December 2008." Fifty-five major natural gas processing plants were in the path of the hurricanes, representing 38% of U.S. processing capacity. Twenty-eight pipelines, most of which move natural gas onshore to processing plants, declared force majeure (occurrences beyond their control) in September, and many were shut down [18]. In 2005, Hurricanes Katrina and Rita destroyed 115 offshore oil/natural gas platforms and damaged 52 others. About three-quarters of all Gulf platforms were in the direct paths of these two Category 5 storms [19].

Vulnerability to Electromagnetic Pulse (EMP) Weapons

An EMP refers to a very intense pulse of electromagnetic energy, typically caused by detonation of a nuclear or other high-energy explosive device. HEMP is an EMP detonated at high altitude to produce more widespread effects. (An EMP, as opposed to a HEMP, can cause relatively local but significant impacts.) Power systems operate in an increasingly complex electromagnetic environment in which large current and voltage components, sensitive electronics, digital signals, and analog waveforms all coexist and interact, leading to increased vulnerability to EMP/HEMP, and IEMI attacks. Also contributing is the growing adoption of smart grid components and systems. In written testimony to the U.S. House Committee on Homeland Security on September 12, 2012, the National Protection and Programs Directorate Infrastructure Analysis and Strategy Division Director stated: "Over the past several decades, the threat to digital and physical infrastructures has grown. For example, today's power grid and information networks are much more vulnerable to EMP than those of a few decades ago" [20].

Vulnerability to Extreme Cold Weather

Recent cold weather extremes have disrupted power markets and triggered generating units to fail across North America. This has raised concerns about the resiliency of some types of generating units and the ability of electric markets to provide efficient market results in these stressed system conditions.

In early 2014, extremely cold weather led to record high natural gas demand, electric demand, and natural gas prices, as well as very high electricity prices. The high natural gas prices were due to gas transportation and storage constraints, gas production losses, and strong demand. Spot prices reached all-time highs in the Northeastern United States. Four NERC regions experienced historically high winter peak electricity demand, and combined with generator outages, caused operation near capacity. Regional transmission organizations (RTOs) and independent system operators (ISOs) declared emergency conditions, implemented emergency procedures, cancelled planned transmission outages, required commitment of some generation, and implemented other measures. Generator outages resulted from mechanical failures in fuel delivery, fuel handling, and generator systems due to the extreme cold. Because natural gas is the marginal fuel for most electric markets, its high price increased electricity prices. The cold weather also affected propane demand, requiring FERC to exercise emergency powers [21].

FERC "does not expect the historic prices at the high end of the spectrum to become the norm. However, the range in prices has tested some of the market systems and procedures used by the RTOs and ISOs and revealed difficulty in achieving efficient market results in stressed system conditions" [21].

In light of these events, John Sturm of the Alliance for Cooperative Energy Services (comprising 21 electric cooperatives in some of the affected RTOs/ISOs) recommended that "physical gas pipeline constraints and gas-power process issues" be addressed. He pointed out that coal and nuclear generation was more reliable during these winter periods than natural gas, solar, and wind generation, and that the predicted increase in the latter type of generation "will likely lead to both greater risk of electric reliability deficiencies and higher costs for consumers on future critical operating days" [22].

In response, NERC issued its Reliability Guideline for Generating Unit Winter Weather Readiness in August 2013 [23]. Providing a general framework for such readiness for North American generating units, the report outlines practices that, while voluntary, are highly recommended. The focus is maintaining generating unit reliability in the face of severe winter weather. It covers safety, management roles and expectations, processes and procedures, evaluating potential problem areas, testing, training, and communications. Identified problem areas included level, pressure, and flow transmitters; instrument air system, valves, drains, vents, screens, and water pipes; and fuel supply and ash handling. An appendix listed key points to address, including work management system; critical instrumentation and equipment protection, insulation, heat trace, and other protection options; supplemental equipment; operational supplies; staffing; communications; and special operations instruction.

ENHANCING POWER SYSTEM RESILIENCY

Enhanced power system resiliency is based on three elements (see Figure 3):

- Damage prevention: the application of engineering designs and advanced technologies that harden the power system to limit damage
- System recovery: the use of tools and techniques to restore service as soon as practicable
- Survivability: the use of innovative technologies to aid consumers, communities, and institutions in continuing some level of normal function without complete access to their normal power sources

Improving the power system's resiliency requires advancement in all three aspects. The most cost-effective approach combines all three.

Damage Prevention

Damage prevention hardens the system through changes in design standards, siting, construction, maintenance, and inspection and operating practices. A utility can adapt its approach to its specific distribution system and work environment. Examples include:

- Enhancing vegetation management
- Enhancing the physical security of power plants, transmission systems, and substations against attack
- Hardening power plants and substations against storm damage
- Developing more resilient nuclear fuel capabilities
- Enhancing nuclear plant cooling strategies
- Selective undergrounding of T&D facilities
- Reinforcing overhead lines

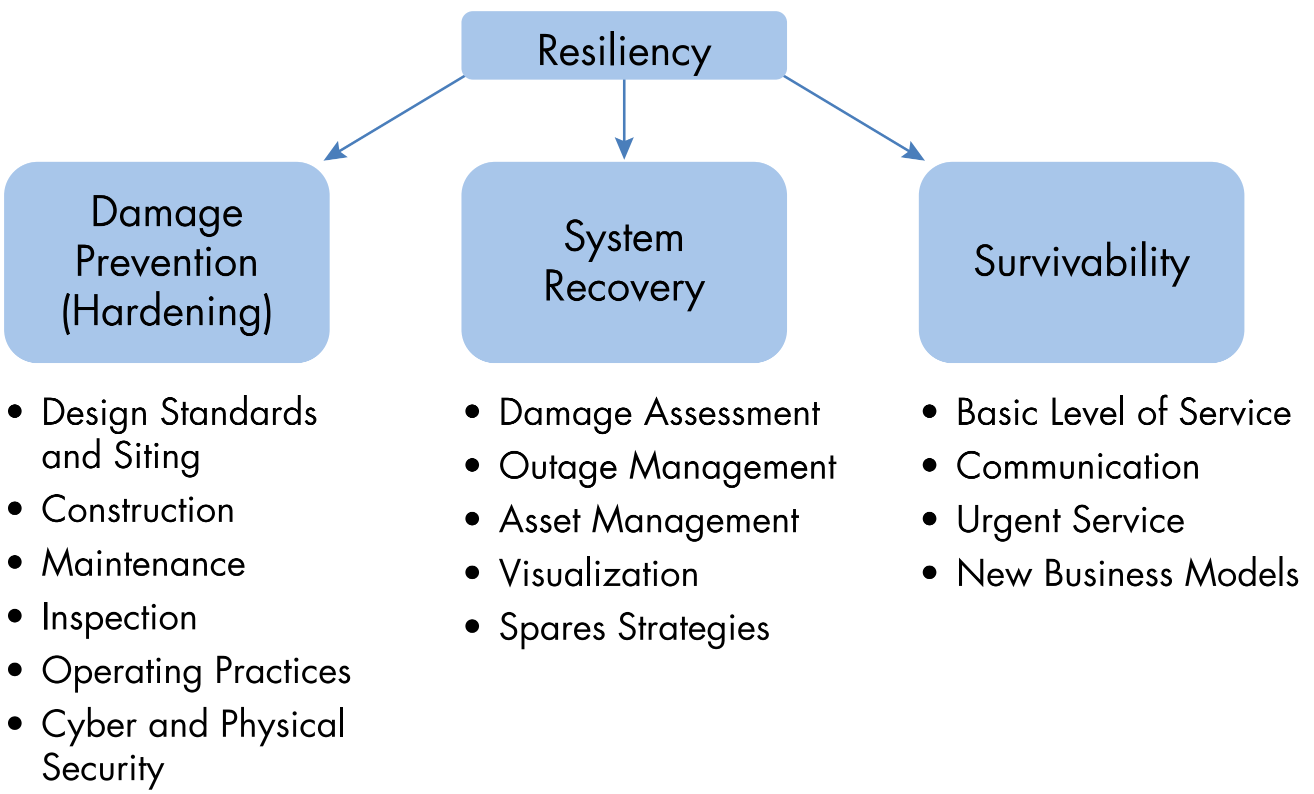

Figure 3. Resiliency Consists of Damage Prevention, System Recovery, and Survivability

- Deploying cyber security measures and R&D actions
- Refining use of hydrophobic coatings
- Enabling dynamic circuit operation
- Pre-emptive operating practices upon the approach of a hurricane or threat of a geomagnetic disturbance

System Recovery

Planning for resiliency requires rapid damage assessment, prompt crew deployment, and readily available replacement components. In recent storms such as Hurricane Sandy, pinpointing affected areas was problematic, as was routing crews through streets blocked by fallen trees. Crews were sometimes idled because they could not reach affected areas. R&D efforts to support recovery include:

- Airborne damage assessment
- Developing advanced outage management systems (OMS)
- Effective use of geographical information systems embedded in an asset management system
- Developing field force visualization tools
- Spares strategies, including availability of recovery transformers
- Emergency response to maintain power plant operation

Survivability

Survivability refers to the ability to maintain some basic level of electricity service to customers, communities, and institutions when they do not have complete access to their normal power sources. Key to this is facilitating communications with customers. Additional R&D should focus on the use of distributed generation options such as plug-in electric vehicles (PEVs), fuel cells, photovoltaics, and high-efficiency generating sets to enable urgent service to cell phones, traffic lights, hospitals, and prisons.

For distribution utilities, survivability has emerged as a new function, requiring new business models and innovation. Current regulatory/business models may make it difficult for utilities to develop and fund programs for survivability of high-impact, low-frequency events, especially when they have difficulty fully funding immediate needs such as vegetation management.

Resiliency Engineering

A recent literature review on resiliency engineering points to the use of reactive, proactive, and predictive approaches [24,25]. In this framework, system recovery is reactive to a high-impact event, but learning from past system recoveries and incorporating lessons learned can lead to proactive approaches. Damage prevention (hardening) and survivability are both clearly proactive. All of these approaches can also be predictive if the potential impacts of events are predicted, approaches for minimizing the impacts are anticipated, and ongoing steps are taken to make the power system more able to tolerate such events through hardening and systems operating practices.

Another key aspect of resiliency engineering is the use of lagging, current, and leading indicators, to measure resiliency. The previously cited literature review on resiliency engineering shows that lagging indicators can be used to define targets based on past performance analysis; current indicators can be derived from leading indicators; and leading indicators are based on industry targets (standards) and/or individual company objectives [24]. Using a control theory analogy, these indicators can be used for closed-loop feedback control and feed-forward control to enhance resiliency based on lessons learned from the past and operation in states that minimize the impact of high-impact, low-frequency events.

Resiliency engineering also involves moving toward performance boundaries. The literature review on this topic examines the boundary to economic failure, which requires efficient processes; a boundary to unacceptable workload, which requires processes to enhance resiliency with less effort; and a boundary of acceptable performance that prevents catastrophic failure. This usually incorporates a factor of safety or margin that defines official work practices, which are significantly removed from failure [24,26]. This heightens the need to optimize the benefits and costs of resiliency improvements (addressed in a separate section of this paper).

ENHANCING RESILIENCY: OVERVIEW

This section describes actions that stakeholders can take today to enhance resiliency and outlines new areas where innovation can be employed to enhance resiliency. Improvements to enhance resiliency can be made in four primary components of the power system (Figure 4). The improvements can address the need to harden the system against, recover from, and enhance the survivability of the effects of high-impact, low-frequency events, and/or other trends that point to the need for resiliency.

