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Lifelines: The Resilient Infrastructure Opportunity

Background Paper

Resilience and Critical Power System Infrastructure

Lessons Learned from Natural Disasters and Future Research Needs

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Abstract

Resilience against infrastructure failure is essential for ensuring the health and safety of communities during and following natural hazard situations. Understanding how natural hazards impact society in terms of economic cost, recovery time, and damages to critical infrastructure is essential for developing robust approaches to increasing resilience. Identifying specific vulnerabilities allows for better communication, planning, and situation-specific interventions. This is particularly relevant in areas recovering from a natural hazard that have the opportunity to build back their infrastructure, and for those currently planning infrastructure expansions. This study considers recent hurricanes, earthquakes, droughts, heat waves, extreme wind and rainfall events, ice and thunder storms as well as wildfires. For many of these, data are available for the same type of hazard in different geographies which provides information not only on specific vulnerabilities, but whether the impacts are location dependent. Where available, specific design considerations, cost information for repairs, and the recommendations for 'building back better' are presented. Above-ground transmission systems were the most commonly affected power system component, with fuel and maintenance supply chains representing a major vulnerability for isolated regions and islands. Generation systems were most commonly affected when a hazard exceeded design limits, particularly in relation to water temperature or wind speeds. Institutional capabilities are important throughout the sector. In all case studies analyzed, the design standards of the infrastructure asset, and the ongoing maintenance of assets and the organized response (or lack of) has major implications for the performance of the electricity grid.

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Resilience and Critical Power System Infrastructure: Lessons learned from natural disasters and future research needs

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Executive Summary

Resilience against infrastructure failure is essential for ensuring the health and safety of communities during and following natural hazard situations. The Swiss Reinsurance Company Ltd (Swiss Re) estimated 2017 global infrastructure losses at 337 billion USD, with all but 7 billion resulting from natural hazards. (Of this, more than half was uninsured.) These losses are expected to grow as climate change continues unless actions are taken to prevent them. Importantly, people and communities in developing and emerging economies are expected to be disproportionately affected.

An understanding of how natural hazards impact society in terms of economic cost, recovery time, and damages to critical infrastructure is essential for developing robust approaches to increasing resilience. Identifying specific vulnerabilities allows for better communication, planning, and situation-specific interventions. This is particularly relevant in areas recovering from a natural hazard that have the opportunity to build back their infrastructure, and for those currently planning infrastructure expansions.

This paper[1], commissioned by the World Bank's Global Facility for Disaster Reduction and Recovery, looks at a range of historical natural hazard events and their impact on power system infrastructure including: generation facilities, transmission and distribution assets, and fuel supply chains. We consider recent hurricanes, earthquakes, droughts, heat waves, extreme wind and rainfall events, ice and thunder storms as well as wildfires. For many of these, data are available for the same type of hazard in different geographies which provides information not only on specific vulnerabilities, but whether the impacts are location dependent. Where available, specific design considerations, cost information for repairs, and the recommendations for 'building back better' are presented.

Within the three categories in the power system, we identify specific areas that require attention:

1) Generation facilities: affected by access to cooling water, preemptive shutdowns when winds exceed design limits, or structural damage from insufficient design.

2) Transmission grids: affected by wind, debris, ice, fire, flood, earthquakes and landslides. Above ground systems tend to be the most vulnerable.

3) Fuel and maintenance supply chains: affected by port closures, damage to roads and pipelines.

In some events, all or many of the assets in each of the categories were affected. In jurisdictions such as the Philippines or Puerto Rico, these events caused catastrophic failure of the electrical grid, and resulted in impacts to livelihoods and wellbeing. These situations help highlight which regions are well-prepared for events as well as their ability to respond and repair damages. Above-ground transmission systems were the most commonly affected power system component, with fuel and maintenance supply chains representing a major vulnerability for isolated regions and islands. Generation systems were most commonly affected when a hazard exceeded design limits, particularly in relation to water temperature or wind speeds. Institutional capabilities are important throughout the sector.

In all case studies analyzed, the design standards of the infrastructure asset, and the ongoing maintenance of assets and the organized response (or lack of) has major implications for the performance of the electricity grid.

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[1] This paper is the result of a contract with the World Bank's Global Facility for Disaster Reduction and Recovery division focused on providing background on the state of understanding related to the vulnerability of power grid system and components to natural hazard events. This include generation facilities, supply chains, transmission networks. The goal of this analysis is to inform resilient planning of power grid systems.

Threat	Table E-1: Overview of Asset(s) Impacted by Natural Hazard Event. Findings from Case Study Analysis										
	System Components										
	Transmission and Distribution	Coal		Natural Gas		Nuclear		Solar		Others	
		SC	Facility Operation	SC	Facility Operation	SC	Facility Operation	SC	Facility Operation	SC	Facility Operation
	Assessment of Risk and Resilience										
Natural/Environmental Threats											
♦ Hurricane	●	*	◐	●	◐	○	◐	*	◐	◐	●
♦ Drought	*	◐	*	◐	*	◐	*	*	*	*	●
♦ Heat Wave	*	*	*	*	*	*	◐	*	*	*	*
♦ Wildfire	◐	*	*	*	*	*	*	*	*	*	*
♦ Earthquake	●	*	*	*	*	*	◐	*	*	*	*
♦ High Winds	◐	*	*	*	*	*	*	*	*	*	○
♦ Winter Weather	●	*	*	○	*	*	*	*	*	*	*

Key to chart:	
♦	Multiple case studies analyzed
●	Major damages, offline >1 week
◐	Moderate damages, offline <1 week
○	Some damage or operating at reduced capacity
*	Unknown impacts or no damages
(red)	All case studies indicate impacts
(orange)	Some case studies indicate impacts
(light yellow)	One case study indicates impacts
(white)	No case study data assessed

Table (E-1) summarizes findings from the case study analysis. The impacts of hazards is shown on generators organized by fuel type, and differentiated impacts include supply chain ("SC") and facility), and separately on transmission and distribution infrastructure. The level of impact (low/medium/high), and whether multiple case studies were assessed are detailed.

Future Work

The impact of natural hazard events on power systems varies based on the asset being analyzed, the standards to which it was constructed, the nature of the hazard event, the institutional landscape, and many other factors. In many instances, design considerations can enhance the resiliency of the asset to withstand and recover from an event. In this context, four recommendations can be made for future work:

1) Establish the likelihood of future disruptions to power systems from region-specific threats. Electricity distribution systems were seen to be particularly vulnerable to wind (resulting from storms, hurricanes, typhoons and more). Historical data on wind velocities with hour level resolution can be used for a geospatial analysis to inform risk and design standards in many regions of the world;

2) Climate change may exacerbate and/or change weather-related natural hazards. Climate models can be used to parameterize predictions for geographically-dependent rainfall and water temperature. A geospatial analysis of where water temperatures are expected to rise, and river flows decrease would be valuable. These data can inform locations where power systems that depend on cooling water could be under increased strain in the future;

3) Region-specific case studies should be conducted to explore how best to implement resilient power systems within different communities;

4) Additional studies should be conducted to better understand critical system interdependencies

(with other sectors and services) and how to mitigate them.

Implementing the above recommendations will generate data to better inform power system planning and resilience of critical infrastructures that couple to them. The work will also provide data that is critical to optimizing the allocation of funds targets to increasing resilience.

Report Structure

The report is organized into five sections with related appendices. Section 1 gives a brief introduction to resilience planning. Section 2, Methodology, provides an overview of the types of data looked at and analysis completed. Section 3 provides the results of the analysis related to the vulnerability of electricity system components and the costs and impacts when affected by different hazard events. This includes transmission and distribution infrastructure and fuel-specific generation facilities. Where applicable, the investigation of vulnerabilities includes the interdependencies of the electricity system including supply chain considerations and repair and maintenance interconnections. Section 3 also provides recommendations for more resilient infrastructure assets and, where available, the costs of doing so. Section 4 includes a detailed case study looking at the impacts, adaptations and costs of Hurricanes Maria and Irma on the power grid in Puerto Rico. Section 5 provides a summarized conclusion of the findings and outlines areas for future work. Appendices A-F provide supplemental information presented in this report, from definitions of terms to additional detailed, case study data. Appendices D and E additionally provide baseline and 'build back better' estimates specific to Puerto Rico.

1. INTRODUCTION

The Swiss Reinsurance Company Ltd (i.e. Swiss Re) estimated 2017 economic losses at 337 billion USD. Of this, $330 billion were from natural hazard events and less than half these losses were insured. These numbers are nearly double those from 2016 and have increased over the past two decades (Swiss Re Institute 2018), Fig. 1. The types of events that caused these losses have a particularly significant impact on critical infrastructure systems (Ouyang, Dueñas-Osorio, and Min 2012; City and County of San Francisco 2014). In the context of societal resilience, electricity supply is centrally important because of the interdependencies with many other critical infrastructure systems. Importantly, these include transportation (including evacuation and access operations), communication infrastructure, heating or cooling for residential and business structures, water services, supply chains for businesses and educational institutions as well as hospitals and other emergency services. For decision makers, specific information focused only on a single infrastructure asset is one part of a larger decision and planning framework that must include interdependencies with other systems (City and County of San Francisco 2014).

