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Article

Enhancing Power Grid Resilience: Evaluating Strategic Tradeoffs Using a Combined Qualitative and Quantitative Approach

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Abstract

As the reliability of electric power becomes increasingly vital to modern American life, strengthening the resilience of the power grid has taken on greater importance. With growing threats from climate change and ongoing physical and cyberattacks, the need to bolster system resilience is expected to intensify in the future. Despite the attention the topic receives, there is a lack of in-depth, data-driven analysis evaluating how effective and economically viable different resilience strategies are. This study uses a mixed-methods approach to examine and evaluate various strategies aimed at improving power system resilience, supporting more informed planning as the grid continues to evolve. Chapter 2 offers a review of resilience measures found in existing literature, noting that the available research often lacks consistency, especially in analyzing costs and performance. By compiling a detailed list of resilience options and summarizing current knowledge on their financial and operational impacts, this chapter contributes a more structured foundation to the field.

Keywords: power grid; power outages; tools for energy model optimization and analysis; FEMA

Introduction

Most disruptions in electric power service are limited in scope and duration. However, large electric power outages of long duration (LLD-outages), which are defined as “blackouts that extend over multiple service areas or states and last several days or longer,” are possible and do occur (National Academies [NASEM], 2017). When LLD-outages occur, they are typically caused by natural disasters including hurricanes, ice storms, floods, wildfires, and earthquakes. However cyber and physical sabotage, operator error and extreme temperatures can also cause cascading outages on the system. The cost of such outages can be great - vulnerable people die; food spoils; water, sewage or energy services fail; pipes freeze; economic output diminishes; and emergency services struggle but such events have historically been rare.

However, as the threat of LLD-outages increases due in part to the effects of climate change, aging infrastructure, and cyber-physical attacks, utilities should devote more attention to planning for extreme outage events. How to make the power grid more resilient is something utilities and policymakers alike are grappling with, but so far, there is little conclusive evidence on whether current strategies are effective, what other advancements and protective measures are needed, and what outage mitigation efforts are worth the investment.

Part of the challenge when investing in resilience is that the concept itself encompasses multiple attributes, fulfilling each of which requires a different set of strategies. Some of these strategies look to reduce the probability of outages occurring in the first place, others aim to shorten restoration time, while others still provide contingency power where needed. Add to this the different social and physical environments in which American utilities operate (different customer socio-economic profiles, institutional arrangements, topography, vegetation, and soil characteristics, among others) and the fact that the performance of resilience strategies can vary under different outage scenarios means that comparing the cost-effectiveness of strategies is difficult¹. Utilities use a range of metrics

to evaluate the reliability of their system, but there are currently no agreed upon grid resilience metrics that enable cross-utility comparisons. Second, given the wide variety and use cases of grid resilience options, current grid resilience research tends to be focused on specific locations and is often undertaken in reaction to specific outage events. Therefore, when utilities and governments explore how to make their grid more resilient, the decision process is somewhat ad hoc and anchored on recent large outage events². Because there are few data to reference when making these decisions, decision-makers may rely on the same, small set of studies that employ assumptions that are not always applicable or appropriate. Resilience investment planning may be difficult, but despite the uncertainties, utilities must often make decisions about how to enhance the resilience of their systems. To that end, this dissertation aims to provide a better understanding of the tradeoffs among resilience strategies and the investments being made by utilities. Although some cross-cutting resilience strategies can provide protection against a wide range of outage causes, including deliberate attacks (cyber or physical), natural disaster outage events tend to be more predictable, have more publicly available data, and can more often be mitigated by similar sets of strategies.

Therefore, this dissertation focuses on the efficacy and cost of resilience strategies as they pertain to extreme weather and climate events.