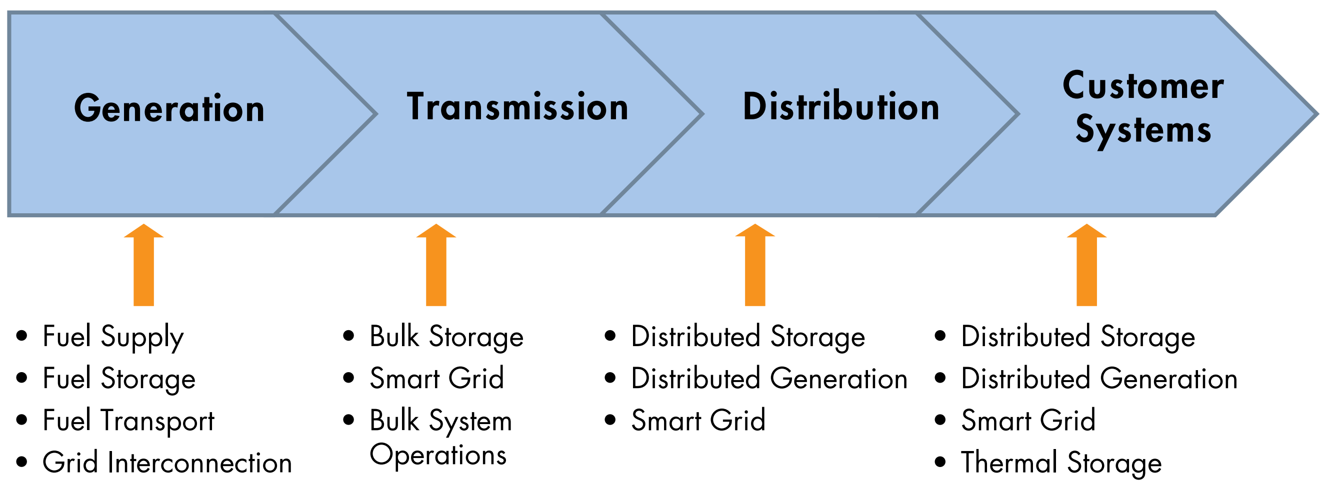

Figure 4. Components of the Power System

This section covers fossil power generation and nuclear power generation.

Fossil Power Plants

Fossil plants experience damage from high-impact events due to flooding and interruptions in fuel supplies, steep ramp rates, fast starts and shutdowns, and extended periods of shutdown. This is based on cycling from cold to hot metal in short periods. Damage mechanisms are:

- High-temperature, high-cycle creep fatigue
- Vibrations—increases in valve body and small-bore pipe cracking
- Stress corrosion cracking due to steam quality changes and chemistry (turbine blading)
- Flow-accelerated corrosion due to changes in mass flow rates
- Wear and tear on pumps and motors due to non-optimal operating points and changing loads

These impacts are expected to increase due to various regulatory and market actions. In California, system operators are being pressured to accept energy from renewables. The dispatch of large wind farms in Texas is forcing fossil plants to cycle routinely. In the upper U.S. Midwest and Canada, renewables are challenging the economics of both fossil and nuclear plant operations. EPRI has applied its US-REGEN model to examine 15 U.S. regions and determine the sensitivity in each to increases in renewables and retirement of older fossil units.

In addition, the power industry is expected in the near future to face increased competition for rights to both water withdrawals and consumption. Researchers at the U.S. Department of Energy's (DOE's) National Energy Technology Laboratory (NETL) have estimated that water consumption in the coal-fired power industry will increase 21% (from 2.4 to 2.9 billion gallons/day) from 2005 to 2030, while consumption for all water users will increase only 7% [27]. Competition is projected to increase for water withdrawal and consumption from agricultural, municipal, and industrial users, especially in water-limited areas of the United States such as the West, Southwest, and certain areas of the Southeast.

What Can Be Done Now?

Emergency Management for Fossil Power Plants: Severe weather, earthquakes, explosions, fires, and chemical releases are some of the emergency situations that can occur at electric power plants. Individually, such events may be unpredictable, but emergencies are inevitable. The degree to which a plant will be adversely affected by an emergency is influenced to a considerable extent by the quality of its emergency management program. EPRI has established emergency management guidelines to support companies in developing programs for fossil generating stations. These guidelines provide the structure and guidance necessary for site-specific plans and establish procedures necessary to evaluate, prepare for, respond to, and recover from various emergencies [28]. Additional guidelines are also available in EPRI's report on Operational Experience with Lessons Learned on Hurricanes [29].

Where Can Innovation Be Employed?

On the fossil generation system, opportunities to enhance resiliency include advanced water technologies, managing interdependence of natural gas and electricity systems, and natural gas storage technologies.

Advanced Water Technologies: Technologies have the potential to reduce water use at fossil power plants, including various dry and hybrid cooling systems. For example, the Thermosyphon Cooler (TSC) Hybrid Cooling System is a dry-heat-rejection technology. It places a natural convection-driven refrigerant loop between a shell-and-tube evaporator and an air-cooled condenser. It can be used in series, upstream of a conventional cooling tower, or possibly in lieu of a conventional cooling tower (see Figure 5) [30].

NERC Recommendations to Address Vulnerabilities Due to Gas-Electric Interdependence: In a 2013 report, NERC assessed the vulnerability of the North American bulk power system to increased dependence on natural gas for electric power generation. The report's recommendations include technological innovation and institutional solutions:

- Implement risk-based approaches to assess impacts and challenges.
- Enhance reliability and resource assessments to reflect risks of natural gas supply disruptions in power generation.

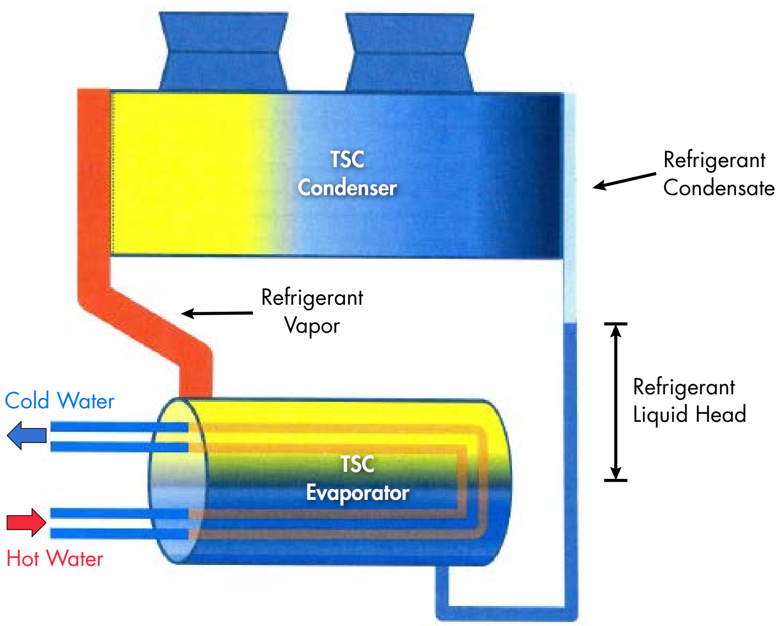

Figure 5. Flow Diagram for the TSC
(figure used with permission from Johnson Controls)

- Implement mitigation strategies regionally, including increased infrastructure and back-up fuel capability.
- Share data and coordinate planning to further analyze the issue.
- Enhance system operators' situational awareness of issues that affect fuel for gas-fired generation.
- Enhance communication and coordination between the power and gas pipeline and supply industries during high-impact events.
- Identify best practices and execute industry drills and table-top exercises with participants in both industries to gain insights and enhance coordination [17].

Natural Gas Storage Technologies: Unlike coal and nuclear plants, natural gas-fired plants do not store significant quantities of fuel on site. The option of compressed natural gas poses concerns with high costs, low storage efficiency, and public safety.

An emerging gas storage technology adsorbs natural gas (methane) in high-density activated carbon with micropores. Preliminary results indicate that this system can store methane at a weight and volume comparable to a high-pressure cylinder, but at a fraction of the pressure. Subsequent research continued the development of methane storage, and examined materials, material packaging, fabrication, and performance of a prototype. The system could be filled from a pipeline supplied by a single-stage compressor without refrigeration and hence at low cost. However, research indicates that potentially only 70-85% of the gas stored can be recovered easily, requiring additional research to confirm or enhance this capability.

Nuclear Power Generation

With respect to damage prevention, nuclear generating plants are designed to withstand a number of postulated external and internal events. These include but are not limited to hurricanes, tornados, tsunamis, aircraft impacts, earthquakes, floods, and fires. The robustness of these designs was proven following Hurricanes Andrew, Katrina, and Sandy, as well as the 2011 Virginia earthquake. Nuclear generating stations have diverse and redundant power supplies to ensure safe shutdown of the reactor without outside power or assistance. Emergency generators (diesel or gas powered) supply AC power, and batteries supply DC power. Some nuclear plants are also designed with emergency injection systems that do not require AC or DC power.

The Tohoku Earthquake and resultant tsunami on March 11, 2011, led to multiple nuclear core meltdowns at the Fukushima complex due to losses of key emergency equipment. As a result of this accident, the nuclear industry has developed a strategy known as the "diverse and flexible mitigation capability" (FLEX) to address many of the recommendations set forth by the Nuclear Regulatory Commission's (NRC's) Fukushima Task Force. This strategy takes into account lessons learned from the Fukushima accident on the need to maintain key safety functions amid conditions where electricity may be lost, back-up equipment could be damaged, and several reactors may be involved. FLEX is a set of portable equipment that is located around the plant so there is more than one set of equipment at diverse locations that can be quickly deployed and connected to provide injection and power supplies for instrumentation. The primary purpose of this equipment is to inject water to keep the reactor and spent fuel pools cool, as well as to provide power to instrumentation for monitoring plant status.

Physical security has always been part of nuclear plant regulations per 10 CFR Part 73—Physical Protection of Plants and Materials, which includes requirements for armed guards and detection systems. Following the events of September 11, 2001, the NRC issued additional regulations in this area. Per 10 CFR 50.54(hh)(2), "Each licensee shall develop and implement guidance and strategies intended to maintain or restore core cooling, containment, and spent fuel pool cooling capabilities under the circumstances associated with loss of large areas of the plant due to explosions or fire …." Additionally, for each nuclear site, the NRC conducts graded exercises on physical threats consisting of mock attacks.

Nuclear power plants also have implemented design and process barriers to defend against cyber-security events in accordance with NERC Critical Infrastructure Protection (CIP) standards, as well as the NRC's Cyber Security rule, 10CFR73.54: "Protection of digital computer and communication systems and networks."

For system recovery, nuclear operators have detailed emergency operation procedures (EOPs), emergency preparedness (EPs), and severe accident management guidelines (SAMGs). Together, these documents provide guidance for safe plant shutdown, damage assessment, critical asset management, and spares. These procedures are all part of a site-detailed emergency plan that involves local, state, and federal authorities.

NERC Standard EOP-005-0—System Restoration Plans, requires that transmission operators (TOs) give high priority to restoration of off-site power to nuclear stations to support safe shutdown. Plant return to service is in accordance with a TO's restoration plan, required by NERC Standard EOP-005-0—System Restoration Plans. Typically nuclear sites have a lower priority for return to service due to longer startup requirements.

What Can Be Done Now?

The key issues regarding nuclear plant resiliency are in the areas of damage prevention and system recovery. For damage prevention, this includes safety system reliability, fuel designs, and emergency response. For system (plant) recovery, this includes fuel supply, water supply, and grid interconnection.