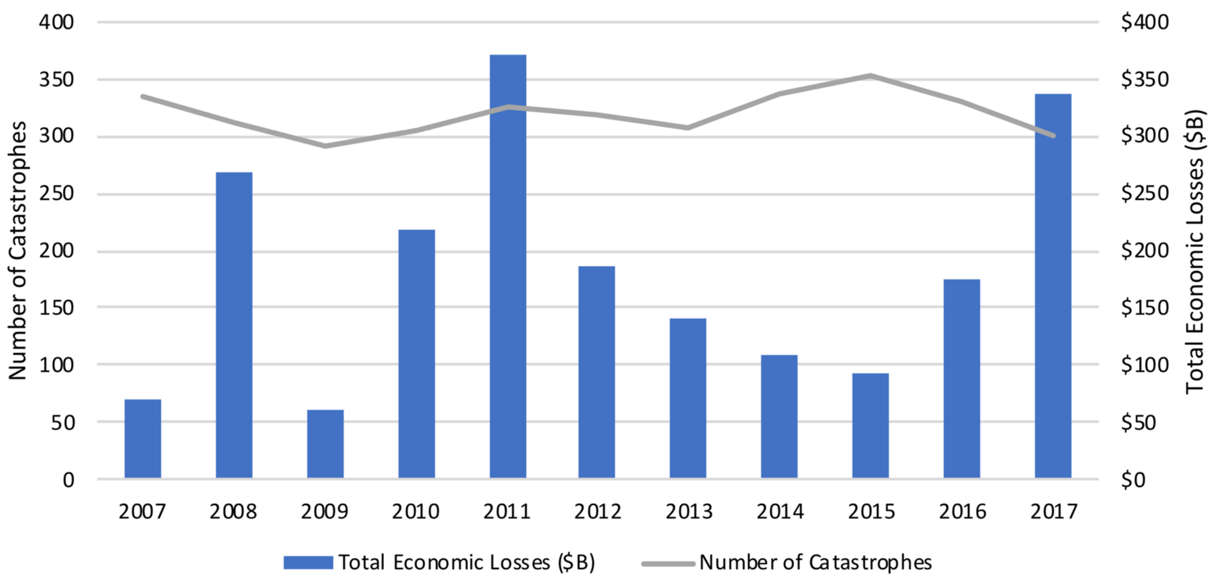

Figure 1. Estimated Global Economic losses from hazard events. The figure shows the estimated cost of hazard events from 2007 to 217. Data from Swiss Re (2018).

Two international frameworks (first, The Hyogo Framework in 2005, and then The Sendai Framework in 2015(UNISDR 2018; Bodenhamer 2011)) have been established for addressing the central issues related to reducing the impact of hazards. In both frameworks, the emphasis for disaster risk management includes several key considerations for policy, planning and the management of critical infrastructure. This includes an explicit focus on understanding risk and exposure, reducing vulnerabilities and increasing the resilience of systems. The Sendai Framework builds on these principles and expands to include an imperative to 'Build Back Better' following a hazard event (UNISDR 2018). In this context, understanding the individual vulnerabilities, and costs of infrastructure system components is particularly important as is overall system resilience.[2]

Work on component-level vulnerabilities in infrastructure systems has typically focused on single-event hazard case studies to provide valuable information of asset performance (J. J. W. Watson and Hudson

[2] Specific definitions for *resilience, build back better, critical infrastructure*, *recovery* and *response* are given in Appendix A.

2015; Chattopadhyay et al. 2016; New York Power Authority et al. 2017). Work on the resilience of interdependent infrastructure systems to has been led by the Association of Bay Area Governments in San Francisco, California, USA. The studies done by this group are specific to earthquakes but lay a foundation for identifying some of the complex interdependencies of different infrastructure systems. They also focus on the assessment of both individual components and system-wide damages to infrastructure assets in the immediate aftermath of a hazard event. Their findings show that the interdependency of critical infrastructure is a main source of concern for society-level planning during and following a hazard event (e.g. City and County of San Francisco 2014). Electricity plays a vital role here because it is fundamental in the operation of many other critical infrastructure systems (Sebastian et al. 2017), Fig. 2.

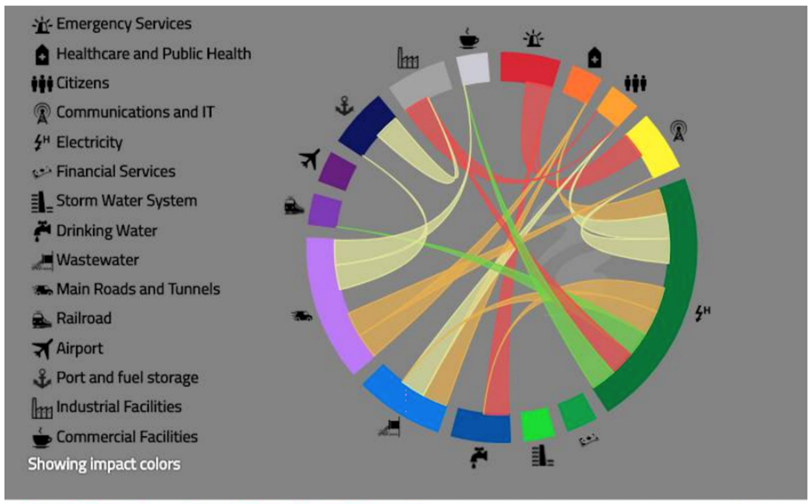

Figure 2. Graphical depiction of some of the key interdependencies between infrastructure systems specific to natural hazard events. Electricity is shown in green and has ties to almost every other infrastructure system. A failure in electricity delivery can affect hospitals, communication infrastructure and transportation (including signals, public and others). Figure from Sebastian et al. 2017.

Estimating the costs from natural hazard events is vitally important for understanding how to maximize the use of funds to decrease vulnerability and build back to more resilient standards. These costs include the cost of repair required for damaged infrastructure assets, the cost to utilities and customers resulting from a power outage, and the larger costs associated with interrupted power system supply. In some cases, costs are reported by government agencies (e.g. the US Federal Emergency Management Agency), estimated by a power utility/authority itself, or captured in national metrics such as the Consumer Price Index (Bureau of Labor Statistics 2018). Such estimates are useful because they can often be compared across a range of events. However, a major challenge is disaggregating which costs are related to the specific systems impacted. In some cases, estimates can be made from the cost of repair through a variety of source documents and bottom-up assessments can be estimated.

Short term costs from an outage event to a utility in the United States can be estimated using the *Interruption Cost Estimator (ICE)* (Lawrence Berkley National Labs, Department of Energy). This tool is designed to estimate the cost of an interruption of electricity to consumers by utility size and state but is specific to interruptions lasting < 24 hours. Estimated costs are provided for different durations and based on utility survey information over several years (M. Sullivan, Schellenberg, and Blundell 2015). An analysis of 34 survey findings in the ICE database show that a one-hour outage costs residential consumers between \$7-\$11 (2013 USD) with a standard deviation of costs ranging \$14-\$21. The variability is based on season (summer is costlier than winter) and the day (weekends are more expensive than weekdays) on which the outage occurs (Sullivan et al. 2018). Findings are also presented for small commercial and industrial customers, with costs ranging from $466 to $742 for a one-hour outage, with the lowest costs found on weekends and during the winter season and the highest costs found in summer and on weekends. The same patterns are found for medium and large commercial and industrial customers, though at higher costs: averaging between $4,190 (weekends) to over $16,000 (weekday outages and summer outages) (Sullivan et al. 2018). The tool is not designed for resiliency planning, especially for events lasting more than twenty-four hours or outside the United States. Nonetheless it could provide a baseline assessment method for resiliency investment and planning and is the focus of recent work comparing generator costs and other aspects of resiliency in post-event evaluations.

Much of the recent work related to power system resiliency has been focused on cyber-security[3]. While a valuable body of research and an important consideration in power system design, this falls outside the scope of the present study and should be a considered in resilience planning, particularly for smart grid systems. Here we focus on understanding component and system vulnerabilities to a wide range of natural disasters found through case study assessments.

2.0 - METHODOLOGY

We consider the power system impacts of earthquakes, wild fires, hurricanes, droughts, floods, heat waves, as well as snow, ice, wind and thunder storms. The assets investigated include transmission and distribution infrastructure (e.g. substations, wires, and poles) as well as fuel-specific generation facilities. The data for the events studied falls into three general categories: hazard event case studies with multiple data sources covering many assets within a power system; single-facility operation disruptions from weather or water-related issues in the United States (McCall, Macknick, and Macknick 2016) or globally (Karagiannis et al. 2017a); major outage events in the United States between 2000 and 2016 focused on the cause of the disruption and customers affected (Mukherjee, Nateghi, and Hastak 2018c). The latter data were limited to customers affected, and the causal event. Where possible, cost estimates to repair damage back to operational capacity was recorded as were recommendations to improve performance. The types of events for which case study level data were available for different hazard events are summarized in Table 1.

This paper does not specifically address the impacts of climate change but instead focuses on empirical assessment of past hazard events and their impacts on the electrical power grid. Many studies cite that the impacts of a changing climate may increase the severity or intensity of natural hazard events and should be considered in the planning of new infrastructure (e.g. Meyer et al. 2013). Some examples of ways to incorporate climate change considerations in planning can be found, including a 2016 study of vulnerabilities of power system infrastructure to flooding (Chattopadhyay et al. 2016) and others focused on different types of critical infrastructure (Schweikert, Espinet, and Chinowsky 2018). This is an important consideration for future work and discussed in the recommendations at the end of this work.

Table 1: Case Study Summary - Over 50 events and more than 700 outages were investigated in this analysis. The 13 events detailed in this table represent analyses that covered multiple infrastructure assets and sources to provide a picture of the impacts of a specific natural hazard event on the electric power system in the affected region.

Hazard	Number of Case Studies	Event Name	Date	Location	Severity	Damaged Assets (for which data was available)

[3] For more information on this important consideration, several resources are available, including The United States' Department of Energy Office of Cybersecurity, Energy Security, and Emergency Response (CESER)(Department of Energy n.d.).