Electric utilities worldwide are facing concomitant challenges that threaten the reliability and resilience of their power systems. Chief among these challenges is climate change, which is affecting power systems in two ways. First, utilities are transforming their energy supply systems to emit less carbon. This often entails the deployment of electricity generation technologies which are often variable, intermittent, flexible, or distributed. Maintaining system resilience after deploying these technologies will require a high level of situational awareness and advanced control strategies, including automation to manage abnormal operations at sub-second timescales. Second, climate change will both change the “normal” environmental conditions for which utilities have optimized their operations and lead to an increase in the frequency and severity of extreme weather events that systems must withstand. Utilities must address these challenges while facing others like aging infrastructure and regulatory reforms that are also influenced by (or influence) their response to climate change.

As a concept, power system resilience is distinct from power system reliability.

Resilience is a power system’s ability to withstand and quickly recover from disruptions caused by major events such as extreme weather or attack. Reliability is the system’s ability to provide power in adequate amounts and of acceptable quality to meet demand during normal operating conditions. Historically, major outage events have not been routine, but they have been common enough to warrant substantial investment by utilities and government over the previous two decades. Unfortunately, little effort has been made to compile information about what different utilities are doing; how expensive and effective these resilience investments have been; how utilities approach resilience investment planning; and what future threats they are most concerned about. The latter is especially relevant to policy makers and could help steer investments in not only technological innovation but also in regulatory capacity and broader coordination.

Here, we present what is to our knowledge a the most comprehensive, publicly available, review of the literature on investments in electric power system resilience designed to mitigate natural disaster caused outages. This review is broad in its scope: in addition to reviewing the academic literature on resilience strategies and their potential utility, it develops and presents a large database of the cost and performance of strategies that enhance power system resilience against natural disasters. This database can be leveraged by analysts in the future to better estimate resilience. It can also be used by utilities and policy makers to develop resilience investment portfolios that are more effective at achieving their power system objectives. It comprise concluding remarks and a list of promising directions for analysts in the future.

Literature on power system resilience tends to fall into one of five categories. First there are studies that propose overarching frameworks that define resilience and what should be considered when increasing resilience, often quantifying the challenges of increased major weather events

However, such reports do not quantify the specific costs and benefits of individual resilience strategies. Studies which do that are typically conducted on behalf of a utility or Public Utility Commission and most often focus on similar sets of strategies: undergrounding power lines, changing pole materials, and vegetation management. Such studies are cited throughout this review. Next, there are post-mortem studies that review the specific impacts of a large outage event which can provide insights to utilities on what needs to be fixed before a similar event occurs, but provide little insight into how to protect against different outage causes. Conversely, there are studies that group resilience investments and report the cost and efficacy of the whole investment Although these reports acknowledge that the resulting resilience is often greater than the sum of its parts, such reporting makes it difficult for any other utility to replicate because one cannot distinguish the impact of individual strategies.

More recently, researchers have been exploring how to incorporate resilience strategies into power system modelling: Pacific Northwest National Laboratory recently launched the “Electrical Grid Resilience and Assessment System” model for Puerto Rico⁴. Similarly modelled undergrounding power lines and generation hardening for hurricanes in Puerto Rico using TEMOA (Tools for Energy Model Optimization and Analysis). Finally, used Computing Resilience Interactions Simulation Platform (CRISP) for considering how distributed batteries and solar photovoltaics could improve resilience during bulk system outages.

To our knowledge only two other studies have attempted to quantify the cost and benefits of a range of resilience options. Richard Brown (Quanta Technology, 2009) conducted a cost- benefit analysis on a wide range of strategies for hurricane resilience in Texas following the devastating impacts of Hurricane Ike (2008) on the Texas power grid. Although thorough in its resilience assessment, this analysis, now over a decade old, focused on hurricanes in Texas.

More recently, the World Bank published two reports, one on the cost and efficacy of resilience strategies for multiple infrastructures including power systems (Miyamoto International, 2019), and one on assessing the threats to power systems Both provide a good overview but focus on generation technologies. This review expands upon previous work to provide a current and exhaustive assessment of the cost and performance of generation, transmission, and distribution system resilience strategies.