Damage Prevention: Critical to preventing damage from an accident is an accurate understanding of the possible threats. This is obtained through the use of tools to analyze and update the design basis threats such as earthquakes, tsunamis, and hurricanes. Similarly, advances in the reliability of emergency power systems (e.g., diesel generators and batteries) and efficient power usage during a prolonged loss of off-site power are also critical to preventing damage from accidents. New designs in fuel and core components can mitigate or lessen accident outcomes, and updates to emergency procedures can help operators respond to an event.

Fuel Supply: Although nuclear generating facilities are designed for worst case external and internal events, the fuel mining, enrichment, and fabrication facilities may not be as robust. Existing U.S. plants operate on an 18 or 24 month refueling cycle, and can obtain fuel from multiple vendors. Events that impact fuel processing facilities would not typically have an immediate plant impact, but could result in a plant shutdown to await fuel delivery from an alternate vendor.

Water Supply: Nuclear generating plants can be affected by droughts, dam breaks, and competition for water. Events that can impact the normal cooling supply (e.g., low river flows or high lake temperatures) have required plants to reduce power and could also prevent plant return to service following a shutdown. Cooling system designs that reduce reliance on limited water resources would allow plant recovery following such events.

Grid Interconnection: For system recovery, nuclear operators have detailed procedures on damage assessment, outage management, asset management, and spares. Recovering a nuclear unit quickly has a large economic impact on the utility, and nuclear operators are skilled at quickly returning a unit to service for expected events that result in a plant trip. Presently there are no detailed plans for returning nuclear plants to service for more severe events that impact the generation interconnection with the grid, such as storms that damage off-site power connection equipment (e.g., transmission lines, substation equipment). The existing transmission system operator (TSO) and nuclear plant operator strategies for grid emergencies focus on assuring safe shutdown conditions for nuclear power plants. Development of additional guidance on plant restoration would be beneficial in this area.

Tools Available Now

Assessment of Nuclear Power Plant Seismic Margin: Nuclear power plant owners and operators can assess a plant's ability to withstand an earthquake of greater magnitude than used as the basis for plant design and still safely shut down for at least 72 hours. This methodology uses a generic screening of systems and component seismic ruggedness and does not require probabilistic calculations [31].

Spent-Fuel Pool (SFP) Accident Characteristics: An EPRI study provides a useful compilation of data, analytical results, and tools that could support safety evaluations of SFPs in general. In turn, this information is a good starting point for any probabilistic risk assessment (PRA) related to spent-fuel pools [32].

Strategic Roadmap for Nuclear Power Plant Emergency Power: EPRI continues to be engaged in the area of nuclear plant emergency power and continues to research technologies and their application to maintain high levels of emergency power equipment reliability and availability. This research helps ensure that these critical systems appropriately evolve, perform, and are maintained to ensure their continued reliability. Identifying and addressing technical issues relating to emergency power systems is critical to overall nuclear plant safety and performance.

The emergency power focus area includes emergency AC and DC power. This includes emergency diesel generator systems, gas turbines, batteries, and uninterruptable power systems (UPS) and inverters. The roadmap provides a summary of completed, ongoing, and planned work associated with plant emergency power systems and components [33].

Severe Nuclear Accident Management: EPRI has developed extensive guidance for severe accident management at nuclear power plants. Guidance for responding to severe accidents was first developed as a result of insights gained from examining the 1979 accident at Three Mile Island Unit 2. To support effective guidance for managing severe accidents, EPRI assembled and described the attributes of phenomena that could be relevant for a core damage event and, based on those descriptions, identified potential actions that could provide effective response. The actions and the technical information that supported the definitions served as the basis for SAMGs put into place at operating nuclear power plants. These guidelines were updated as a result of the March 2011 accident at the Fukushima Daiichi plant [34].

Where Can Innovation Be Employed?

For nuclear generation plants, opportunities to enhance resiliency include accident tolerant fuel design, off-site power reliability projects, and advanced water technologies.

Program on Technology Innovation: Coated Molybdenum-Alloy Cladding for Accident-Tolerant Fuel: EPRI has been investigating cladding materials such as molybdenum (Mo) alloys that may enhance tolerance to fuel and core damage under station blackout accidents. Such materials may eliminate or reduce fuel integrity concerns under design basis loss-of-coolant accident (LOCA) events and also provide margins for beyond design basis LOCA events. The combination of superior high-temperature mechanical properties and acceptable neutronic properties make Mo alloys a potential alternative for light water reactor (LWR) fuel cladding for enhancing tolerance to severe accidents and for use in systems that demand structural integrity [35].

Nuclear Off-site Power Reliability (NOPR) Roadmap: EPRI has launched a joint Nuclear Power Delivery and Utilization (PDU) project to improve off-site power reliability to nuclear sites. Off-site power is the preferred power supply to nuclear units during an accident in lieu of site emergency systems. Innovative technologies such as use of hydrophobic/iceophobic coatings for transmission components (e.g., insulators and bus work) are being evaluated to enhance system weather resistance. Coordination with the ongoing PDU Transmission Resiliency project is also part of the roadmap in order to develop guidelines for plant return to service following major events.

ENHANCING RESILIENCY: GENERATION

Advanced Water Technologies: Technologies have the potential to reduce water use at nuclear power plants, including various dry and hybrid cooling systems. For example, the TSC Hybrid Cooling System is a dry-heat-rejection technology. It places a natural convection-driven refrigerant loop between a shell-and-tube evaporator and an air-cooled condenser. It can be used in series, upstream of a conventional cooling tower, or possibly in lieu of a conventional cooling tower (see Figure 5) [30].

Transmission system equipment fails and causes power outages much less frequently than distribution equipment, but its failures affect many more customers, and outage costs can be much higher. This fact, combined with the high cost per mile or per piece of transmission equipment, has historically led to greater attention to transmission system reliability.

According to the Edison Electric Institute (EEI), there are now more than 200,000 miles of high-voltage transmission lines greater than 230 kV [36]. The U.S. DOE National Transmission Grid Study, 2002, reported 187,000 miles, according to the voltage levels shown in Table 1 [37].

Table 1. Transmission Line Miles [37]

Voltage (kV)	Miles
230 AC	85,048
345 AC	59,767
500 AC	32,870
765 AC	4,715
250-500 DC	3,307
Total Miles	**184,707**

In general, monitoring transmission assets is more cost-effective and beneficial than any other asset class [38]. Although transmission lines are a backbone of the grid, thousands of miles are unattended and not monitored in any way. Transmission lines have seasonal ratings that need to be considered by operations and planning. With respect to load, there is little if any real-time monitoring other than at substations for operators.

An estimated 58,000 substations in the United States reduce voltage between the bulk transmission system and the distribution feeder system, and serve as critical hubs in the control and protection of the electricity grid.[3]

What Can Be Done Now?

EPRI has established a transmission resiliency initiative to help utilities enhance the resiliency of their transmission and substation systems. Figure 6 shows the overall flow of activities and corresponding research tasks involved in the research effort. The process begins with characterization of the various threats, which include physical attacks, GMDs, severe weather, and EMP/IEMI attacks.

One important aspect of threat characterization is the potential likelihood and severity of various magnitudes of threats. This process is followed by assessment of component vulnerability, as a function of the severity of each threat. The next step is to assess the potential impacts of the various threats, given the component vulnerability and the likelihood. These can include customer impacts (e.g., number of customers interrupted and outage duration), utility impacts (e.g., equipment damage and repair/restoration costs), public impacts (e.g., security and safety), and regulatory impacts (e.g., uninformed regulation). Next, the cost-effectiveness of mitigation options (countermeasures) is assessed. In some cases, where gaps exist, countermeasures may be developed. A framework for decision support is provided to determine which option, or collection of options, may be implemented.

After this detailed analysis process is completed, the next step is to conduct testing and trial implementation. Stakeholder feedback is solicited throughout these activities. The feedback loop involves assessing vulnerability and impacts of the hardened components and implemented recovery processes and technologies to assess the cost-effectiveness of these investments. The feedback loop can also be viewed as an opportunity to first assess individual threats and then assess multiple threats in a coordinated way. Results can then be communicated to stakeholders, and action plans set [39].

[3] *This amount was derived from FERC data that shows investor-owned utilities (IOUs) operate 40,619 substations at voltage levels ranging from just above 1 kV to 765 kV. Since IOUs represent roughly 70% of all U.S. customers, the number of existing substations (see Table 2) was thus calculated to be 58,027 (40,619/.7 = 58,027).*

ENHANCING RESILIENCY: TRANSMISSION

Actions can be taken in a number of areas to enhance the transmission system's resiliency:

- Targeted transmission undergrounding
- Vegetation management
- Enhancing relay resiliency
- Severe weather resiliency
- Protection from flooding
- Protection from tsunamis
- Protection from seismic events
- Protection from EMPs
- Protection from physical attacks
- Protection from cyber attacks
- Operating strategies for protection from GMDs
- Backup power generation
- Stored and shared spare components
- Systems restoration

Targeted Transmission Undergrounding: Burying transmission lines removes them from harm's way of trees and most lightning strikes. However, the cost can be prohibitive—several times more than overhead transmission—and does not ensure 100% reliability. For example, severe storms also may bring flooding, and many underground devices are not designed to operate under water. For underground facilities, once the water recedes, troubleshooting and restoration may take longer than with overhead transmission systems. An economical and effective hardening strategy may be to bury selected portions of the system.

Vegetation Management: Utility compliance with NERC Standard FAC-003 on Transmission Vegetation Management is increasing the resiliency of transmission systems during extreme weather events. Utilities are clearing to the edge of their easements and/or their property boundaries to reduce the chance of an outage from trees falling into the wire security zone. Many utilities are also working with owners of property adjacent to easements to remove additional trees.

Integrated vegetation management promotes a diverse community of low-growing plants that suppress tall growing species. This achieves financial benefits and enhances ecological services while improving resiliency. The process integrates basic knowledge, stakeholder perspectives, a toolbox of treatments, applied knowledge, and experience. Because tall trees can still emerge from the lower-growing

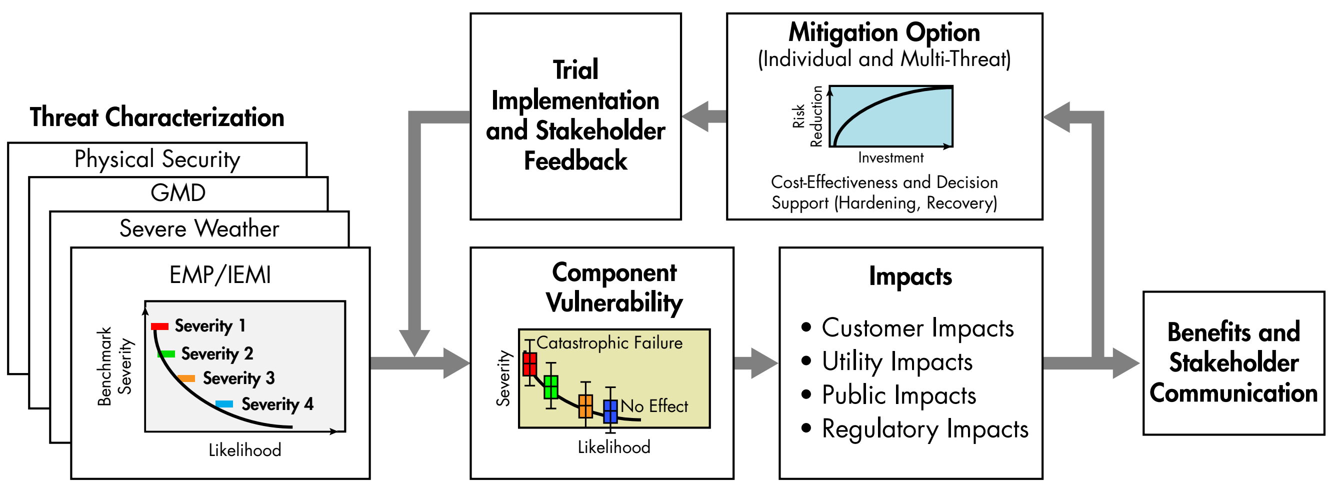

Figure 6. Overview of EPRI Transmission Resiliency Research Activities [39]

species, right-of-way inspection technologies are needed, and EPRI is developing and evaluating several of these.