Earthquake	2	Christchurch Earthquake	2011	Christchurch, New Zealand	Magnitude 6.3	Transmission lines, substations, backup generators
		N/A	2011	Virginia, United States	Magnitude 5.8	No damages, curtailment of generation facilities
Hurricane/ Typhoon	4	Typhoon Haiyan/Yolanda	2013	The Philippines	Category 5	Transmission lines, poles, substations, geothermal plant, oil barge
		Hurricane Sandy	2012	Northeast, United States	Post-tropical cyclone	Transmission lines, distribution system, fuel generation plants, supply chain infrastructure
		Hurricane Maria	2017	Puerto Rico	Category 4	Transmission grid, distribution system, generation facilities, ports, supply chain infrastructure
		Hurricane Maria	2017	U.S. Virgin Islands	Category 5	Transmission grid, distribution system, generation facilities, ports, supply chain infrastructure
		Hurricane Harvey	2017	Texas, United States	Category 4	Transmission grid, ports, refineries
Drought/ Heatwaves	2		2011	Texas, United States	D4 ("Exceptional")	Thermoelectric plants (curtailment)
			2018	France		Generation facilities (curtailment)
Wildfires	1		2007	California, United States	33,195 acres burned	Transmission lines, generation facilities (curtailment)
Storm	4	Tropical Storm Dolores	2015	California, United States	Heavy rainfall, lightning	Transmission lines
		Thunderstorm	2013	Virginia, United States	Strong winds	Transmission lines
		Thunderstorm	2015	Minnesota, United States	Wind, heavy rain	Transmission poles, transmission lines, transformers

					damaged
	Snow/ice	2014	Maryland, United States	Ice	Transmission lines

3.0 - VULNERABILITIES AND FAILURES

The following results consider all reviewed data including outage information, facility-specific curtailments and case studies. Table 2 presents the major outages in the United States (2000-2016) summarized by cause. Half of all events are attributed to natural hazard events. Notably, where outages were due only to damage to operability disruptions, more than half of all classified events were due to the transmission and distribution infrastructure.

Mukherjee, Nateghi, and Hastak (2018) examined the cause, location, duration and impact (MW lost, customers affected) of every major electrical outage in the United States between 2000-2016. Over 1,500 events were included in the dataset, and each outage event was categorized by the major cause. Fifty percent of all major outage events in the examined period were due to natural hazard events, Table 2. System Operability Disruptions account for approximately 8% of outages, of which more than 50% were transmission/ distribution interruptions issues (where classified). Fuel Supply Emergency caused outages 3% of the time, with data on the fuel type for each outage: coal (35%), hydroelectric facilities (12%), natural gas (14%) and petroleum (2%) and unknown accounting for the rest.

Table 2 - Major Outages in the Continental United States (2000-2016), summarized from Mukherjee et al. 2018.

Cause	Percent of all events
Natural Hazards	**50%**
Hurricane	10%
Heat Wave/Drought	1%
Earthquake	<1%
Winter Weather	18%
Flooding	<1%
Wind	11%
Wildfire	1%
Storm	29%
Fuel Supply Emergency	**3%**
Coal	35%
Hydroelectric	12%
Natural Gas	14%
Petroleum	2%
System Operability Disruptions	**8%**
Classified events: Transmission Distribution	54%
Intentional Attack	**27%**
Other	**11%**

McCall et al. (2016) examined the impact of water-related issues on generation facility operation. It focused on all water-related curtailments in the United States between 2000-2015. A total of 37 events were recorded for nuclear, coal and hydroelectric facility operations.
The majority of curtailments occur due to water intake and/or discharge issues related to water temperature (>90%) with many of these (79%) occurring during heatwave/drought conditions. Specific design and operation parameters associated with environmental regulations and permitting were the major cause of curtailment (water temperatures exceeding permitted levels and/or water availability). The remaining curtailments are attributed to winter weather (McCall et al. 2016).

When combined with the case studies assessed in this analysis, similarities were found across geographies, hazard events and other parameters that might affect design standards, policy practices and cost considerations. Three general categories with common corresponding causes were identified in the vulnerability of the power grid system:

1) Transmission grid failures
    a. Wires above ground ruined by wind, debris, snow, ice, flood, fire, or earth movement
    b. Wires below ground affected by flooding, liquefaction, landslide, but much less vulnerable overall than above ground

2) Generator failures
    a. Limited access to cooling water or water of low enough temperature
    b. Hazard events that exceed operational limits
    c. Hazard events that exceed structural limits
    d. Flood or earth movement

3) Fuel and maintenance supply chain failures
    a. Port closures for fuel delivery
    b. Pipeline damage for fuel delivery
    c. Road damages for fuel delivery / repair operations
    d. Backup generators requiring diesel stored on site

A detailed description of the findings which lead to the above vulnerabilities is given below by sub-system component: first for transmission grid and then by fuel type, which includes both the generation facility vulnerabilities and supply chain considerations. In each section vulnerabilities to infrastructure and supply chain are given as well as possible methods to increase resiliency.

3.1 – Transmission Grid

Vulnerabilities. In nearly every case study, Table 1, transmission infrastructure represented the most vulnerable part of the power system. Particularly in geographies with less redundant systems, the time required to restore transmission lines constituted the majority (or sole) reason for the lag in recovery time. This was seen in Puerto Rico, where restoration of power across the island took nearly a year despite many solar and other generation facilities' quick recovery times (U.S. Energy Information Administration 2018) (see Section 3.3).

Transmission lines are vulnerable to most meteorological impacts of a hazard event, including wildfires, high winds, freezing rain, snow, earth movement (liquefaction, earthquake, landslides) and debris. The most common vulnerability and damages occurred from wind resulting from hurricanes, storms, winter weather or debris picked up by wind. All infrastructure in earthquake areas where liquefaction occur saw damages (Watson 2013). Wind was found in many case studies to topple transmission lines and poles (Thompson 2011; Sinclair Broadcast Group 2013; Hoffman and Bryan 2013; Sinclair Broadcast Group 2012; Dispatch 2015).

Wildfires present an interesting and unique vulnerability to transmission and distribution infrastructure. Various case studies illustrate that during high risk conditions (drought, high temperatures, high wind), curtailments were used to reduce the risk of transmission infrastructure causing a wildfire. The potential risk was illustrated in California (USA) in 2017 when transmission lines were identified as a likely cause of fire start. Here San Diego Gas & Electric was found liable for causing three fires that led to three deaths and the destruction of 1,300 homes. The utility ultimately paid out $2 billion in settlements (Daniels 2017). Recent wildfires have put Pacific Gas and Electric, a large utility in California, under scrutiny due to $10 billion in liabilities from fires in 2017 and unknown amounts from ongoing fires in 2018 (McNeely 2018). A key parameter in overall grid vulnerability was the geographic distance between generation facilities and end-use. Summary vulnerabilities identified in the case studies are detailed in Table 3, with detailed case study data presented in Appendix B and C.

Transmission infrastructure was also seen to be acutely dependent on other infrastructure for its recovery, e.g. transportation, because equipment and materials must be brought to each site for repair. Specific design standards identified to reduce the vulnerability of the grid and the costs are summarized in Table 4.

Table 3: Transmission Grid and Distribution Infrastructure, Key Vulnerabilities				
	Hurricane	Winter Weather	Wildfires	Earthquake
Transmission and Distribution	* Wind damage can topple lines and poles(Thompson 2011; Sinclair Broadcast Group 2013; Hoffman and Bryan 2013; Sinclair Broadcast Group 2012; Dispatch 2015) * Damage to transmission tower foundations due to erosion and/or landslides (Karagiannis et al. 2017b) * Moisture and dirt infiltration (Karagiannis et al. 2017b) * Inaccessibility due to flooding (Hoffman and Bryan 2013) * Substations at risk of flooding (New York Power Authority et al. 2017)	Icing on transmission lines	* Damaged power lines can cause fires and fires can damage transmission lines causing power outages (Rogers 2017) * Trees falling on power lines due to strong winds can spark fire (Daniels 2017)	*Vulnerable to liquefaction (N. Watson 2013) *Landslide *Buried lines vulnerable to flooding

Resilient Design Guidelines. The design parameters used for transmission and distribution infrastructure relate directly to their performance during and after a natural hazard event. In New Zealand, case studies following the earthquakes in 2010-2011 highlight the value of pre-emptive investment in infrastructure. Estimates show that $6 million spent to harden transmission and distribution infrastructure resulted in $30-50 million reduction in direct asset replacement costs (Fenwick and Hoskin 2011). Specific to a case study performed in Puerto Rico, detailed data can be found in Appendix D and E.

Table 4 – Transmission and Distribution, Resilient Design Guidelines			
	Hurricane	Earthquake	Wildfires
Transmission and Distribution	* Poles and towers should be of design and material to survive 240 kph sustained winds (U.S. Department of Energy 2018b) * Enable integration of microgrids (New York Power Authority et al. 2017) * Build flood barrier around site based on observed worst case flooding plus a foot or more for design safety margin (New York Power Authority et al. 2017) * All critical electricity system assets should be located at BFE +1 meter or 0.2% flood elevation or sited outside of the floodplain entirely (U.S. Department of Energy 2018b) * Build substations at higher elevations [66] * Poles should have deeper subgrade support to withstand min. 1 meter of water (New York Power Authority et al. 2017) * Towers in Philippines only designed to withstand winds of 185 kph while Yolanda had winds greater than 220 kph (Rappler.com 2013)	* Build to withstand events greater than events in the past and update aging infrastructure (N. Watson 2013) * Determine threshold of acceptable risk and cost increment. (Stevenson et al. 2011) *Upgrade major cables, switchyards, and substations to seismic standards (Fenwick and Hoskin 2011)	* Harden grid by replacing wooden poles with steel ones, better insulating power lines, and burying power lines (Rogers 2017) * Be aware of max winds towers and poles can withstand (NDRRMC 2014) * Turn off power lines in time of high fire risk to prevent wildfires (Daniels 2017)

3.2 – Generation Plant Vulnerabilities by Fuel type

Generation plant vulnerabilities were investigated using case study and curtailment data. By comparing impacts across geographies and hazards, specific guidelines about resilience (or lack the of) of specific power generation systems (fuel types) can be made. The following sections are organized by fuel type (petroleum, coal, natural gas, nuclear, solar and others (including Wind, Hydroelectric, Backup Diesel Generators, Geothermal). For each fuel type, vulnerabilities are detailed specific to the facility and the supply chain or interdependent infrastructure. Additionally, where information was available, the costs of damages and impacts are detailed from specific case studies along with recommendations for more resilient design. A comprehensive case study of component level damages and corresponding baseline and build back better costs are provided in Section 4 specific to Puerto Rico.