Compared to power lines, generation units are robust and have largely avoided big outages. However, when they do have outages, it can be devastating, as for example most recently the 2021 February freeze in the southern part of the US. 44% of outages were caused by generator units not sufficiently “winterized”, while 27% of outages were due to natural gas fuel supply issues Additionally, recent generator failures related to flooding from Hurricane Sandy in New Jersey and Hurricane Florence in North Carolina also remind us that extreme weather events can disrupt thermal power generation.) outlines how weather-related events can impact generation facilities and their fuel supplies reproduced in Table 1.

Table 1. Weather related events and their impact on coal, gas, and oil-fired power plant installations (INST) and their resources (RES).

Event	Coil, gas, oil INST	Coal RES	Gas RES	Oil RES
Extreme Heat	Increased load due to cooling of buildings Influence on efficiency of steam and gas cycles	Self-ignition of coal stockpiles	Expansion in gas pipelines	Expansion in oil pipelines
Extreme Cold/Frost	Increased corrosion due to frost Influence on efficiency of steam and gas cycles	Freezing of coal to ground	Contraction in gas pipelines, loss of pressure	Contraction in oil pipelines, loss of pressure
Hail	Damage from direct hits			

Corrosion of buildings				
Heavy precipitation	Corrosion of buildings Accessibility concerns	Stockpiles need sufficient drainage Erosion of particles Reduced efficiency due to wet coal		
High wind events	Uplifting of roofs and tiles Damage to insulation and cooling towers	Damage to storage tanks by wind pressure or debris impact	Damage to storage tanks by wind pressure or debris impact	
Thunderstorms with lighting	Direct hit to structures Overvoltage in distribution of electricity	Lightning hit of storage areas resulting in fire	Lightning hit of storage areas resulting in fire	Lightning hit of storage areas resulting in fire
Water temperature/droughts	Impact water cooling systems			
Floods/ sea- level rise	Inundation of site	Inundation of stockpiles	Influence on storage tanks Collision with debris	

When it comes to extreme temperatures, Murphy, Sowell, and Apt (2019) showed, using 23 years of data for 1,845 generators in PJM, that for many generator types the probability of unavailability increases both at very low temperatures and very high temperatures, meaning that at temperature extremes generator outages are correlated. So, events like the 2011 and 2021 freezes are likely to happen again if no adjustments are made. Because southern US generation facilities are often not enclosed in buildings to avoid overheating in the summer, other winter weather protection methods include

- Heat tracing – the application of a heat source to pipes, lines, and other equipment that must be kept above freezing;
- Thermal insulation – the application of insulation material to inhibit the dissipation of heat from a surface; and
- Windbreaks – temporary or permanent structures erected to protect components from wind.
- Temporary heating - install portable heaters to maintain ambient air temperature
- Drain non-essential water systems and determine that the water in essential water systems [is] circulating.

The cost for winterizing generator units is estimated to be between \$60,000-\$600,000 per unit

Natural gas fuel supply was another problem during the recent Texas freeze event, which was due to a combination of decreased natural gas production, low pressure, and natural gas commodity and pipeline transportation contracts not allowing for flexibility. However, historically this interdependency with the natural gas system in the US has not caused many outages. Of the gas-fired power plant failures tracked by NERC from 2012-2018, only 5% of the MWh lost were due to fuel shortages (Freeman, Apt, & Moura, 2020). The authors additionally noted that securing firm contracts to ensure priority of natural gas went to electric utilities instead of private companies would have avoided many of these outages. Having generators that can run on more than one fuel type as well as fuel storage can help avoid fuel related outages for all types of thermal generation. For example, the Florida utilities use dual fuel generators at all generating facilities, so if the natural gas supply is cut-off, they are prepared to run on diesel and can do so without stopping to change fuel⁵. Similarly, Guam Power Authority (GPA) is in the process of building a 180MW generating facility that can run either on ultra-low sulfur diesel or natural gas (U.S. Energy Information Administration.

Lastly, the US Federal Emergency Management Agency (FEMA) has developed damage functions for flooding and earthquakes affecting conventional power plants. The FEMA HAZUS 2.1 manual for flooding estimates the damage power plants experience when inundated as shown in Table 2 (FEMA, n.d.-a). Functionality is assumed to be lost at 4 feet of inundation and that control and generation facilities are on the second floor. Strategies to mitigate flood damage include installing flood monitors, raising equipment, installing flood protection walls and ensuring power plants are not built on flood plains.