Enhancing Relay Resiliency: Actions to enhance resiliency related to relays include replacing electromagnetic relays with microprocessor-based relays; standardizing relay protection schemes; incorporating an alternative setting group with microprocessor-based relays; and developing a means to automate the switchover to the alternate storm settings group.

Severe Weather Resiliency: EPRI has prepared a guidebook to help utilities identify data sources for input to a preliminary high-impact, low-frequency assessment methodology that EPRI documented in 2014, utility internal methodologies, or some combination [40, 41]. The ultimate goal is to help utilities assess the optimal aggregate set of mitigation technologies to increase resiliency to severe weather. The guidebook directs readers to information sources to develop input data for their chosen methodology, including projected severe weather costs, probability of their occurrence, and mitigation options and costs. Severe weather types covered in the report include hurricanes, severe ice storms, tornadoes/derechos, and severe persistent flooding. The guidebook does not document case studies with actual data, but instead directs readers where to locate the needed data.

Protection from Flooding: Protecting transmission assets from flooding can be accomplished in various ways, including reinforced towers, substations, and underground systems and equipment. Options include raising existing—and installing new—flood walls; adding to spare parts inventory; incorporating submergible transformers, switches, and pumps; sealing manhole covers and conduit/cable penetrations; shrink-wrapping cabinets; storing emergency supplies remotely; using weatherproof enclosures; and establishing a corporate emergency response center.

Protection from Tsunamis: Actions to protect power plants and substations from tsunamis can include belts of trees and mangroves to provide barriers to waves, locating cooling water intake structures offshore, using design principles that inhibit the scouring or erosion created by waves, and preventing damage from debris.

Protection from Seismic Events: Utilities use the Institute of Electrical and Electronic Engineers (IEEE) Standard 694 (Recommended Practice for Seismic Design of Substations) to qualify substation equipment for seismic movements. Information is unavailable for dynamic response that may be used to better analyze equipment and permit its evaluation in case of limited configuration changes, such as insulator substitution. EPRI is launching a project to assess seismic issues and to address the present standard's deficiencies, especially those related to details left unspecified.

Protection from EMPs: Protecting the entire power grid system or even all high-value components from EMP/HEMP attacks is impractical because of the prohibitive costs, time, and effort in proportion to the likelihood of an EMP/HEMP-enhanced nuclear strike. Three approaches are possible in addressing this threat: shielding, standby and backup equipment, and stored and shared components.

In one example of shielding, the U.S. military, under the MIL-STD-188-125 standard, deploys technology for protecting fixed and mobile installations from EMP effects. Ground-based shielding detailed in the standard refers to "subscriber terminals and data processing centers, transmitting and receiving communications stations and relay facilities for both new construction and retrofit of existing facilities." The standard calls for EMP mitigation for all military command, control, communications, and computer systems, including the electromagnetic energy point of entry to these systems. Although extremely costly, adhering to this standard would greatly enhance protection of the North American power grid's SCADA operations, including smart grid components and systems [42].

EPRI has recently characterized electromagnetic threats, including EMP and IEMI, and described how its planned research in this area fits together [43, 44].

Protection from Physical Attacks: The following are key parts of an effective physical security approach:

- **Physical Barriers Around Security Perimeters:** Physical barriers can prevent access to substations by people and ground vehicles, and can enclose equipment housings and racks (see Figure 7).

Figure 7. Physical Barriers, which are Commonly Installed in Substations for Safety, Can Provide Some Level of Security.

Such barriers are commonly constructed in substations for standard safety considerations.

- **Remote Monitoring:** Remote monitoring detects intruders and monitors equipment. Remote monitoring and surveillance of perimeters and access points detects approaching intruders and those attempting entry. Motion sensors and thermography are often used for remote monitoring. Operators can potentially also utilize visualization tools to assess power system health, and security can be evaluated by monitoring asset health sensors of critical equipment. These can include infrared sensors, vibration sensors, level and pressure gauges, and flow gauges.
- **Vulnerability Assessment:** Vulnerability assessment of critical components is needed and can include ballistic vulnerability. This can be accomplished by coordinating a lessons-learned database on material vulnerability based on real-life examples. Controlled testing of components such as transformers can complement this work.
- **Recovery and Response:** Effective response after a physical attack is vital and should include the following:
  - Consider the safety of staff responding to the attack. Considerations need to be different than when responding to a standard equipment failure, given the potential for a follow-up threat (e.g., gunfire or blast).
  - Environmental impacts may differ from those of a normal equipment failure, due to both the failure mode and magnitude of the event or spill.
  - The spares and replacement plan may need to be adjusted, because they are usually based on the historical failure rate of equipment. In a physical attack, the potential is greater for damage to multiple assets, requiring sufficient spares and an approach

to address this aspect specifically.

– Address operational recovery and response. To enhance survivability, utilities could run a series of physical breach scenarios and develop an operational framework for operating a degraded grid, for example, by diverting power around disabled equipment to load centers and increasing the output of local generation.

Protection from Cyber Attacks: The industry's extensive cyber security effort includes EPRI, the U.S. DOE, and NERC. Prominent EPRI efforts so far have focused on securing wireless substations; extending the application of the Intercontrol Center Communications Protocol (ICCP, aka Telecontrol Application Service Element 2, TASE.2); and identifying home area network (HAN) and advanced metering cyber security requirements.

NERC hosted GridEx II 2013, a two-phase cyber security scenario exercise involving thousands of utility workers, business executives, National Guard officers, FBI anti-terrorism experts, and government officials from the United States, Canada, and Mexico. The drill simulated physical attacks and cyber attacks that could take down large sections of the power grid in order to:

- Validate the electricity industry's readiness to respond to a security incident, incorporating lessons learned from GridEx 2011.
- Assess, test, and validate command, control, and communication plans and tools for NERC and its stakeholders.
- Identify potential improvements in physical and cyber security plans, programs, and responder skills.
- Evaluate senior leadership policy doctrine and triggers in response to major grid reliability issues.

NERC hosted GridEx III on November 18-19, 2015. Independent of GridEx II 2013, individual utilities could reduce their company's risk related to cyber security breaches through this four-step process: 1) develop failure scenarios, 2) assess their cyber resiliency, 3) conduct penetration testing on their systems, and 4) refine their cyber resiliency plan.

Operating Strategies for Protection from GMDs: Operating strategies to mitigate GMD effects focus on actions derived from operations planning, real-time operations, and long-term stakeholders. NERC released Advisory Actions to address each of these [45]. In 2013, the NERC GMD Task Force produced operating procedure templates incorporating best practices from throughout the industry in monitoring and effects mitigation. These provide a starting point for utilities in creating or updating their operating procedures. The task force also is leading efforts to examine system operator training materials and recommend improvements to increase operators' knowledge [46].

Backup Power Generation: The design and manufacture of storable and easily transportable backup power generators is required for restoring damaged facilities. Government and power industry stakeholders could warehouse the hardware in hardened, geographically-dispersed locations for rapid transport to restore power more quickly to any section of the affected grid [47].

Stored and Shared Spare Components: Another element essential to recovery is available components that can be shared quickly among geographically-dispersed stakeholders. For various components and systems, the industry can assess vulnerability to high-impact events and determine the inventory necessary to provide backup components where needed. Transformers, generation equipment, SCADA systems, above-ground relays and controls, and other embedded processors are candidates for stockpiling. Three initiatives are addressing the need for spare components:

- NERC Spare Equipment Database (SED) will securely connect entities that need replacement transformers with those that have spares available in the event of simultaneous loss of multiple transformers [48].
- EEI Spare Transformer Equipment Program—The Edison Electric Institute's Spare Transformer Equipment Program (STEP Program) was launched in 2006 in response to the 9/11 terrorist attacks to manage resources in response to a terrorist attack. About 50 transmission providers participate, representing about 70% of the U.S. transmission grid [49]. Defined stakeholders could take greater responsibility for the inventory, research, and securing of hardened facilities for these parts depots, including a coordinated and clear command and distribution network for parts delivery and repair. Realizing this vision would require cost and feasibility studies, as well as research that identifies the most vulnerable components under different event scenarios. An important consideration (and complication) is that many components are now manufactured outside the United States.
- Recovery Transformer—A consortium of the U.S. Department of Homeland Security (DHS) Science & Technology Directorate (S&T), transformer manufacturing company ABB Inc., CenterPoint Energy Inc., and EPRI have developed a prototype transformer that could be deployed to replace a damaged or destroyed transformer in about a week instead of several months to prevent sustained power outages (see Figure 8). Known as a "recovery transformer," the prototype is being tested at a CenterPoint Energy substation. A large transmission substation transformer can be taken out of service by disasters such as

Figure 8. Recovery Transformer – (Photo Courtesy of DHS S&T)

earthquakes or tornadoes, geomagnetic disturbances, internal failure, or by terrorist acts. Efforts so far have demonstrated the effectiveness of modular transformer design and accessible substation design to enable rapid deployment, replacement, and recovery. Future research could extend this work to other transmission components.

System Restoration: Effective, rapid power system restoration is an important aspect of resiliency, involving complex decisions and controls. System operators in the control center, working with field crews, re-establish the generation and transmission systems, pick up loads and restore the services, and return the system to a normal operating condition. To prepare for restoring service, the following need to be considered [50]:

- Black-start capability that supports the ability to supply limited amounts of power to generators and other power-system equipment before they can be brought back online
- Line/cable charging strategies and other means of voltage and reactive power control
- Need to disable or adjust certain protective systems, such as those for under-voltage, under-frequency, and synchronization checks
- Restoration policies that include islanding requirements and monitoring of voltage, frequencies, and phase angles

EPRI is working on various research projects to enhance restoration:

- **Generic Restoration:** A decision support tool is needed to assist power grids in system restoration planning, operator training, and ultimately, in an online restoration environment. EPRI has developed the Generic Restoration Milestones (GRMs) and a comprehensive methodology for power system restoration based on these milestones. It is developing and demonstrating a prototype decision support tool for evaluating system restoration strategies, and investigating other issues related to restoration [51].
- **Optimal Black-start Capability:** The Optimal Black-start Capability (OBC) tool is used to evaluate black-start capability based on currently available black-start capable units and optimal locations and capacity levels for new black-start units. Its optimization capabilities can be used to reduce restoration time and increase system generation capability after new black-start units are installed at the optimized locations and amounts [52].

Where Can Innovation Be Employed?

On the transmission system, innovation can be employed to enhance resiliency in the following areas:

- Online monitoring of load tap changers
- Hydrophobic coatings
- Energy storage
- Vegetation inspection technologies
- Enhancing cyber security resiliency
- Enhancing physical security resiliency
- Protection from GMDs

Online Monitoring of Load Tap Changers: Development of online monitors can increase transformer resiliency with load tap changers. One of first problem indicators with a load tap changer is increased concentration of ethylene in oil. It usually indicates overheated oil and is often due to high resistance across load-bearing contacts caused by the accumulation of carbonaceous deposits (coking) between the contact surfaces. A corresponding drop in the acetylene concentration frequently precedes this, which may be due to the acetylene being consumed in the chemical formation of the coking deposits [53].