3.2.1 - Oil-Fired Generation Facilities. Oil-fired generation facilities are generally used for small proportions of overall electricity generation within a larger system and represent facilities constructed before 1980. This is due to relatively higher costs of fuel when compared to natural gas or other similar sources (Dubin 2017). The largest natural hazard vulnerabilities are from hurricanes, droughts and heatwaves (see Table 5).

	Table 5: Oil-Fired (Petroleum) Generation Facilities, Impacts from Case Studies		
	Hurricane	Drought/Heat Wave	Flooding/Storm Surge
Direct impacts	* Damage to plant infrastructure due to high winds and flooding (New York Power Authority et al. 2017) * Cooling tower damage (New York Power Authority et al. 2017) * Power barges off shore at risk to strong winds and storm surge (Joint UNEP/OCHA Environment Unit 2013)	* Low water levels to be used for cooling and high temperatures (25°C) that regulations prevent from being discharged (Harto and Yan 2011)	* Refineries shut down due to heavy rainfall and flooding (Hoffman and Bryan 2013)
Supply chain effects	* Damages to ports can disable supply chain (where imports are required for fuel delivery) (New York Power Authority et al. 2017) * Damages to pipelines, roads can disrupt fuel delivery to generation facilities		

Facility vulnerabilities for oil-fired generation were identified in some studies (including Puerto Rico). Plants were damaged due to high winds, specifically of the cooling tower structure. In two case studies reviewed, damages from wind, storm surge and flooding shut down the facility and caused costly damaged (see also Section 4 of this report) (Hoffman and Bryan 2013; Joint UNEP/OCHA Environment Unit 2013). During Typhoon Haiyan in the Philippines, the Estancia Oil Barge was ripped from its moorings offshore, causing an oil spill along the coastal areas (Joint UNEP/OCHA Environment Unit 2013).

Supply Chain and Interdependencies for Oil-Fired Generation Facilities. The main vulnerabilities identified in supply chain and interdependencies with oil-fired capacity is the supply chain of fuel and water required for cooling. Facilities require petroleum (or petroleum products) to operate, with delivery relying on pipelines, roads, and/or ports for delivery. In cases where these interdependent infrastructures are damaged, plant operation is reduced or shut down completely (New York Power Authority et al. 2017). This was seen in Puerto Rico following Hurricanes Irma and Maria, where port closures resulted in an estimated loss of 1.2 million barrels per day of petroleum, over the course of 11 days, and directly affected the major generation stations which relied exclusively on imported fuel types (U.S. Department of Energy 2018a). Similar closures occurred in Texas during the same events in 2017 as well as in New York and New Jersey during Hurricane Sandy (U.S. Department of Energy 2018a). In Hurricane Sandy, it was noted that, "Due to its harbour and terminal infrastructure, the oil and gas supply chain is particularly prone to storm surges. At the same time, it is greatly dependent on secure power supply. Due to power outages, infrastructures such as pipelines, oil terminals, storage tanks and filling stations could hardly

Table 7: Coal Facility Generation, Key Vulnerabilities	
	Drought/Heat Wave
Direct impacts	
Supply chain effects	Low water levels to be used for cooling and high temperatures (25°C) that regulations prevent from being discharged (Harto and Yan 2011)

function" (Comes and Van de Walle 2014).

All oil-fired facilities reviewed rely on intake water for circulation in the cooling systems and are vulnerable to flooding, storm surge, high temperatures of intake water and low amounts of water availability for intake water. In most case studies, permitting regulations resulted in curtailment or closure of facilities when intake water exceeded the permitted temperatures (approximately 75 degrees Fahrenheit in most studies) (McCall, Macknick, and Macknick 2016).

Costs, Impacts and Resilient Design Considerations for Oil-Fired Generation. Flooding and inundation can be mitigated by putting facilities at elevation and away from coastal regions. Hardening facilities to withstand the highest predicted winds, or other stressing events, expected during a facility lifetime can protect against structural damage. The cost to repair damaged facilities depends significantly on what was damaged, but at the high end would be the replacement cost. A summary of costs and recommendation from relevant studies is summarized in Table 6.

Table 6 - Oil-Fired (Petroleum) Generation Facilities, Costs and Resilient Design Guidelines		
	Hurricane	Drought/Heat Wave
Oil	*Estimated Cost:* $718,000/MW to repair PREPA (Puerto Rico) oil generating facilities (New York Power Authority et al. 2017) *Design Guidelines:* * Locate facilities away from coast to avoid flooding from coastal storm surge (New York Power Authority et al. 2017) * Elevate facilities (U.S. Department of Energy 2018b) * Design to withstand Category 4-5 wind speeds 210 kph (U.S. Department of Energy 2018b)	* Install power mix that doesn't all depend on water for generation (Alvaro 2018)

*3.2.2 - Coal-Fired Generation Facilities***.** Coal fired generation facilities are most vulnerable to droughts, heatwaves, and supply chain considerations (see Table 7). Flooding was identified as an important criteria for resilient facility design and a 2016 study in Bangladesh particularly noted that the historical guidelines for flood design are likely to be inappropriate for future conditions (Chattopadhyay et al. 2016).

Vulnerabilities of Coal-Fired Facilities were found to be similar to those for oil-fired ones. Findings specific to the assessed case study literature are summarized in Table 7.

Supply Chain and Interdependencies for Coal-Fired Generation Facilities. Similar to petroleum and natural gas facilities, coal generation plants require on-demand fuel delivery, although typically plants have some on site reserve available. In the United States, between 2000-2016, 35% of all outages related to a fuel supply emergency were for coal generation facilities, the largest of any fuel type (see Table 2). In a study in Bangladesh, additional vulnerabilities identified in the supply chain included the mining, transportation and storage of coal vulnerable to natural hazard events including flooding (Chattopadhyay et al. 2016).

All facilities reviewed rely on intake water for circulation in the cooling systems and are vulnerable to flooding, storm surge, high temperatures of intake water and low amounts of water availability for intake water. In most case studies, permitting regulations resulted in curtailment or closure of facilities when intake water exceeded the permitted temperatures (approximately 75 degrees Fahrenheit in most studies) (McCall, Macknick, and Macknick 2016). In a study that includes climate change considerations, thermal electric power stations (including coal) were identified to have increasing vulnerability in the future specifically due to increased ambient temperatures and water availability that will affect water required for cooling (Chattopadhyay et al. 2016).

Costs, Impacts and Resilient Design Considerations for Coal-Fired facilities. As with oil-fired capacity, flooding and inundation can be mitigated by putting facilities at elevation and away from coastal regions. Hardening facilities to withstand the highest predicted winds, or other stressing events, expected during a facility lifetime can protect against structural damage. The cost to repair damaged facilities depends significantly on what was damaged, but at the high end would be estimated by the replacement cost.

*3.2.3 – Natural Gas-Fired Generation***.** Natural gas fired generation facilities are most vulnerable to droughts, heatwaves, and supply chain considerations (see Table 8).

Table 8: Natural Gas Facility Generation, Key Vulnerabilities	
Drought/Heat Wave	Hurricanes
* Low water levels to be used for cooling and high temperatures that regulations prevent from being discharged (Harto and Yan 2011)	*Broken pipelines limiting gas distribution (Hoffman and Bryan 2013)

Supply Chain and Interdependencies of Natural Gas-Fired Generation. The main vulnerabilities identified in supply chain and interdependencies with natural gas plants is the supply chain of fuel and water required for cooling. Facilities require liquid natural gas (or other fuel product) to operate, with delivery relying on pipelines, roads, and/or ports for delivery. In cases where these interdependent infrastructures are damaged, plant operation is reduced or shut down completely (New York Power Authority et al. 2017). This was seen in Puerto Rico following Hurricanes Irma and Maria, where port closures directly affected the major generation stations which relied exclusively on imported fuel types (U.S. Department of Energy 2018a). Similar closures occurred in Texas during the same events in 2017 as well as in New York and New Jersey during Hurricane Sandy (U.S. Department of Energy 2018a).

All facilities reviewed rely on intake water for circulation in the cooling systems and are vulnerable to flooding, storm surge, high temperatures of intake water and low amounts of water availability for intake water. In most case studies, permitting regulations resulted in curtailment or closure of facilities when intake water exceeded the permitted temperatures (approximately 75 degrees Fahrenheit in most studies) (McCall, Macknick, and Macknick 2016). In the 2011 Texas drought, lack of water available for cooling resulted in curtailment of production from all thermoelectric plants, resulting in increased prices to consumers (EIA 2011; Harto and Yan 2011).

Costs, Impacts and Resilient Design Considerations of Natural Gas-Fired Generation. As with oil and coal-fired capacity, flooding and inundation can be mitigated by putting facilities at elevation and away from coastal regions. Hardening facilities to withstand the highest predicted winds, or other stressing events, expected during a facility lifetime can protect against structural damage. The cost to repair damaged facilities depends significantly on what was damaged, but at the high end would again be the replacement cost. Costs and resilient design guidelines are summarized in Table 9.

Table 9 – Natural Gas, Costs and Resilient Design Guidelines
Drought/Heat Wave
• Install power mix that doesn't all depend on water for generation (Alvaro 2018) • air cooling • backup cooling water supplies • put facilities at elevation to avoid flooding • avoid coastal regions.

3.2.4 – Nuclear-Fired Generation. Nuclear power plants are built to robust design standards, reducing the impacts of most events (such as high winds, storms). The only nuclear power plant curtailments or shut downs observed, except for one, in this analysis occurred because of pre-emptive closure (in the case of predicted hurricane-force winds and/or storm surge for coastal plants) or issues with the intake water used for cooling. The primary cause seen for the pre-emptive closures were hurricanes, while issues with intake water used for cooling were caused by drought, heatwaves, and winter weather (see Table 10). The only power plant reviewed that sustained damage was the Fukushima Daiichi Plant in Japan following a magnitude 9 earthquake and tsunami, which was considerable.