Table 2. FEMA HAZUS 2.1 model estimates for power plant damage based on flooding depth.

Depth(ft)	1	2	3	4	5	6	7	8	9	10
Percent Damage	2.5	5	7.5	10	12.5	15	17.5	20	25	30

Table 3 shows the damage and restoration times estimated by the FEMA HAZUS 4.2 earthquake model for power plants. Seismic anchoring is defined in the earthquake manual as “anchored equipment in general refers to equipment designed with special seismic tiedowns or tiebacks, while unanchored equipment refers to equipment designed with no special considerations other than the manufacturer's normal requirements”(FEMA, n.d.-b). The avoided damage benefits of seismic anchoring are seen at higher levels of peak ground acceleration (roughly 0.4 and higher), but FEMA estimates no difference in restoration time between earthquake hardened and unhardened facilities.

Table 3. FEMA 4.2 HAZUS model estimates for generation seismic damage and restoration time.

Distribution circuit Damage	Estimated median Peak Ground Acceleration (g) that	Estimated median Peak Ground Acceleration that	Median restoration time (days)
	would cause this damage on a substation with unanchored/standard components	would cause this damage on a substation with anchored/seismic components	
Slight: turbine tripping, light damage to the diesel generator, or by the building being in the Slight damage state	Small (<100MW): 0.10 Medium/large (>200MW):0.10	Small (<100MW): 0.10 Medium/large (>200MW):0.10	0.5
Moderate: chattering of instrument panels and racks, considerable damage to boilers and pressure vessels, or by the building being in the Moderate damage state	Small (<100MW): 0.17 Medium/large (>200MW):0.22	Small (<100MW): 0.21 Medium/large (>200MW):0.25	3.6
Extensive considerable damage to motor driven pumps, or considerable damage to large vertical pumps, or by the building being in the Extensive damage state.	Small (<100MW): 0.42 Medium/large (>200MW):0.49	Small (<100MW): 0.48 Medium/large (>200MW):0.52	22.0
Complete: extensive damage to large horizontal vessels beyond repair, extensive damage to large motor operated valves, or by the building being in the Complete damage state.	Small (<100MW): 0.58 Medium/large (>200MW):0.79	Small (<100MW): 0.78 Medium/large (>200MW):0.92	65.0

Nuclear power plants are similar to fossil fuel generation in that they are already designed to be highly resilient, however they face the additional concerns of ensuring the water-cooling system for the reactors and diesel backup are equally resilient. Ali Ahmad (2021) showed that climate induced disruptions have increased from 0.2 outage per reactor-year in the 1990s to 1.5 in the past decade. He also indicated that the disruptions due to drought and heatwaves although historically rare are most disruptive because they affect the water-cooling system. Heatwaves and lack of rainfall across France in the summer of 2022 stretched the limits of nuclear plants, which were kept on even though they were discharging hot water into the rivers, which can endanger wildlife (Reuters, 2022). In the fall of 2022, France also has almost half of their nuclear

fleet offline for maintenance due to corrosion, which had been deferred over the last decade and is exacerbated by river water levels decreasing due to 2022 heatwaves (France24, 2022).

Although uncommon, extreme cold temperatures can also damage the water-cooling system. During the 2021 February freeze, one of the nuclear units, with a 1,300MW rating, at South Texas Project plant tripped due to feedwater pumps going offline. Researchers have been looking into alternatives to water cooling such as recirculating water (but this brings down thermal efficiency on an already expensive generation source) dry-cooling (but this relies on ambient air- temperature) and using other coolants than water (gases or liquid metal) but currently nothing exists commercially.