Hydrophobic Coatings: Hydrophobic coatings are being applied to various components in the transmission and distribution system (see Figure 9). By helping components shed precipitation, these coatings mitigate water damage on non-ceramic insulators and can facilitate ice removal. EPRI projects are assessing their performance, reliability, and application [54].

Energy Storage: Energy storage has the potential to transform the electric power infrastructure, enhancing resiliency by facilitating the integration of variable energy resources and improving the capacity factor or utilization of transmission, distribution, and conventional generation. If energy storage cost and performance is to enable wide-scale deployment, these innovations are needed in research, development, and demonstration:

- Basic research of new electrochemistries and their practical realization
- Detailed studies of the effects of higher penetration of renewable sources on grid operations and the retirement of a large percentage of traditional generation
- Demonstration projects of new storage technologies to technology readiness level 7-8 that expand the use of storage to enhance grid performance

Vegetation Inspection Technologies: Integrated vegetation management promotes diverse communities of low-growing plants that suppress growth of tall growing species. Because breakthrough of tall growing plants can still occur, right-of-way inspection technologies are also needed (see Figure 10). EPRI is developing and evaluating several inspection technologies.

Enhancing Cyber Security Resiliency: The EPRI Cyber Security and Privacy Program is examining several aspects of cyber resiliency, including how cyber incidents can impact the power system. As part of the U.S. Department of Energy's National Electric Sector Cybersecurity Organization Resource (NESCOR) program, failure scenarios were developed for key smart grid domains such as wide-area monitoring, protection and control, distribution grid management, and distributed energy resources. EPRI is using these scenarios in developing cyber security tabletop exercise scenarios, modeling the impact of cyber incidents

Figure 9. Hydrophobic Coatings

on electric system reliability, and developing a penetration testing framework for power delivery equipment and protocols [55].

Enhancing Physical Security Resiliency: EPRI has characterized the physical security threat, and characterized how its physical security research activities fit together [56, 57]. Technology opportunities to improve the physical security of substation and transmission line assets include:

- **Blast and Ballistic Protection of Substation Assets:** The University of Kentucky is developing blast and ballistic mitigation solutions for critical power transformers [58]. EPRI has summarized ballistic and blast testing for vulnerability assessment and mitigation by others and conducted preliminary ballistics testing at a major utility [59,60]. Further work is needed to identify, evaluate, and apply mitigation solutions.
- **Self-Healing Tanks and Radiators:** Research is needed to determine the feasibility of applying existing self-healing tank and radiator technology to transformers and circuit breakers. Needed evaluations include heat transfer impacts, oil condition impacts, and life expectancy.
- **Online Infrared Imaging:** To autonomously assess substation assets, EPRI has deployed four online infrared systems at utility sites to gain field experience and is developing algorithms for alarms based on the conditions observed. EPRI is working with Southern Company to deploy the system on a substation robot. Online infrared systems should be coupled with other sensors, such as acoustic and vibration monitors, and intelligence so that cameras can automatically identify threats.
- **3D Acoustic Ballistic Monitoring:** Commercial systems are in development and deployment that can identify and pinpoint the location of gunfire over a wide area (e.g., ShotSpotter and others) [61]. Research is needed to determine the feasibility of applying the available technology to substation security so that operators and first responders can verify gunfire and the source to assess damage effectively and to respond rapidly and safely.
- **Monitoring Vandalism of Overhead Transmission Lines:** EPRI has developed a suite of low-cost, low energy consumption, wireless transmission line sensors, one of which is being deployed to monitor conductor vibration (see Figure 11). Algorithms could

Figure 10. Transmission Inspection Technologies Identify Breakthrough of Tall Species in a Vegetation Management Program

be developed to identify bolt removal or sawing of steel structural members. The sensor could be modified to monitor acoustic and local electric field signals that would indicate individuals on or near the structure.

- **Application of Current and Emerging Online Monitoring Technologies:** Research is needed to determine whether existing online monitoring technologies and communications systems can be adapted and used to better monitor physical security. For example, if monitoring transformer oil level, an algorithm could alert operators to the simultaneous loss of oil in multiple transformers, triggering a security alarm, in contrast to a low oil signal in a single transformer, which would trigger an asset health alarm.

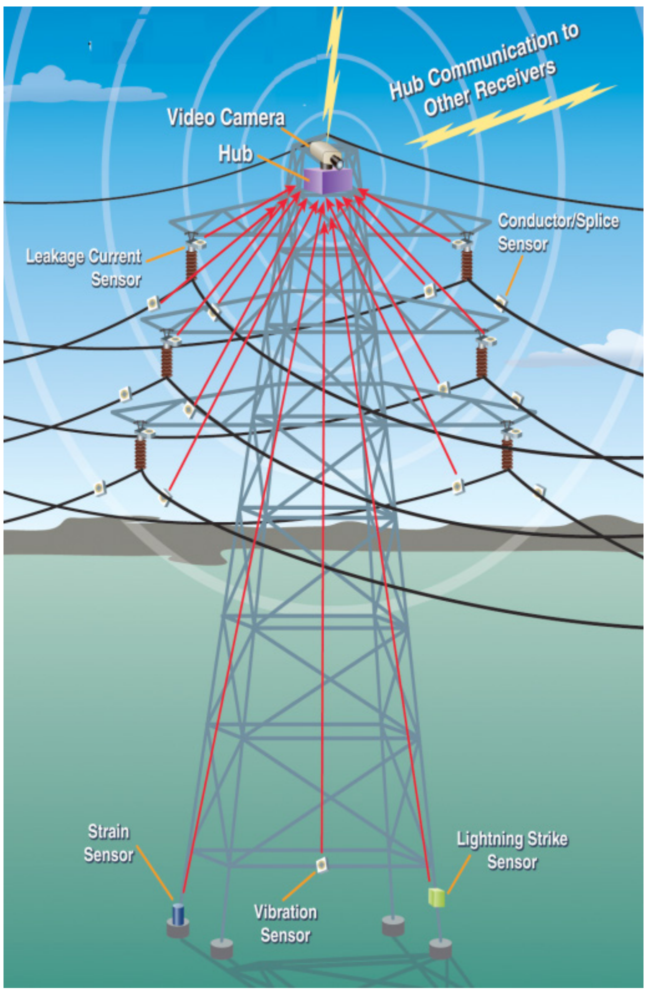

Figure 11. EPRI Transmission Line Wireless Sensor System

To begin a collaborative process of addressing physical security threats, EPRI and the North American Transmission Forum (NATF) in 2013 sponsored the Physical Security Summit, bringing together more than 90 representatives from utilities, regulatory, and government agencies to share information and insights [62].

Protection from GMDs: The NERC GMD Task Force work plan supports the industry's operators and planners in assessing and mitigating risks from geomagnetic disturbances. Supported by contributions from EPRI and various equipment manufacturers, software companies, and government and private researchers, the task force is developing open-source tools, models, and resources that will advance the capabilities utilities have for understanding risks from disturbances and developing strategies to address identified impacts [46].

Planners will soon have more open-source tools available to study GMD effects on their system. The task force is developing an application guide for calculating geomagnetically-induced currents (GIC) in the power system. The guide will provide a theoretical basis for GIC calculations necessary for planning studies and vulnerability assessments. Open-source analytical models for transformer var loss are being developed to support system power-flow studies. System planners will be able to draw upon the task force's Planning Study and Vulnerability Assessment guide to perform system studies and develop strategies to mitigate identified risks [46].

Looking ahead, NERC staff and task force leaders will help validate the results from the application of the tools and models, providing insights to enhance their use by system planners, and expand upon models with additional data. This could take advantage of others' studies to assess their systems' vulnerability to GMD, along with their monitoring and mitigation strategies. Comparing these results and data with results produced by the task force's study tools will support validation and improvements for updated guides, tools, and models. Additionally, several long-term studies of transformers' thermal and magnetic behavior will enhance the initial models [46].

In collaboration with NERC, the utility industry, and other stakeholders, EPRI is building on two decades of research in geomagnetic disturbances to develop the knowledge and tools for understanding, predicting, and mitigating their impacts on power systems. Figure 12 shows the activities and corresponding research.

The process first defines the GMD storm scenario, followed by various modeling and simulation activities. This is followed by storm forecasting and prediction (in associated projects with NOAA and NASA), as well as vulnerability assessment. (EPRI's focus is on developing tools.) Mitigation measures and devices can then be defined, followed by testing and evaluation in lab simulations and in the field. Utilities will benefit from integrating many of these into their risk management processes. Measurement of storm parameters, geomagnetic fields, geomagnetic-induced currents, transformer impacts, and power system impacts provide data that support these activities. An important result of this work is enhanced industry awareness of the threat, vulnerability, and mitigation opportunities, spanning power system planning, operations, asset fleet management, and risk management. A feedback loop includes improvement in mitigation measures, as well as forecasting and prediction methods.

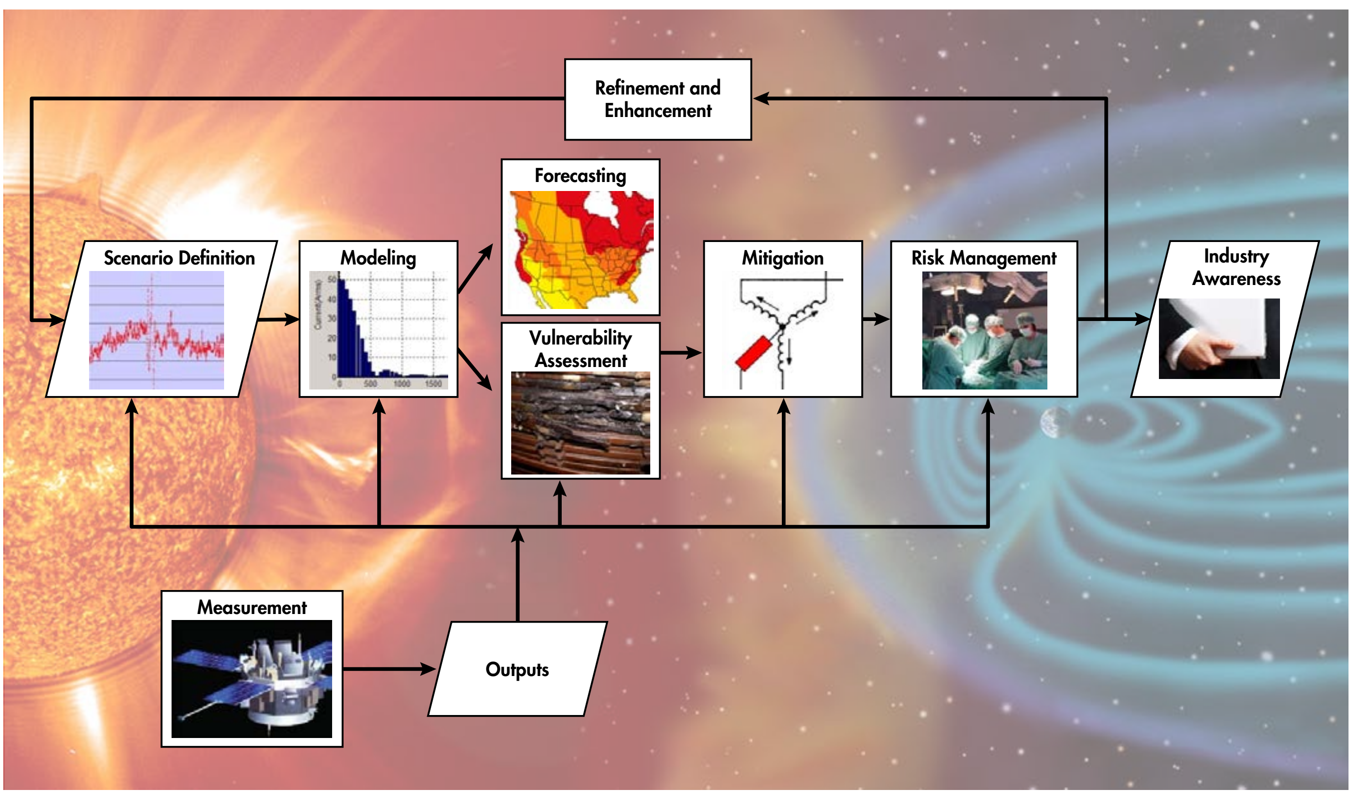

Figure 12. Overview of GMD Research Activities
(Photo sources: NOAA Space Weather Prediction Center; SOHO (ESA & NASA))

ENHANCING RESILIENCY: DISTRIBUTION

Relative to the transmission system, the distribution system's greater complexity, exposure, and geographic reach results in inherently greater vulnerability to disruption of any kind. Based on a reliability measure of average total duration of the interruptions experienced by a customer, more than 90% of the minutes lost by consumers annually are attributable to distribution events.