Nuclear power plants are the most robust generation type reviewed in terms of facility design and limited reliance on the fuel supply chain. This was particularly evident in Texas following Hurricane Harvey where nuclear power was able to operate at full capacity throughout the event. This allowed for continued electricity supply despite the demand deficit seen from reductions in generation facilities located on the coast which were more affected by storm surge and flooding for longer time periods (Conca 2017).

Table 10: Nuclear Power Plants, Key Vulnerabilities		
Hurricane	Drought/Heat Wave	Earthquake
* United States safety procedures require plants to shut down or reduce output when hurricane-force winds 117 kph are present or if water levels exceed certain flood limits (Foro Nuclear) * High water levels threaten cooling units (Steve Mufson 2012) * Automatically shut down if plant loses power from grid (Steve Mufson 2012)	* Shut down or curtailed when intake cooling water temperature is too high (25°C) (Harto and Yan 2011) * Shut down or curtailed when discharge temperature is too high due to local environmental regulations (Harto and Yan 2011)	* Automatically shut down if plant loses power from grid (Mufson 2012) * Damage occurs when force exceeds design basis (N. Watson 2013)

Vulnerabilities of nuclear-fired facilities included power plant curtailments or shut downs. In all cases reviewed in this analysis, excluding Fukushima Daiichi plant, these occurred because of pre-emptive closure. Generally, these were due to predicted hurricane force winds or detected seismic levels exceeding a design threshold. Because of strict permitting and regulations in the United States, when plants were shut down pre-emptively, there was often a large lag time before being able to operate again. Inspections are required, particularly in the context of an earthquake. No damages were found to a nuclear facility in the studies reviewed for this analysis with the exception of the tsunami impact on the Fukushima Daiichi facility.

Supply Chain and Interdependencies of Nuclear-Fired Generation. Generation For nuclear power plants, fuel can be stored on site and refueling is far less than other power sources, ranging in the timescales of years. The only identified impact on supply chain and interdependencies are when demand shifts and the water used for cooling. For demand shifts, nuclear power is not as quickly able to adjust power production as other technologies including natural gas. Generally, this is accounted for with forecasting and planning.

The largest vulnerability of nuclear power facilities is the intake water used for cooling. High temperatures can make it difficult for water to reach temperatures cool enough to be discharged and, due to permitting restrictions, may require generation curtailment (Galbraith 2011). A case study on the 2011 Texas heat wave was performed and augmented with facility-specific data for curtailments at several facilities, including a study finding 25 water-related curtailments in the United States between 2000-2015 (McCall et al. 2016). The impacts on power generation were similar across all data reviewed: water availability and temperature affected generation systems that rely on cooling water. The majority of curtailments occur due to water intake and/or discharge issues related to water temperature (>90%) with many of these (79%) occurring during heatwave/drought conditions. One example occurred for winter weather, where snow and ice restricted the amount of intake water available. Specific design and operation parameters associated with environmental regulations and permitting were the major cause of curtailment (water temperatures exceeding permitted levels and/or water availability). This was also seen in France in August 2018. Here four nuclear reactors were shut down because river temperatures were too high to allow for water discharge (Shugerman 2018).

Costs, Impacts and Resilient Design Considerations for Nuclear-Fired Generation. The key vulnerability of existing nuclear power plants is the reliance on intake water for cooling. The design guidelines for constructing a facility include seismic considerations (where applicable) and resilience to withstand high windspeeds, flooding, and other hazards, Table 11.

Table 11 – Nuclear Power Plants, Costs and Resilient Design Considerations

Hurricane	Drought/Heat Wave	Earthquake
* Design plants to withstand winds up to 580 kph (Reuters 2011) * Steel reinforced concrete containment with at least 1-meter thick walls (Conca 2017) * Build plants at higher elevations (Steven Mufson 2012) * Keep backup generators in case of power failure (Steven Mufson 2012)	* Install power mix that doesn't all depend on water for generation (Alvaro 2018)	* Build plants to withstand earthquakes above maximum magnitude recorded (N. Watson 2013)

One modification that has been made is found in Arizona (USA): The Palo Verde plant. This facility does not sit on a body of water but instead uses recycled municipal water (APS 2018) and therefore operates under different rules for intake and discharge temperatures. This reliability on grey municipal water changes the regulations for cooling water and may provide an operational case study for future designs.

3.2.5 – Solar Generation. Solar generation facilities are unique in that they can operate at almost any size, from a single panel to large, utility-scale plants. In the case studies reviewed, the main vulnerability of solar was found to be high winds that damaged the panels, although this was directly related to the design standard they were built to. For detailed information, see Section 4.

Although research is ongoing on the topic, solar (and other intermittent renewables) create a potential vulnerability in the electricity system. This was seen in Puerto Rico following Hurricanes Irma and Maria, where one solar facility was at operational capacity within a week, but curtailed from production for several months due to damages in the transmission grid and concerns about the stability of power production in the larger mix (U.S. Energy Information Administration 2018).

Solar Facilities were seen to be vulnerable to flooding (resulting in landslides or damage to foundations) and high winds. In Puerto Rico, four facilities were impacted by Hurricanes Irma and Maria, with three sustaining significant damage. The fourth facility was built to higher design standards and sustained less damage (see: Section 4).

Supply Chain and Interdependencies of Solar Facilities. The fuel supply chain vulnerabilities of renewables (wind, solar) are less vulnerable than traditional fuels relying on on-demand delivery. The uncertainty of weather and limited timescales for forecasting are areas for improved resiliency. Many case studies cited the use of solar panels following a hazard event for basic electricity provision, and the stockpiling and coordinated planning for post-disaster intermittent energy options was one recommendation for increasing resiliency (Fthenakis 2013; Ranada 2014a). Lack of transportation infrastructure would be limiting to their use in this capacity as well as to their repair.

Costs, Impacts and Resilient Design Considerations of Solar Facilities. The main case study where damages were observed is described in detail in Section 4 and highlights the importance of design standards in the resilience of utility-scale solar.

Table 12 – Solar Power, Costs and Resilient Design Guidelines	
	Hurricane
	* Panels and all components built at least 2 meters off the ground on mountings designed to avoid floods (Limperis 2017a) * Panels reinforced to withstand Category 5 winds (250 kph) (Limperis 2017a) * Need to be small and portable if being moved to areas in need (Ranada 2014b)

3.2.6 - Backup Diesel Generators

Vulnerabilities of diesel generators. The most widely observed damages to diesel generators found in the analyzed case studies was due to flooding (Table 13). In some locations, diesel generators are stored in the basement of a facility; when flooding, storm surge, or other damages occur, the generators are inundated and become inoperable. Damage to diesel generators from flooding was a major contributor to the meltdown of reactors at the Fukushima Daiichi nuclear complex, where backup power would have extended the time for a response effort.

Table 13 – Other Fuel Generation Facilities, Key Vulnerabilities			
	Hurricane	Drought/Heat Wave	Earthquake
Diesel Generators	* Temporary relief and backup for other power plants (NDRRMC 2014; Steve Mufson 2012; Ardagh et al. 2012) * Reliant on immediate on-demand fuel supply (Powell, Hanfling, and Gostin 2012)		* Serve as backup during times of grid related power outages (NDRRMC 2014; Ardagh et al. 2012) * Severe shaking can cause sump sludge which leads to failures

			(Ardagh et al. 2012)

Supply Chain and Interdependencies of diesel generators.
Diesel generators are often used as backup electricity when an outage occurs (NDRRMC 2014). Fuel is often stored on-site, but with longer outages or poor planning (such as not storing the fuel and generators in the same space), this can result in limited operation and have a significant impact on other critical facility operations that rely on electricity, such as hospitals or communication infrastructure (Powell, Hanfling, and Gostin 2012). In many examples, the co-location of fuel and generators is important (to minimize transport time and effort between generator and fuel required to operate).

Costs, Impacts and Resilient Design Considerations of diesel generators. The resilience of diesel generators was seen to depend on the ability to resist flooding and to have adequate fuel supply on hand.

Table 14 – Resilient Design Considerations, Diesel Generators
Flooding, (Hurricane, Storm Surge, Tsunami)
Store fuel next to generators Store generators above predicted flooding levels (water, debris, mud)

3.2.7 – Other Renewables (Wind, Hydroelectric, Geothermal)
Limited data was assessed for other important power generation technologies in terms of case study data, although this is an area for future work. Table 15 lists key vulnerabilities identified in this analysis for geothermal plants, hydroelectric plants, and wind farms.

Table 15 – Other Fuel Generation Facilities, Key Vulnerabilities

	Hurricane	Drought/Heat Wave	Earthquake
Geothermal	* Water and wind damage to cooling towers (Rappler.com 2013)		
Hydro	* Mud and water damage to generation plants (New York Power Authority et al. 2017)	* Low water levels limiting generation capacity, forcing closure (Alvaro 2018)	
Wind	* Blades ripped from poles due to high winds. Facilities are shut down when wind speeds exceed set threshold (typically 88 km/hour) (Conca 2017) * Damage to vertical posts (New York Power Authority et al. 2017)		

Diesel Generators	* Temporary relief and backup for other power plants (NDRRMC 2014; Steve Mufson 2012; Ardagh et al. 2012) * Reliant on immediate on-demand fuel supply (Powell, Hanfling, and Gostin 2012)		* Serve as backup during times of grid related power outages (NDRRMC 2014; Ardagh et al. 2012) * Severe shaking can cause sump sludge which leads to failures (Ardagh et al. 2012)

Vulnerabilities of wind, hydro, and geothermal. Wind farms were found to be particularly vulnerable to hurricane force winds and debris, resulting in damages in Puerto Rico and Texas. Damages to geothermal facilities in The Philippines were seen due to hurricane force winds and flooding resulting from Typhoon Haiyan.