Hurricanes can cause damage as well, particularly due to flooding which moves debris closer to the water intake canals of the nuclear reactors. Adding flood protection such as earthen dams and sandbags can help prevent issues with the water system. Additionally, ensuring secure facilities can withstand high wind speeds is important, which usually already part of the design specifications. For example in 1992 when Hurricane Andrew damaged two nuclear power plants at Turkey Point Florida (Hess, 2016), the eye of the storm passed directly over the site with wind gusts up to 175 mph and still only caused damage to non-safety-related systems which included 6 damaged turbine canopies, radioactive-waste building ductwork failures, and the collapse of a high-water tank.

Lastly, nuclear plants are complex systems that are expensive to build. When everything is done by the book, current regulatory practices ensure safe and resilient systems, it's when humans error that can cause problems. For example, the Fukushima reactor meltdown, although triggered by the 2011 large earthquake and tsunami event in Japan, could have been avoided if safety protocols been followed correctly. They were not because of collusion between nuclear regulatory agencies and the nuclear power industry

Hardening Solar PV Panels

The biggest threat to solar panels is large storm events that bring high winds and deposit large amounts of debris across solar farms and rooftops, destroying many of the panels. For example, during Hurricane Sandy ~5 percent of solar panels within a one million square foot rooftop array in New Jersey were damaged by wind. After Hurricane Maria in 2017, Puerto Rico lost about 40% of the islands PV power (Kwasinski, 2018; The Weather Junkies, 2017). One of the utility scale plants in Puerto Rico was relatively undamaged, partially due to avoiding the eye of the storm, but also from using elevated panels to avoid flooding and "reinforced to withstand winds of category 5 hurricanes"

Only a few studies have attempted to model PV wind damage from hurricanes. Goodman (2015) modelled a two-story residential home with a standard array of 20 modules. Through empirical experimentation, Goodman found that rooftop design and degree of tilt for rooftop PV panels caused a much larger variation in fragility curves than what current wind modelling suggests. Higher dimensional racking (2-D) (number of dimensions a structural member spans) does much better than the smaller designs, being able to withstand on average between 110-130 mph wind gusts compared to smaller designs that can withstand 70-90 mph wind gusts.

Additionally, having a gentler slope of the rooftop (15 degrees instead of 30 or 45) increases ability to withstand higher wind gusts by about 20 mph. In addition to panels breaking due to wind damage, PV generation can be reduced during hurricanes due to cloud coverage. Cole, Greer, and Lamb (2020) showed that PV generation during 18 hurricanes from 2004-2017 in the US produced 18-

60% of their clear-sky potential. However, they were able to rebound 72 hours after the storm had passed.

When it comes to deciding how to harden solar panels against tropical cyclones, reports from the National Renewable Energy Laboratory (NREL) (Belding, Walker, & Watson, 2020; Elsworth & Geet, 2020) and Rocky Mountain Institute (RMI) (Stone & Burgess, 2018) provide solutions and cost estimates:

- PV modules should be through-bolted to their racks and with all fasteners locked or torqued appropriately. Through-bolting costs 0.6¢/W for ground mounted PV and 0.7¢/W for rooftop mounted and fastener locking costs anywhere from 0.1-1.5¢/W.
- Use marine grade/stainless steel especially in areas exposed to corrosive salt water and likely costs 1.1¢/W for ground mounted PV and 1.2¢/W for rooftop mounted
- Ensure PV panels can withstand high wind pressures, NREL recommends greater than 3600 Pa, while RMI recommends 5,400 Pa ratings and cost 10¢/W more than traditional panels.
- Use a three rail instead of two-rail racking system for more attachment points and using tubular or square supports for the racking frame to prevent twisting. A third rail would cost an extra 5.9¢/W and tubular frame costs 12¢/W extra for ground mounted PV.
- Ground mounted PV systems also need to avoid flooding damage by ensuring equipment is elevated on pads (0.8-1.0¢/W) or encased in watertight containers as well as ensuring PV sites are not in flood prone areas.
- Ground mounted PV also can use a wind-calming fence, which is “made up of a porous material which allows lower pressure wind to pass through while higher pressure wind is deflected above the fence,” and likely costs 6-14 ¢/W.

RMI estimated that a 1 MW solar system with extra hardening, would cost about \$90,000, which is about a 5% increase in costs compared to a baseline 1 MW system.