Hardening the distribution system to prevent damage will require changes in design standards, construction guidelines, maintenance routines, inspection procedures, and recovery practices, and will include the use of innovative technologies. A utility's approach to all of these will be determined specifically by its distribution system and work environment.

What Can Be Done Now?

Several actions can be taken to prevent damage to the distribution system, including vegetation management, targeted undergrounding, overhead distribution reinforcement, enhanced cyber security, load reduction, restoration management, and damage prediction and response.

Vegetation Management: Tree trimming is fundamental for mitigating local distribution outages (see Figure 13). Recently, utilities have effectively used the results of storm damage and subsequent restoration in assessing vegetation management and tree trimming programs. This application of storm data allows a critical review of trim specifications, damage, and clearance standards, while facilitating regulatory enforcement of tree trimming rights [63].

Targeted Undergrounding: Installing distribution lines underground protects them from trees, damage from vehicles, and most lightning strikes. However, the cost can be prohibitive—5 to 15 times more than that of overhead distribution—and does not ensure 100% reliability. For example, severe storms may also bring flooding, and many underground devices, such as network protectors, are not designed to operate underwater. For underground facilities, once the water recedes, troubleshooting and restoration may actually take longer than with overhead distribution systems. An economical option may be to bury selected portions of the system (see Figure 14). Such targeted undergrounding can be an effective hardening investment strategy. Understanding that restoration time is related to accessibility, it may be most cost-effective to use undergrounding for portions of a circuit that are harder to access. EPRI has initiated a project to evaluate targeted undergrounding and investment [64].

Figure 13. Utilities are using results from storm restoration in assessing their vegetation management programs

Reinforcing Overhead Distribution: Some of the most effective actions to enhance resiliency are relatively simple and straightforward, such as adding structural reinforcement to existing distribution lines. Examples include adding guy wires or using steel poles to increase the strength of the lines to withstand higher wind and snow loading. Some utilities now routinely make these improvements during system restoration. Another effective action is to reinforce lines leading to a population center. An example is to design two of four lines serving a population center to withstand higher winds [65].

Cyber Security: Utilities are increasingly susceptible to cyber security threats. No single, permanent technical or operational solution exists to prevent cyber attacks; a suite of technologies and tools is necessary to meet evolving threats. The threat to cyber security is constant and must be considered as a potential terrorist weapon in conjunction with physical attacks. Cyber security is a heightened concern in situations in which a distribution system is already damaged or compromised by storms.

Figure 14. Targeted Undergrounding

Utilities can take many steps to better prepare for and mitigate cyber attacks, including identifying attack scenarios and failure scenarios, using modeling techniques to assess the system's ability to withstand attacks, and developing a playbook for responding to attack. EPRI is developing guidelines and models that may be useful to the utility to prepare for future incidents [66].

Load Reduction: During outages, an established industry practice is to use load reduction programs to reduce demand on the system from customers that still have service. This may be necessary as distribution systems operate closer to their limits, during transmission outages, or when it's necessary to reconfigure distribution circuits. Although this may reduce demand by only 5-15%, it can be useful to aid recovery in some situations. Options include:

- Media appeals using conventional and social media
- Voluntary load-reduction programs
- Interruptible tariffs
- Demand-response programs such as direct load control, time-of-use rates, etc.
- Conservation voltage reduction through distribution automation

Restoration Management: Utility restoration management practices include procedures and systems to shift from centralized to decentralized restoration management. These practices must be tailored to disruptions of different magnitudes and types, such as wind, flood, tsunami, earthquake, and attack.

Damage Prediction and Response: Current and next-generation weather prediction models can provide high-resolution predictions of wind speed, wind direction, rainfall, and other meteorological parameters

The Smart Grid

With its reliance on digital devices, the smart grid is more vulnerable to cyber or coordinated cyber-physical attacks than the conventional grid. NERC points out that the risk of such an attack "has become more acute over the past 15 years as digital communicating equipment has introduced cyber vulnerability to the system, and resource optimization trends have allowed some inherent physical redundancy within the system to be reduced" [14].

Yet the power system's resiliency will be greatly enhanced by implementing a smart grid, with its ability to monitor, protect, and automatically optimize the operation of its interconnected elements. These encompass central and distributed generators, the high-voltage network, the distribution system, industrial users and building automation systems, energy storage installations, and consumers with their thermostats, electric vehicles, appliances, and other household devices.

The definition of the smart grid builds on the work done in EPRI's Smart Grid Resource Center (IntelliGrid Program), the DOE Smart Grid Implementation Strategy team (previously the Modern Grid Initiative, MGI), and the GridWise Architectural Council (GWAC) [68, 69, 70]. Among MGI's seven defining smart grid attributes, one is its ability to operate resiliently against attack and natural disaster [71]. It resists attacks on both physical structures (including substations, poles transformers) and the cyber-structure (markets, systems, software, communications). Sensors, cameras, automated switches, and intelligence are built into the infrastructure to observe, then react and alert when threats are recognized within the system. The system incorporates self-healing technologies to resist and react to natural disasters. Constant monitoring and self-testing are conducted against the system to mitigate malware and hackers.

associated with outages. Laboratory and field studies of the mechanisms under which key electric infrastructures fail can also be conducted, particularly after large events such as hurricanes, winter storms, and severe local storms. Better understanding of failure mechanisms combined with improved weather predictions can result in decision-support tools equipping emergency operations managers to stage physical and human assets, prioritize key infrastructures for restoration, and reduce response time and cost.

Where Can Innovation Be Employed?

Enhancing distribution resiliency can be driven in part by innovation in pole and line design, dynamic circuit reconfiguration, rapid damage assessment (including airborne damage assessment) and crew deployment, field force data visualization, and prioritizing resiliency investments.

Pole and Line Design: Certain pole and line design configurations are less susceptible to damage from trees and falling limbs (see Figure 15). Although system hardening is the intuitive solution, significant interest is focused on better understanding how overhead systems fail and innovating technologies to minimize the restoration effort. Research is assessing overhead components and crossarms, pole treatment options, and the effect of third-party components (telephone, CATV, etc.) [67].

Distribution Aerial Structure of the Future: Research is also underway to develop advanced overhead distribution structures (Figure 15). It addresses engineering standards, innovative coatings, sensors, and a third-party girdle device. Testing and analysis will define options for modifying overhead distribution engineering standards to improve the resiliency in the face of severe weather. Advanced coatings with anti-icing and anti-contamination can reduce probability of failure, and specialized reflective coatings can facilitate damage assessment. Radio frequency sensors on distribution transformers, conductors, and structures can provide situational awareness on the state of the structure, whether the circuit is energized, and whether load is being served. A novel design for third-party attachments that pivots and does not perforate the pole will reduce failures.

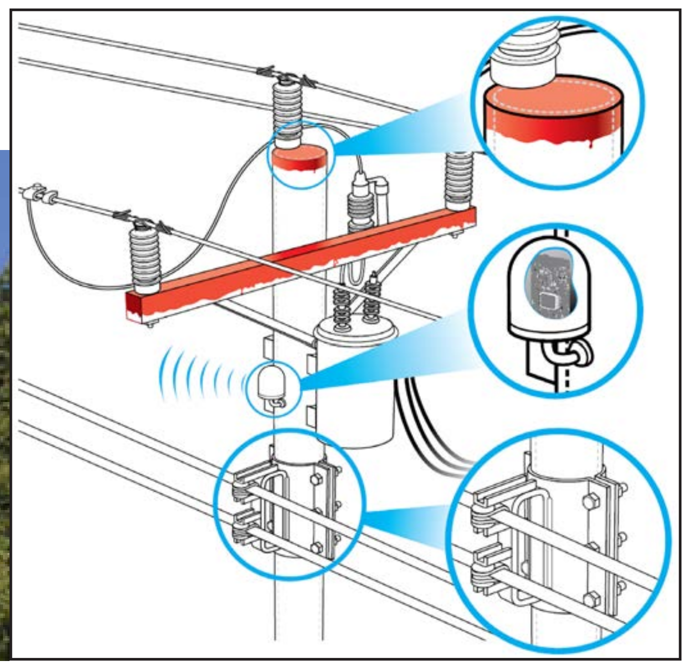

Figure 15. Pole and Line Design, and Distribution Aerial Structure of the Future

ENHANCING RESILIENCY: DISTRIBUTION

Dynamic Circuit Reconfiguration: Dynamic circuit reconfiguration is an operational design that offers the opportunity to combine advances in information technology, communications, and sensors with innovative restoration practices (see Figure 16). Many utilities have successfully deployed distribution automation with optimal network reconfiguration. These systems deploy automated distribution switches/sectionalizers/reclosers, sensors, communications, control systems, and data analytics to automatically reconfigure circuit connections to maximize service restoration. These systems limit the number of customers affected by faults on the feeder mains by directly tripping (reclosers) or sectionalizing (switches or sectionalizers). Once the fault is isolated to one section of the feeder, the systems enable service restoration to unaffected sections from adjacent feeders. Additional research is needed to ensure compatibility with new technologies (such as distributed photovoltaics, storage, microgrids, etc.) [67].