Supply Chain and Interdependencies of wind, hydro, and geothermal. Hydroelectric facilities and diesel generators were seen to be heavily reliant on their supply chain for fuel – in this case, water and diesel gas, respectively. In Malawi, capacity was reduced by half because of low water levels at the largest hydroelectric plant during a 2017 drought and heatwave. Nearly all of Malawi's electricity is generated through hydroelectric plants, highlighting a potential vulnerability if precipitation patterns change in the future. Similar impacts from drought and heatwaves were seen in Tanzania in 2015 and Mozambique in 2016 (Alvaro 2018). Hydroelectric plants account for 12% of all Fuel Supply Emergency outages in the United States in the period 2000-2015 (Table 2) (Alvaro 2018).

Costs, Impacts and Resilient Design Considerations of wind, hydro, and geothermal. The resilience of wind farms was found to depend in part on the wind velocity that the turbines were designed to withstand. Hydroelectric facilities were seen to be vulnerable to blockages, but also flooding (through potential erosion of dam structures). Repair costs were found to be dependent on damage type and extent. Design considerations from the studies considered in this analysis are summarized in Table 16.

Table 16 – Other Generation Facilities, Costs and Resilient Design Considerations			
	Hurricane	Drought/Heat Wave	Earthquake
Wind	* Poles and blades reinforced to withstand Category 4-5 wind speeds 210 kph (U.S. Department of Energy 2018b)	* Can help prevent outages water supply is low (Scanlon, Duncan, and Reedy 2013; Faeth 2013)	
Hydro		* Install power mix that doesn't all depend on water for generation (Alvaro 2018)	

SECTION 4.0 – PUERTO RICO CASE STUDY

The Commonwealth of Puerto Rico is a set of islands in the Caribbean Sea southeast of the continental United States. It consists of several islands, with the majority of occupants on the largest and main island of Puerto Rico. Energy use in the Puerto Rico is about 1/3 the consumption per capita of the United States. The generation portfolio consists of many fuel types including coal, oil, natural gas and renewables including solar, wind and hydroelectric. The vast majority of electricity is generated using fossil fuels, all of which are imported. The electricity sector is run by PREPA, a government run agency that owns the transmission and distribution infrastructure as well as ~ 85% of the main island's generating capacity (U.S. Energy Information Administration 2018). In September 2017, Hurricanes Irma and Maria hit Puerto Rico and caused severe damage to all critical infrastructure, including the power grid. These events provide ideal case studies for understanding the impacts that a hazard can have on power infrastructure including: asset-level damages, interdependencies within the electricity grid system and with other critical infrastructures, the impact of supply chain disruptions, considerations for planning and policy, and the costs of building back better.

Hurricane Irma was a Category 5 storm that made landfall on September 6, 2017, and left 70% of electricity customers without power and damaged critical infrastructure (Campbell, Clark, and Austin 2017; New York Power Authority et al. 2017). On September 20, 2017, Hurricane Maria made landfall in Puerto Rico as a Category 4 storm with wind speeds of over 250 kph (Campbell, Clark, and Austin 2017). These storms caused catastrophic damage, especially to the electrical grid (Central Intelligence Agency 2018). Hurricane Maria brought torrential rainfall with a range of 38 to over 100 centimeters, resulting in widespread flooding across the island (Campbell, Clark, and Austin 2017). The northern coast was severely impacted as the rotation of the hurricane led to severe coastal storm surge, which coupled with major rain runoff from the central mountains resulting in sustained flooding (New York Power Authority et al. 2017). The damage was so extensive that even undamaged generators could not supply power (U.S. Energy Information Administration 2018). The damage resulted in electrical power outages to 90% of the island as well as loss of housing and infrastructure and contamination of potable water (Central Intelligence Agency 2018).

Puerto Rico's Office of Emergency Management reported that the storms had incapacitated the central electric power system, decimating transmission and distribution lines across the island and caused widespread wind and flood damage to substation, distribution, and generating facilities (Campbell, Clark, and Austin 2017; New York Power Authority et al. 2017). Hurricane Maria was the worst storm to hit the island in over 80 years, and the cost of the damage is estimated in the tens of billions of dollars (Central Intelligence Agency 2018). The request for disaster recovery funds, submitted by the Governor of Puerto Rico Ricardo Rossello in November 2017, totaled just under a trillion dollars. The second largest category in this request, behind housing, was for nearly at nearly $18 billion to restore the power grid and increase resiliency (R. Rossello 2017).

Much of the island's electricity is generated at power plants on the southern coast, while the largest population centers are in the north, making the system highly dependent on its 2,400 miles of transmission and 30,000 miles of distribution lines in the island's forested, central mountain range (U.S. Energy Information Administration 2018). Due to staffing shortages at PREPA, no one had been cutting back the jungle growth on these south to north transmission lines (Ferris 2018). As a result, the combination of long distances, inaccessibility, and wind and tree damage led to a near total wipeout of the electricity grid when Hurricane Maria hit (Ferris 2018). In particular, transmission lines and towers in the center of the island were severely damaged by high winds that were funneled through changes in the terrain (New York Power Authority et al. 2017). In all, approximately 101 transmission line segments, 636 poles, and 673 conductors/insulators were damaged by the storm, Table 16 (New York Power Authority et al. 2017).

In early October 2017, only 20% of all transmission lines in Puerto Rico were functioning (Ferris 2018). Steep hills and muddy slopes in the north-south corridor made access to damaged transmission lines difficult, leading to repair times lasting up to a year in some locations (New York Power Authority et al. 2017). Virtually 100% of PREPA customers did not have power for over a week following the storm, and this slow pace of recovery meant that many customers were left without power for several months (U.S. Department of Energy 2018a).

Generally, generating facilities were not as badly damaged as the transmission and distribution system (Table 15) (U.S. Energy Information Administration 2018). Most renewable generating facilities sustained modest amounts of damage (see Table 15); however, none of these facilities were able to connect to the power grid for several months (U.S. Energy Information Administration 2018). Small amounts of solar and hydropower were able to reconnect to the transmission system in late 2017; however, the first wind farm reconnected in February 2018 (U.S. Energy Information Administration 2018). Puerto Rico's second largest solar farm and second largest wind farm were both badly damaged and are not expected to be in service until 2019 (U.S. Energy Information Administration 2018).

4.1 - Power Generation

While Puerto Rico has some renewable solar, wind, and hydropower resources, the island has no reserves or production of conventional fossil fuels and primarily relies on imported fossil fuels (U.S. Energy Information Administration 2018). Approximately three-fourths of the energy used in Puerto Rico comes from petroleum products, most of which are imported through the ports of San Juan, Guayanilla, and Ponce (U.S. Energy Information Administration 2018). These ports were closed for 5 to 14 days following Hurricane Maria, leading to an estimated loss of 1.2 million barrels of petroleum per day during this period (U.S. Department of Energy 2018a).

Solar

The experience of Puerto Rico's solar farms in the aftermath of Hurricane Maria exemplify the importance of understanding the intra-system interdependencies and role that resilient designs can play in the vulnerability of systems. The extent of damages to transmission infrastructure was the primary driver of electricity recovery in Puerto Rico; specifically, different solar energy farms proved to have different levels of resilience during the 2017 Hurricane season in the Caribbean. While Hurricane Maria's flooding rains and winds heavily damaged a few of Puerto Rico's solar farms, including the second largest solar farm on the island where a majority of recently added solar panels were ripped from their foundations, many sites sustained minimal to no damage, Table 16 (Smith, 2017). The Illumina solar farm located on the southern coast is estimated to have lost a quarter of the modules from the 24 MW system to the storm (Limperis 2017). In contrast, there were hardly any damages to systems with adaptive designs (Limperis 2017). The solar farm in Loiza on the northern coast remained almost untouched by the hurricane (Limperis 2017). The panels at the site were specifically designed to outlast hurricanes: to prevent flood damage, each panel was built at least 2-meters off the ground and reinforced to withstand winds of Category 5 hurricanes (approximately 251 kph) (Smith 2017).

While a majority of solar farms sustained very little damage, a major factor preventing solar farms from exporting power to the grid was the complete destruction of the transmission and distribution system. This prevented sites from being able to reconnect to the grid and operate at full capacity. Apart from some torn away modules, Pattern Energy's 101 MW Santa Isabel wind farm sustained minimal damage following the storm (Limperis 2017). While the farm lost power in the days following Hurricane Maria's landfall, within a week, the farm informed Puerto Rico's Electric Power Authority (PREPA) that it was ready to return to normal operations (Merchant 2018). However, over seven months after Hurricane Maria, generation remained 75 percent curtailed because of grid issues (Merchant 2018). Similarly, AES' Illumina solar farm also was curtailed for months due to transmission work delays (Merchant 2018). Further, PREPA did not authorize the 24 MW solar farm in Guyama to begin exporting power to the grid until February 2018, and then only at 10% of the farms' normal generation. Of particular concern was that solar power could create instability with the recovering transmission network in the area not able to support the amount of electricity potentially being fed into it (Gallucci 2018). Over a year after the storm, in October 2018, the site was only operating at 74 percent capacity (Gallucci 2018).