Solar panels fare well in cold temperatures, but sometimes heavy snowfall can crack PV panels if the snow weight is not distributed evenly over the panels (Office of Energy Efficiency & Renewable Energy, 2017). To circumvent this, steeply inclined panels can help ensure that snow slides off panels before causing too much damage (Power Magazine, 2014).

Wildfires and extreme heat can also cause problems for solar panels. There is nothing readily available now, but researchers are looking at increasing temperature ratings for panels using heat-resistant material (Arpin et al., 2013) and installing devices that can automatically remove ash covering panels, which can decrease solar efficiency by 30% (Marsh, 2021).

Emergency Planning and Government Coordination

In 2006, the Florida Public Service Commission declared that all utilities in Florida needed to develop and maintain a natural disaster preparedness and recovery program and increase their coordination with local governments. All five of the investor-owned utilities hold regular workshops and hurricane drills to coordinate with local governments in emergency preparation: Emergency Operation Centers consist of stakeholders from multiple organizations. TECO budgets roughly \$500,000 annually for emergency management which is “used to finance human capital and preparedness resources (i.e., emergency notification system, weather services, resilience management product, etc.), including internal and external training and exercises to test plans”(Tampa Electric Company (TECO), 2014).

U.S. utilities have a long tradition of providing mutual assistance for system recovery after major disruptions. EEI maintains a webpage with detailed on-line information about mutual assistance (Edison Electric Institute, n.d.-a). APPA provides similar details on mutual in the context of public power systems (American Public Power Association, n.d.). Of course, as the recent cases of disruptions in Puerto Rico and the Virgin Islands demonstrate, mutual assistance becomes more complicated in the context of power systems in remote locations and on islands. Power companies are generally responsible for restoration of service after a disruption and set aside an annual budget for emergencies that can cover more moderate outages. In unusual circumstance involving major

disruptions, Federal assistance may become available if the damage crosses state lines and is widespread enough to warrant Federal assistance to restore power. However, Federal support for costs associated with power system recovery can only be provided once the president has invoked the Stafford Act a major disaster declaration or emergency declaration has been issued (U.S. Department of Homeland Security, 2017).

Utilities have identified lists of responsibilities, chains of command during outages and even instruction manuals for the repair processes, so everyone clearly knows their responsibilities during an emergency. Edison Electric Institute (2014) emphasized the importance of communicating to the public with “one-voice” and designating a central point of contact to communicate “with crews, state and federal government officials, news agencies and customers to ensure the continuity of communication and information for the most accurate assessments and response estimates (Sheth, K., & Patel, D. 2024).”

Finally, having a good workforce management system can streamline restoration time – Quanta estimates by 20%. A workforce management system should include applications that manage (Quanta Technologies, 2009):

- Track crews and trucks
- Spare parts inventory management
- Expertise matching and scheduling
- Work management (generate work orders and track their progress)
- Workforce management
- Resource management

Conclusions and Future Work

Despite increased interest in understanding the tradeoffs to increasing power system resilience, there is still very little empirical evidence to support any one strategy.

Undergrounding power lines and changing utility pole material have the most robust literature base, but the cost estimates found have a wide range, and the benefits are still disputed. The other strategies reviewed typically have only one or two sources with empirical evidence and often pertain to a specific outage threat.

This review suggests that transmission and distribution hardening strategies could be beneficial in a wide range of outages and already have high deployment, making them currently the most cost effective. Generation resilience strategies, on the other hand, are much newer and therefore not as well tested, and also require specific enhancements for specific outage threats, making their investment potentially less worthwhile.

Our work can be used by analysts to input data into energy models that are increasingly considering a resilience component. For example, Lawrence Berkeley National Laboratory is using this data in their online resilience tool for islanded systems (Framework for Overcoming Natural Threats to Islanded Energy Resilience).

To continue to build this resilience database, further engineering analyses should be done on hardened systems, as more utilities default to higher standards. Additionally, collecting outage data from utilities on single events as well as information on their resilience initiatives can provide real world data on the cost and performance of resilience strategies.

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