Damage Assessment and Crew Deployment: Proper resiliency planning must provide for rapid damage assessment and crew deployment. To respond and recover more quickly, the U.S. electric industry has developed effective mutual assistance programs, calling in crews from across a region to restore downed lines, poles, and transformers. The host utility provides logistical support in

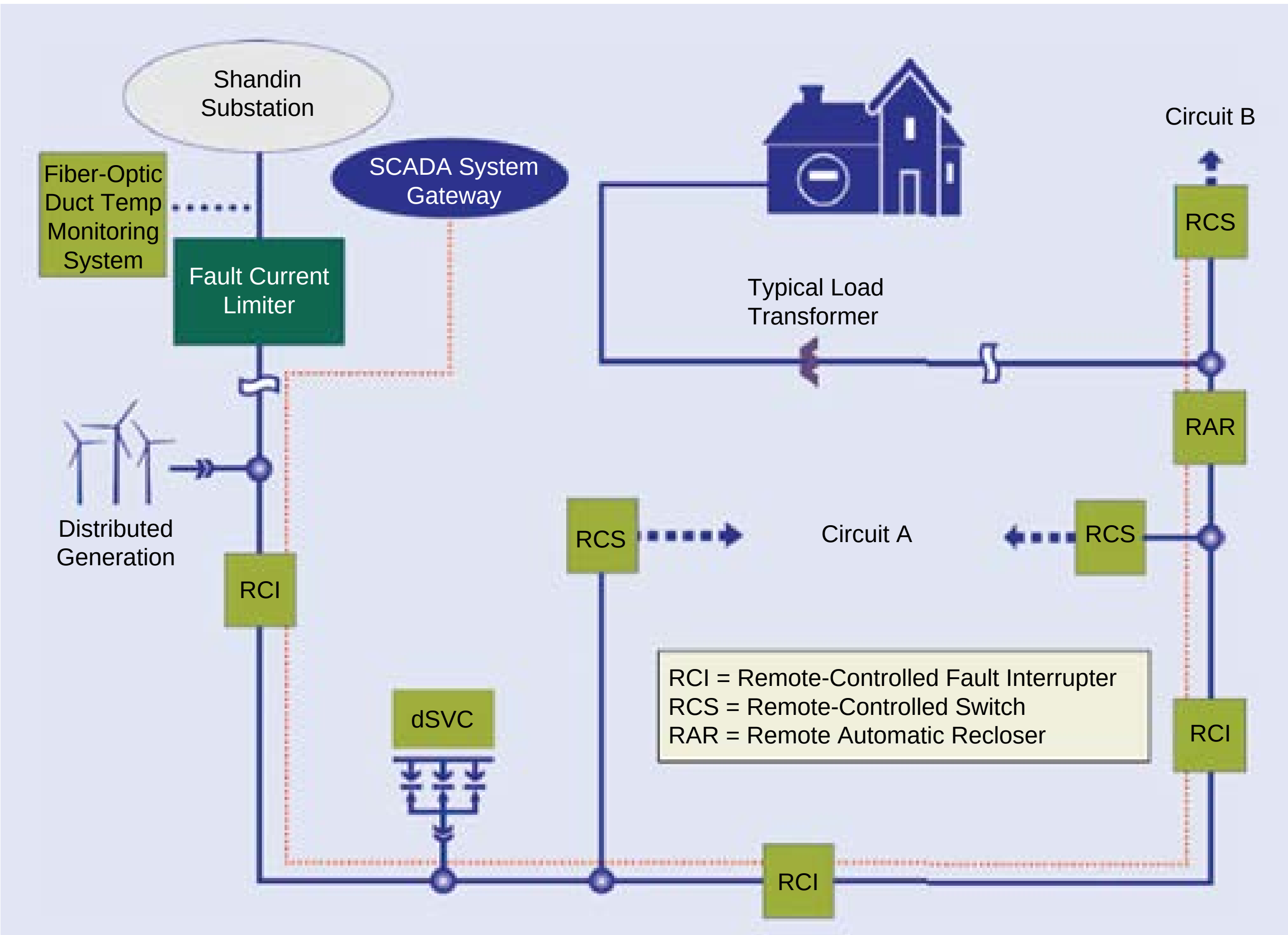

Figure 16. Circuit Auto-Reconfiguration (Graphic courtesy of Southern California Edison)

lodging, food, and fuel; provides the necessary spare parts; and dispatches crews.

Recovery requires prompt damage assessment, access to damaged assets, and readily available replacement components. During major storms affecting the northeastern United States in recent years, pinpointing affected areas was problematic, as was routing crews around blocked streets. Crews were sometimes idled because they could not reach affected areas.

Airborne Damage Assessment: EPRI completed preliminary tests showing that both small piloted aircraft and unmanned aerial vehicles (UAV) or drones equipped with high-resolution cameras, global positioning systems, and sensors can be effective in damage assessment (see Figure 17). UAVs equipped with EPRI's Airborne Damage Assessment Module (ADAM) can be small and light enough to be handled by a technician, and can quickly survey devastated areas that are difficult to reach by roads blocked with downed trees or other obstacles. Implementing ADAM requires integration with three key distribution operations systems: the OMS, the Geographical Information System (GIS), and the asset management system. The use of ADAM-equipped aircraft could substantially reduce costs and response time. It could also aid in assessing system conditions in normal situations. EPRI research will conduct further test flights and assess the accuracy of the sensors and cameras to determine if it is sufficient to assess equipment such as insulators [72].

Figure 17. Using UAVs for Damage Assessment

Field Force Data Visualization: EPRI is developing data visualization technology for utility engineering and field operations. Using computer tablets and smart phones, these systems would allow real-time data retrieval when a user points the mobile device at a distribution pole or at transmission and distribution conductors. For example, as a field technician aims the hand-held device camera at a pole structure, the screen displays the camera image, with the one-line circuit drawing overlaid, and all of the pertinent asset data available from the GIS (see Figure 18). Recovery crews can use such tools to retrieve detailed information on assets in the field, and to determine quickly which components should be dispatched for repair and replacement [73].

Prioritizing Resiliency Investments: EPRI is undertaking research to provide a decision support tool to identify investments optimal for hardening the distribution system against extreme weather and other unusual conditions. It will be necessary to understand outage causes, determine suitable options to mitigate or reduce outages, vet outage reduction options to define effectiveness, and build a decision support tool to prioritize hardening and storm response investments. This project focuses on the identification and analysis of various types of investments [74].

A related project focuses on prioritizing investments. EPRI is producing a primer based on a literature review of portfolio prioritization concepts, methods, and management. It will serve as a reference for utilities to develop consistent methods for improving distribution resiliency. The process integrates risk mitigation and asset management, equipping each utility to create a defined collection of options (portfolio) that produces the highest defined business value subject to a constrained budget.

Figure 18. Enabling the Field Workforce

ENHANCING RESILIENCY: CUSTOMER SYSTEMS

Of the more than 142 million U.S. electric power customers, 13% are commercial and industrial accounts. The customer base is expected to grow 16% over the next 20 years to more than 165 million (see Table 2). By then many appliances will be demand response-ready, increasing significantly the number of individual communication-connected end nodes. (Also, some may be served by distributed generation.) As described earlier, as customers increasingly rely on digital devices, their tolerance decreases for even brief outages, placing additional pressure on utilities to enhance resiliency.

What Can Be Done Now?

Given the relatively rapid evolution of customer expectations, now is an opportune time for utilities to reassess their role in maintaining power to essential services such as traffic lights, prisons, and hospitals, and in providing customers uninterrupted access to communications and modern conveniences.

Communicating with Customers: During outages, customers consistently cite the importance of knowing the estimated time of restoration. Accurate estimates are undermined when utilities lack accurate information as to which customers or groups of customers are without service.

Utilities are using the Internet and smart phones to enhance the targeting and speed of their communications. For example, Commonwealth Edison Company (ComEd) facilitates outage reporting and communication through its interactive outage map on ComEd.com that customers can use to determine the location and scope of outages and to obtain estimated times of restoration. ComEd also offers a mobile application for iPhone® and Android™ devices that enable customers to report outages and check restoration status [75].

Community Energy Storage: In the future, the electricity enterprise may benefit from cost-effective and reliable bulk energy storage to help balance and optimize bulk power supply and demand. Distribution-level energy storage offers potential advantages, such as enhanced reliability and support of self-sufficiency. EPRI is examining the functional requirements and storage technology capabilities for mitigating the effects of variable renewable generation, improving reliability, and facilitating service when the distribution system is damaged. Certain battery technologies may be approaching a stage of development at which they can be considered for distributed storage at a community or individual customer scale [76].

Where Can Innovation Be Employed?

For customers, opportunities to enhance resiliency include plug-in electric vehicles (PEVs) as a power source, photovoltaics (PV) systems as a backup, matching consumer load to PV capabilities, urgent services, and microgrids.

Table 2. U.S. Electricity Customers [85]

Number of Electric Customers	2007	2030	Load Growth
Residential	123,949,916	143,928,676	19,978,760
Commercial	17,377,219	20,178,151	2,800,932
Industrial	793,767	921,709	127,942
Transportation	750	750	0
Total	**142,121,652**	**165,029,286**	**22,907,634**

ENHANCING RESILIENCY: CUSTOMER SYSTEMS

Using PEVs as a Power Source: Both all-electric and hybrid PEVs could supply energy to a home during an outage (see Figure 19). Hybrid electric vehicles also could operate as a gasoline-fueled generator to provide standby power. Automakers are interested in the concept, but the technologies require further development.

Nissan Motor Co., Ltd. recently unveiled a system that enables the Nissan Leaf to connect with a residential distribution panel to supply residences with electricity from its lithium-ion batteries. The batteries can provide up to 24 kWh of electricity, which is sufficient to power a household's critical needs for up to two days [77].

Using PV Systems as a Backup: Increasingly, consumers are installing rooftop PV systems to augment grid-supplied electricity. Usually limited by roof area and sized to meet an economically viable portion of the building's electrical needs, these systems cannot supply 100% of a residence's typical demand, nor do the systems, as currently configured, allow for operation as independent microgrids to supply part of a residence's needs. EPRI assessments have identified inverter and control designs that could convert PV systems into self-sufficiency technologies, but few inverter manufacturers have stepped forward to serve this need [78].

Figure 19. EV Power Source (Courtesy: Nissan) [77]

In 2011, two DOE projects demonstrated inverter products (Princeton Power and Petra Solar) that can operate while tied to the grid or islanded. Other companies report development of similar products. With a proper transfer switch (perhaps controlled by the utility), such products could provide backup power to residences or a community during an outage [79].

Matching Consumer Load to PV Capabilities: Existing PV array controls cannot match the electrical demand of a residence without the presence of grid supply or local storage. Companies are developing residential circuit breaker panels that allow the control of individual circuits and appliances. Control devices could be developed to weave these breaker panels into the PV system, so that when grid power is lost, load is automatically curtailed to balance supply and load for the residential microgrid. These systems also could manage the ramps that occur as the sun rises and sets, or as clouds block sunlight.

Urgent Services: An opportunity exists to identify innovative technologies that can provide limited services or urgent services to critical aspects of community infrastructure. Only a few of these technologies have been identified, and fewer still have been researched. EPRI proposes research to address this, including programs to encourage (or provide) citizens cell phone solar chargers during long outages, the use of internal combustion engines to energize cell phone chargers, flashlight battery chargers, and critical medical devices; and self-sufficient traffic light systems with LEDs and solar PV backup.

Technologies described in this section are only a few of those available or that have the potential to be developed, demonstrated, and assessed. EPRI is initiating a collaborative project to identify and assess potential survivability solutions.

ENHANCING RESILIENCY: CUSTOMER SYSTEMS

The preliminary scope includes:

- Identify areas to improve survivability through urgent services.
- Scan and identify available technologies that can improve customer survivability.
- Screen the cost/benefit/performance, application, and maturity of these technologies.
- Create a knowledge base of what consumers can do now and what requires additional R&D to accelerate technologies' development and deployment.

Microgrids: A system comprising sub-units is geared to survivability, and the use of distributed generators could make the power system more resilient to severe weather or even terrorist attack [80]. Such a system could configure microgrids with distributed generation, electric and thermal energy storage, and an array of energy management and control systems. To reconfigure the power system for microgrids and survivability, and to prepare for changes in consumer demand and related technology, utilities need to assess the barriers and incompatibilities associated with integrating distributed resources such as local storage, demand response, distributed generation, and renewable resources [81].

To enhance resiliency, microgrids can be configured to operate in tandem with the bulk supply system during normal conditions, but disconnect and operate as independent islands in the event of a bulk supply failure or emergency [82]. In such configurations, the generators must all work together to control voltage, frequency, VARs, and other parameters, and do so in an environment in which the microgrid may periodically reconfigure by attaching itself to adjacent microgrids or breaking apart in smaller microgrids. This requires the highest level of communication among generation devices and adaptive grid command and control that can shift from one controller to the next as the system changes state. The generator protection schemes and operating set-points will have to adapt each time that the system changes state. This approach needs considerable research. Such systems could be augmented by customer-installed energy storage.