Table 15: Summary Damages to Solar Plants From 2017 Hurricanes, Puerto Rico			
Plant Location	**Gen. Capacity**	**Damages**	**Design Specifications**
Humacao	44 MW	* The first phase of the solar farm, (finished in 2016) fared relatively well (Limperis 2017) * The solar modules of the northern expansion still under construction, consisting of 52 MW, were almost completely ripped from their mountings (Limperis 2017) * Majority of newly added solar panels ripped from foundation and completely destroyed by winds (Smith 2017)	* System fitted with Fonroche modules (Limperis 2017)
Guayama	24 MW	* Satellite imagery estimates a quarter of modules were ripped from their mountings by the storm (Limperis 2017) * Site back to 74% generating capacity by mid-October (Gallucci 2018) * Curtailed because of transmission system damage (Gallucci 2018)[4]	
Loiza	27 MW	* Minimal damage (Limperis 2017)	* Panels and all components (inverters, transformers) built several (at least 2) meters off the ground on mountings designed by TSK to avoid floods (Limperis 2017) * Reinforced to withstand Category 5 winds (251 kph) (Limperis 2017) * Design withstood both the hurricane and the torrential rainfall well (Limperis 2017)
Isabela	58 MW	*Apart from occasionally torn away modules, almost no damage was caused (Limperis 2017)	* Example of resilient design (Limperis 2017)

4.2 - Other Considerations

The Puerto Rican government was facing challenges prior to the arrival of Hurricane Maria (Campbell, Clark, and Austin 2017). In the last decade, Puerto Rico's economy has shrunk by over 15 percent, and this economic downtown has coincided with a sharp rise in the price of oil, which generates the majority of the island's electricity (Central Intelligence Agency 2018). Prior to the 2017 hurricane season, the island's electricity infrastructure was in poor condition, largely due to underinvestment and a lack of

[4] Note: there are conflicting reports concerning the extent of damages at the Guayama wind farm. This highlights the need for more complete coverage of storm damages.

maintenance (Campbell, Clark, and Austin 2017). PREPA's electricity generators were 28 years older than that of the U.S. average, and the outage rates of these generators were 12 times higher than the U.S. average prior to the arrival of Hurricanes Irma and Maria (U.S. Energy Information Administration 2018). Only 15% of transmission lines on the island were built to Category 4 storm criteria (New York Power Authority et al. 2017).

4.3 – Resiliency and Building Back Better

As repairs and rebuilding occur, PREPA has evaluated rebuilding resilience options (and has been the subject of several reports, including New York Power Authority et al. (2017), Rossello (2017), and Bloodgood and Martinez (2018)). Drawing on these and other sources, Table 16 provides asset-level estimates of costs for rebuilding damaged power infrastructure. Recommendations (where given) for rebuilding to a more resilient design standard are also included as are the estimated incremental costs of doing so. More detailed information is provided in Appendix E. Other resilience options are being explored; for example, Siemens Industry, Inc. (2018) presents a vision for mini-grid based systems designed to withstand outages better than an existing island-wide grid.

Results show that the cost of building back better, when compared to baseline estimates, varies greatly in magnitude based on the component. For example, hardening of the transmission grid (lines, poles, circuits) are generally relatively low incremental costs (~10%). Appendix D provides detail on the costs, damages, and baseline and resilient unit cost estimates for upgrading infrastructure design. Results show that there is approximately 3-40% increase in cost to upgrade transmission and distribution infrastructure to withstand Category 3 hurricanes, while there is a 24-70% increase in cost to upgrade to Category 4 hurricanes (130 mph sustained windspeeds). When wood poles (low windspeed design) are compared with tubular steel poles, for example, costs may increase as much as 200% (see Appendix D).

Table 16: Reported damages following 2017 Hurricane season in Puerto Rico. When available, costs represent estimates specific to the Puerto Rico grid (New York Power Authority et al. 2017). Where costs were not available, estimates were used from various sources *(see:* PG&E 2018; California ISO 2012; Curry and Wilson 2012)

Power System Component	**Transmission Lines and Structures 115 kV**	**230 kV**	**Distribution Circuits**	**Substations**
Number damaged	84 Line Segments, 230 Towers/poles	17 Line Segments, 106 Towers/Poles	900	252
Baseline Unit Repair Cost	1.4/mile	1.6/mile	0.91/mile	\$5.5 - \$9.5 (depending on capacity)
Build Back Better Unit Cost	1.5/mile	1.9/mile	2.0/mile	15/substation
Incremental Better Unit Cost	0.1/mile	0.3/mile	1.09/mile	277/substation
Incremental Better System Cost	41*	13*	357*	4155*

**Note* - not all costs add up exactly; much of the available information did not include cost information or exact miles (unit damages reported in segments or number of poles, while costs are given in miles). Estimates were made from available information. Where missing from Puerto Rico-specific documents, estimates were made using equivalent U.S. based design structure and components.

A final consideration for resilient infrastructure design is the incremental design costs relative to the probability that an event occurs over the lifetime of the infrastructure. While a full analysis of the power grid infrastructure in Puerto Rico and occurrence of hurricane-level storms is outside the scope of this paper, Table 17 provides an estimate based on historical storm occurrences since 1901. More detail is provided in Appendix D and E. Taken together, this information lays a foundation for a probabilistic risk assessment and cost-benefit analysis of different infrastructure investment decisions and is an area for future work.

Table 17: Summary statistics for windspeed events occurring in Puerto Rico, 1901-Present. Data for windspeed recorded in one-minute sustained wind speeds at approximately 100 meters above ground elevation. (For details on calculation, see Appendix E). *Data from:* National Centers for Environmental Information (2018)

	Top Windspeed for Category (miles/hour)	Top Windspeed for Category (km/hour)	Annual Prob. Of 1 event	Number of Storms since 1901
Tropical Storm	40-74	63-118	10.6%	14
Hurricane - Category 1	74-95	119-153	2.5%	3
Hurricane - Category 2	96-110	154-177	2.5%	3
Hurricane - Category 3	111-129	178-208	0.8%	1
Hurricane - Category 4	130-156	209-251	2.5%	3
Hurricane - Category 5	>156	>251	0.8%	1

5.0 – SUMMARY OF FINDINGS

5.1 – Power Grid Infrastructure

Generation plant vulnerabilities were the broadest area in our case studies. However, the data do suggest specific guidelines about resilience (or lack the of) of specific power generation systems (fuel types) in the context of specific hazards. For example, in Section 4, the performance of 4 solar photovoltaic farms in Puerto Rico are detailed to show how the design parameters of a system define the impact it sustains from a hurricane event. Similarly, in Section 3.1.3, transmission and distribution investments totaling $6 million made in New Zealand for higher seismic design standards are estimated to have saved Orion an estimated $30-50 million in direct asset replacement costs during the 2010-2011 earthquake events (Fenwick and Hoskin 2011). In this context, an important finding is that more robust design standards (such as a higher design threshold for wind speed) is directly related to performance during and after a hazard event. A next step in assessment would be to calculate the relative incremental cost of a more or less robust asset design and both the dividend in terms of performance in a hazard situation and the resilience dividend[5].

[5] The resilience dividend is defined as the value of more resilient infrastructure *in the absence* of the event it is designed for. This can include things like aesthetics, job creation and performance in other events than the specific design threshold. It is similar to the idea of 'co-benefits', but explicitly tries to value to benefit to a community of spending more on infrastructure that is more resilient beyond the resilience to a specific event.

A key finding in this study is the vulnerability of different generation technologies to the fuel supply chain. In a hazard situation, damage often occurs to other infrastructure systems including pipelines, roads, and ports. The interdependencies between these supply systems and others are important for understanding the impact a hazard has on society. Generation technologies that require on-demand fuel delivery notably include natural gas, oil, and coal fired systems. While some on-site reserve is typical with coal, it is less common for natural gas and oil-fired capacity making the supply chain of these systems vulnerable to many hazards. This was seen in Puerto Rico following Hurricanes Irma and Maria, where port closures resulted in an estimated loss of 1.2 million barrels per day of petroleum, over the course of 11 days, and directly affected the major generation stations which relied exclusively on imported fuel types (U.S. Department of Energy 2018a). Similar closures occurred in Texas during the same events in 2017 as well as in New York and New Jersey during Hurricane Sandy (U.S. Department of Energy 2018a). These fuel supply chain vulnerabilities are in contrast to renewable sources (wind, solar) and generations which keep a supply of fuel on hand (e.g. diesel generators used for short term backup) and those which require less frequent refueling (i.e. nuclear).

Four recent hurricane events and one typhoon event were investigated. These included Hurricane Sandy (Northeastern United States), Hurricane Harvey (Texas, United States), Hurricanes Irma and Maria (Puerto Rico and U.S. Virgin Islands) and Typhoon Haiyan/Yolanda (The Philippines). The recent hurricane events in Puerto Rico also resulted in several useful documents relating to the energy grid infrastructure and damages it sustained during the hurricane events. Particularly useful in this instance is a detailed assessment (New York Power Authority et al. 2017) of individual power generation stations, transmission line failures and design recommendations for recovery efforts. Puerto Rico provides an ideal case study for assessing power system vulnerabilities because of its isolated grid, its diversity in fuel generation technologies and the availability of information following the event. The recent hurricanes here can also be compared directly with impacts in the US Virgin Islands, a much smaller set of islands 180 kilometers east of Puerto Rico. The US Virgin Islands were hit by the same hurricanes, at similar or higher strength, and saw similar devastation to the power systems. Despite this, the rebuilding efforts, time, planning and other factors differ notably with those of Puerto Rico (e.g. U.S. Department of Energy 2018a). These events then present a unique opportunity to compare the recovery efforts and identify best practices related to preparation and building back better.

Drought and heat waves often coincide and may exacerbate the severity of both events. High temperatures can make it difficult for water to reach temperatures cool enough to be discharged and, due to permitting restrictions, may require generation curtailment (Galbraith 2011). A case study on the 2011 Texas heat wave was performed and augmented with facility-specific data for curtailments at several facilities. The impacts on power generation were similar across all data reviewed: water availability and temperature affected generation systems that rely on cooling water. This was also seen in France in August 2018. Here four nuclear reactors were shut down because river temperatures were too high to allow for water discharge (Shugerman 2018). There are examples of adaptation to these challenges, highlighting both policy and design considerations. During the 2011 heat wave in Texas, water typically allocated to farmers in the area was directed to power plants despite regulations detailing the opposite prioritization (Faeth 2013). Partially due to the aggressive installation of wind power in years prior, the increased demand was met through these alternative generation sources but resulted in much higher prices than normal (NOAA 2011; EIA 2011). The Palo Verde plant in Arizona (USA) also has a unique approach to cooling water. This facility does not sit on a body of water but instead uses recycled municipal water (APS 2018).