COST/BENEFIT ANALYSIS FOR RESILIENCY

Despite growing concern over the critical need for enhanced resiliency in the electric power sector, there is no standardized framework for assessing resiliency levels or evaluating potential options for improvement. While high-impact, low-frequency events are not preventable, the goal of resiliency—damage prevention, recovery, and survivability—is to limit associated costs. A flexible framework for cost-benefit analysis can help evaluate and prioritize investments to improve power system resiliency, and to weigh their value relative to other uses of scarce capital.

Analysis Considerations and Complexities

EPRI has developed a general framework for such analyses to inform utility grid investments [83]. In addition to the typical challenges related to infrastructure investment decisions, there are important distinctions when considering resiliency. Resiliency introduces new complexities due to emerging risks in a changing natural, social, and economic environment that are described below.

Resiliency addresses high-impact events, the consequences of which can be geographically and temporally widespread (e.g., potentially affecting a state or region, and lasting days or weeks), while more conventional investments to address reliability tend to be more common, local, and smaller in scale and scope. Reliability investments are typically evaluated using an estimated lost load value based on conventional survey-based methods. However, these valuation estimates may not be applicable to extended or widespread service interruptions, so a different method is needed for estimating the cost of extreme event outages.

Long-term investment in resiliency must also consider the power system's evolution as new technologies emerge. A number of end-states could result, each with capabilities beyond today's grid and with different emphasis on resiliency and quality metrics. For example, today's power systems aim to provide electricity service at constant voltage and frequency. Modern loads, driven by power electronics, are often less sensitive to supply variations, which may allow partial relaxation in power-quality related investment. In another example (not allowed by present standards), DER coupled with automated distribution networks may allow portions of the power system to island into microgrids in a disaster. Microgrids could sustain service to those affected by the grid outage, then resume interconnection when the larger power system is restored.

A central characteristic of extreme events is the fact that their impacts are uncertain and incompletely understood. In conventional cost-benefit analysis, prospective investments can be evaluated by comparing the costs and benefits expressed in present-value currency terms, which make comparisons straightforward. Resiliency investments are considered to avert the consequences of events characterized by low probability, uncertain timing, and high severity (while the costs are certain and large). If costs or benefits are not known with certainty, then the analysis must account for this from an expected risk perspective. Risk is traditionally defined as a function of the hazard (i.e., probability) and the consequence. Consequence can be further described as a function of exposure and vulnerability. One conceptual framework for risk from extreme events is depicted in Figure 20 from the Intergovernmental Panel on Climate Change (IPCC).

The scale and risk characteristics of the various high-impact, low-frequency risks described in the beginning of this paper can be very challenging to analyze. Moreover, there is no unifying perspective or framework for cost-benefit analysis of resiliency efforts, though there is much interest in advancing the state of the art.[4]

[4] *For example, the Department of Energy (DOE) formally established the Partnership for Energy Sector Climate Resilience in April 2015, an agreement with 18 electric utilities to develop and pursue strategies to reduce climate and weather-related vulnerabilities. See http://energy.gov/epsa/partnership-energy-sector-climate-resilience*

COST/BENEFIT ANALYSIS FOR RESILIENCY

Despite growing concern over the critical need for enhanced resiliency, there is no standardized framework for assessing resiliency levels or evaluating investment options. In the absence of more appropriate metrics, many power companies are estimating the value of lost load (VOLL) with the Interruption Cost Estimate (ICE) calculator—a tool used to estimate reliability planning benefits. However, EPRI research has demonstrated that this is an incomplete metric for the broader range of objectives ranging from power quality to resiliency. Furthermore, the existing survey base is limited in terms of outage duration (only surveys outages up to 16 hours), regional coverage (omits Northeast United States), and is focused on everyday reliability (neglects key characteristics of extreme events).

The landscape of resiliency efforts and analytical frameworks is diverse and lacks a unifying perspective. In addition to the typical challenges related to infrastructure investment decisions, climate resiliency presents new complexities and emerging risks in a changing natural, social, and economic environment with uncertain and incompletely understood impacts. Some companies may be required by regulators or agencies to pursue resiliency, while others may be considering proactive measures. Research suggests that in both cases, companies are struggling to determine how much resiliency to pursue and how these measures can be justified in economic terms for approval or cost recovery.

The topic of resiliency is timely and presents a worthwhile research opportunity to inform the electricity industry on key issues and approaches for evaluating resiliency investments.

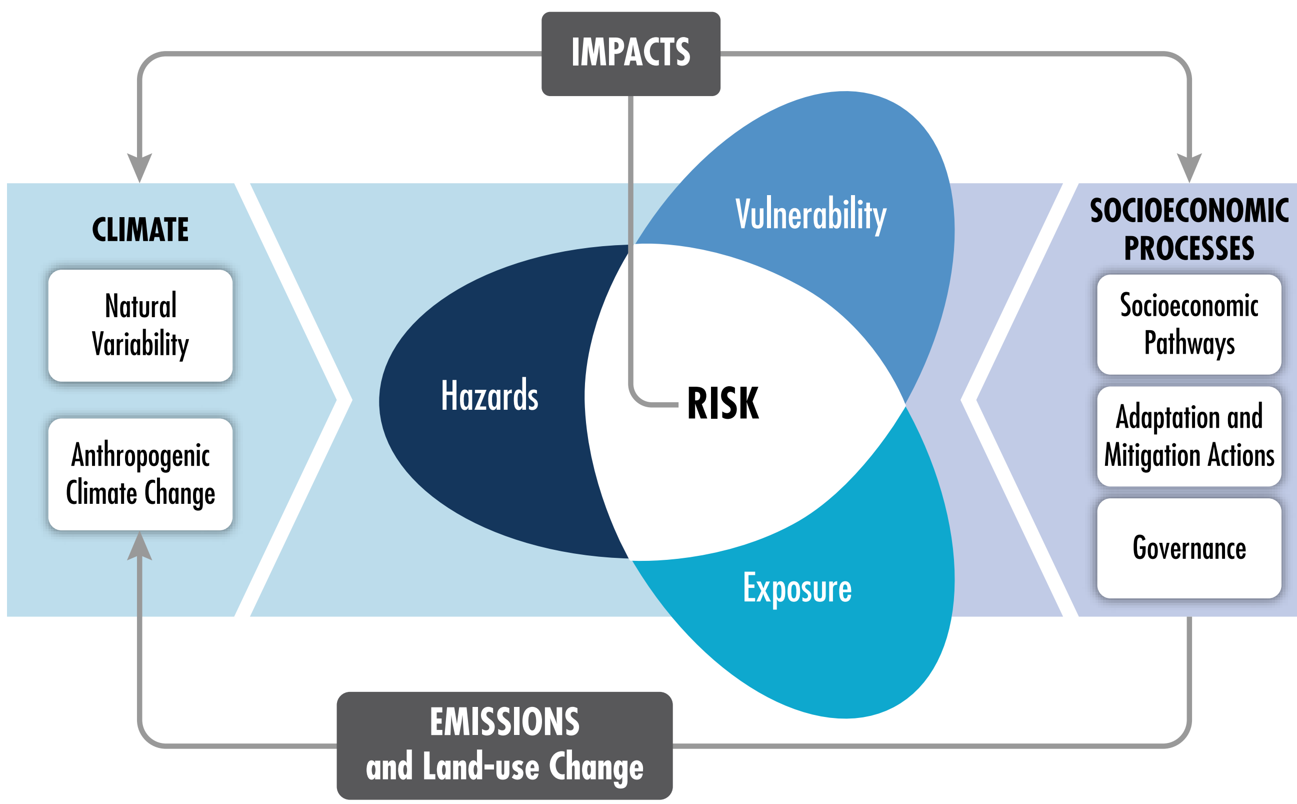

Figure 20. One conceptual framework for risk from extreme events from the Intergovernmental Panel on Climate Change (IPCC) [84]

CONCLUSION

In examining the electricity sector and trends related to fuel prices, load growth, energy policy, and the penetration of distributed generation and demand response, EPRI and its members have determined that the power system needs to be more resilient, flexible, and connected [1]. Recent extreme events and important trends reveal the central role of electricity in supporting critical infrastructure and society, and demonstrate that, despite best efforts and long-standing reliability, portions of the power system can be vulnerable to failure. The development and deployment of innovative technologies, frameworks, and strategies constitute an important step toward a more resilient power system in the face of a changing natural, social, and economic environment with uncertain and incompletely understood impacts. This paper lays the foundation for a more comprehensive research roadmap to increase power system resiliency. The next step is to identify research gaps, and work with electric utilities, fuel suppliers, government agencies and non-governmental organizations, world-wide research entities, universities, technology providers, and other stakeholders to assemble a roadmap and action plan to accelerate science and technology.

ACRONYMS

AC	alternating current
ADAM module	automated damage assessment
AMI	advanced metering infrastructure
BWR	boiling water reactor
CBA	cost/benefit analysis
CIP	Critical Infrastructure Protection
CO	carbon monoxide
CO2	carbon dioxide
ComEd	Commonwealth Edison Company
CT	combustion turbine
DC	direct current
DER	distributed energy resources
DHS	U.S. Department of Homeland Security
DOE	U.S. Department of Energy
DR	demand response
DTCR	dynamic thermal circuit rating
EEI	Edison Electric Institute
EIA	Energy Information Administration
EM	electromagnetic
EMP	electromagnetic pulse
EOP	emergency operating procedures
EPRI	Electric Power Research Institute
EV	electric vehicle
FEMA Agency	Federal Emergency Management
FERC Commission	Federal Energy Regulatory
GDP	gross domestic product
GHG	greenhouse gasses
GIC	geomagnetic induced current
GIS	geographic information system
GMD	geomagnetic disturbance
GRM	generic restoration milestone
GW	gigawatt
GWAC	GridWise Architectural Council
HAN	home area network
HAP	hazardous air pollutant
HCLPF of failure	high confidence of a low probability
HEMP	high altitude electromagnetic pulse
I&C	instrumentation and control
ICCP Protocol	Inter Control Center Communication
ICE	internal combustion engine
ICE	Interruption Cost Estimate
IEEE Engineers	Institute of Electrical and Electronics
IEMI interference	intentional electromagnetic
IOU	investor-owned utility
IPCC Change	Intergovernmental Panel on Climate
ISO	independent system operator
IT	information technology
kW	kilowatt
LOCA	loss of coolant accident
LED	light emitting diode
LEN	local energy network
LTC	load tap changer
MGI	Modern Grid Initiative
Mo	Molybdenum
MW	megawatt
NASA Administration	National Aeronautics and Space

ACRONYMS

NERC North American Electric Reliability Corporation

NESCOR National Electric Sector Cybersecurity Organization Resource

NETL National Energy Technology Laboratory

NOX nitrogen oxides

NOAA National Oceanic and Atmospheric Administration

NRC Nuclear Regulatory Commission

OBC optimal black-start capability

OMS outage management system

PEV plug-in electric vehicle

PHEV plug-in hybrid electric vehicle

PRA probabilistic risk assessment

PV photovoltaics

R&D research and development

RTO regional transmission organization

S&T Science and Technology

SAMG severe accident management guidelines

SCADA supervisory control and data acquisition

SiC silicon carbide

SED spare equipment database

SOX sulfur oxides

SSE safe shutdown earthquake

STEP spare transformer equipment program

T&D transmission and distribution

TASE Telecontrol Application Service Element

TRL technology readiness level

TSC thermosyphon cooler

UAV unmanned aerial vehicle

UPS uninterruptible power supply

VOLL value of lost load

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