Drought conditions threaten thermoelectric plants (including coal and nuclear generation facilities) by reducing the availability of cooling water (Galbraith 2011). Several droughts in Sub-Saharan Africa have resulted in documented power losses. The country of Malawi generates 98% of its power from hydroelectric plants and, in 2017, saw capacity reductions of 50% (from 300 MWe to 300 MWe) due to low water levels. As a result, rolling blackouts lasting over 24 hours were required (Alvaro 2018). Similar issues were seen in Tanzania. In 2015 the country was forced to shut down all hydropower due to two years of drought conditions (Alvaro 2018). In several cases, hydroelectric power facilities planned for installation in dams sit in river basins recently affected by severe drought, a hazard event that may increase with climate change ((Alvaro 2018; Conway et al. 2017).

Pre-emptive curtailments were found to occur as a precaution when a hazard event was projected to be imminent at or above safe operating thresholds for a facility. This includes most generation types and a range of hazard events. In cases of drought, a lack of water availability for cooling systems was found to be a cause of curtailment or shutdown (also discussed in the next section on generation-specific vulnerabilities). In cases of extreme heat, the temperature limits set on intake or discharge water from cooling systems may require shutdown of a plant unless special permissions are granted to exceed normal thresholds, often seen at 25°C (Eaton 2012); (Morris 2015).

The impacts of climate change are a particularly important consideration where weather can impact power systems (Mukhi et al. 2017). Particularly, in regions where precipitation patterns are predicted to change and temperatures increase, this may have impacts on facility operation. The consideration of available resources over the life-cycle of a facility during plant design is one factor to increase resiliency.

5.2 – Other Considerations: Planning and Policy

In case studies where a catastrophic failure of the power grid was seen (such as The Philippines or Puerto Rico case studies), a few findings emerged in the context of response and recovery. First, pre-emptive planning is critical. This can take many forms, including storage of diesel generators and fuel in critical sites, such as hospitals (Powell, Hanfling, and Gostin 2012), storage of repair vehicles and equipment close to distribution stations or key points in the grid and stockpiling and coordinated planning for post-disaster intermittent energy options (such as rooftop solar panels) (Fthenakis 2013; Ranada 2014a).

In large-scale disasters, existing aid relationships and political agreements can facilitate the quick deployment of temporary infrastructure. When this does not exist, there can be delays in response efforts (NDRRMC 2014; Ranada 2014a);(FEMA 2018b)). Pre-emptive planning can also be important as it typically includes an emphasis on maintenance to address vulnerabilities that may exist because of aging infrastructure or other factors. In Puerto Rico, for instance, some of the challenges relating to transmission infrastructure damage and restoration times was dependent on the jungle growth around the lines, limiting access (Ferris 2018). In the context of 'building back better', pre-emptive planning may allow for quicker restoration at lower costs for higher design standards than would be possible if more resilient design is not considered until after a hazard occurs. This was seen in a comparison of Puerto Rico and the US Virgin Islands. Here the same events (Hurricanes Irma, Maria and Harvey) were analyzed in two very close geographic locations that showed different recovery patterns. In April 2018, FEMA and the Virgin Islands Water and Power Authority announced plans to harden the power grid in the U.S. Virgin Islands so that it can withstand hurricanes with winds up to 321 km/hour. This will be accomplished by placing critical transmission lines underground, replacing wooden transmission and distribution poles with stronger, composite poles, and developing micro electric grids (FEMA 2018a). In contrast, no such formal plans have been announced to strengthen Puerto Rico's power grid.

An important finding that applies across supply chains, generation facilities, and the electricity grid is that redundancy can directly contribute to more stable grid operation even in a non-normal event. Redundancy of transmission lines can allow power to be re-routed if a single line is damaged, and this can reduce curtailment of plants and limit disruptions to consumers. Where multiple generation technologies exist within a power grid, redundancy can reduce recovery time, as can redundancy in supply chains. This was particularly evident in Texas following Hurricane Harvey where nuclear power was able to operate at full capacity throughout the event and wind farms were curtailed during the event but most immediately came back online, covering much of the demand deficit seen from reductions in generation facilities located on the coast which were more affected by storm surge and flooding for longer time periods (Conca 2017).

6.0 - CONCLUSIONS

The impact of natural hazard events on power infrastructure varies based on the asset being analyzed, the standards to which it was constructed, the hazard event, its severity and duration, as well as many other factors. Yet across geographies and hazards, some generalizations are possible. In many instances, design and planning considerations can enhance the resiliency of the asset to withstand and recover from an event. This is true for wildfires, drought, heat waves, flooding, hurricanes, earthquakes and more. As climate change continues to accelerate the pace and severity of weather-related events, quantifying the benefit to proactive adaptation and construction of the power grid requires better understanding. To this aim, this paper has identified several key vulnerabilities and adaptation considerations, including generation facility-specific considerations, supply chain differences in fuel types and the transmission grid.

This paper details three general areas of vulnerability: Supply chains for fuel and maintenance; Generation facility cooling systems and safe operating thresholds; Transmission infrastructure, particularly for above ground transmission lines. System-wide catastrophic failures due to extreme natural hazard events were also seen, especially in developing regions. Each of these findings is detailed in Section 3, including (where available) associated estimated costs and design considerations for more resilient operation of the grid.

6.1 – Areas for Future Work

An important area of future work is to establish the likelihood of future disruptions to power systems from region specific threats. In particular, electrical distribution grids were found to be generally vulnerable to many natural hazards, but wind in particular. Historical wind data is available at high spatial and temporal resolution for much of the world. This can be used to identify regions where electrical grids would be at significant risk and to advise building and maintenance standards to ensure their resiliency. Climatological predictions for future rainfall and temperature also available and can be used to inform where cooling water might become limited. Similarly, historical data on wildfires can be used to identify regions at particular risk for these events. These predictive data can be used to design better systems, and to inform 'build back better' efforts.

Additional case studies on geography specific natural hazard events should also be undertaken. Several cities in Sub-Saharan Africa, Southeast Asia and South America cite aging, failing or inadequate energy infrastructure as ongoing considerations. Additional case study work for these locations could help inform the best techno-economic approach to increasing resilience. Appendix F contains information on some developing regions of the world that are of interest for future work. This includes a list of severe natural hazard events (Table F-1) and a list of geographic regions with regions of interest for case study work based on hazard exposure and an infrastructure gap (Table F-2). As an example, Lagos, Nigeria has over 20 million persons, lacks critical power, and other, infrastructure and is prone to natural hazard events including flooding and sea level rise (Gandhi 2018; Soleye 2015; Business Journal 2017; 100 Resilient Cities 2018b; Busari and Osman 2017). Kigali, Rwanda cites similar issues regarding infrastructure, energy shortages, and exposure to flood, droughts, and severe storms (Byumvuhore 2018; May and Kamurase 2009; 100 Resilient Cities 2018a; Al Jazeera 2018; Davis 2017).

The interdependencies of infrastructure systems are complex, poorly understood, and affect the ability to recover from a hazard events. Future work in this area should consider a larger range of events and geographies, specifically as they relate to design considerations, although data availability is a limitation. A particular topic of interest is the interdependence of power systems with other critical infrastructure such as roads, pipelines, emergency services and communication infrastructure. How to avoid cascade failures when one system is damaged is an important for future work. Finally, the value of different types of generation and distribution networks (large, centralized vs. smaller, distributed systems) should be considered in the context of other stresses on a system, including conflict and man-made disasters. Understanding the benefit to smaller distributed systems that require less transmission distances and have a smaller, localized geographic impact if compromised is an important area of study in geographies with ongoing conflict.

Additional work on geographically specific hazard probabilities, coupled with the associated generation and distribution system vulnerabilities, can be used to inform location specific design and rebuilding standards. This information could help to better allocate development and redevelopment funds. Consideration of exposure to a hazard (particularly in terms of siting facilities near coasts, waterways or within floodplains) can impact the amount of damages seen. Specific engineering design standards listed in Table 4 and Appendices B, C and D can be used as a reference point in this work.

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APPENDIX A

Definitions for selected terms used in this study. All definitions found in: *Secretary-General. "Report of the Open-Ended Intergovernmental Expert Working Group on Indicators and Terminology Relating to Disaster Risk Reduction." United Nations General Assembly, November 1, 2016.*

- **Build back better**: The use of the recovery, rehabilitation and reconstruction phases after a disaster to increase the resilience of nations and communities through integrating disaster risk reduction measures into the restoration of physical infrastructure and societal systems, and into the revitalization of livelihoods, economies and the environment
- **Critical infrastructure**: The physical structures, facilities, networks and other assets which provide services that are essential to the social and economic functioning of a community or society
- to the social and economic functioning of a community or society
- **Resilience:** The ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management.
- **Recovery:** The restoring or improving of livelihoods and health, as well as economic, physical, social, cultural and environmental assets, systems and activities, of a disaster-affected community or society, aligning with the principles of sustainable development and "build back better", to avoid or reduce future disaster risk.
- **Response:** Actions taken directly before, during or immediately after a disaster in order to save lives, reduce health impacts, ensure public safety and meet the basic subsistence needs of the people affected.

APPENDIX B – CASE STUDY FINDINGS: DAMAGES AND IMPACTS TO TRANSMISSION AND DISTRIBUTION INFRASTRUCTURE

This appendix provides a table (B-1) detailing the results of the case study analysis specific to damages and impacts to transmission and distribution infrastructure.

Table B-1 Selected Case Study Impacts to Transmission and Distribution Infrastructure					
Location	**Event**	**Date**	**Reason**	**Detail**	**Effect**
The Philippine s	Hurricane	2013	Category 5: Strong winds	Damaged 248 towers, 318 poles, and 7 substations mainly in the Visayas (Jagnarine-Azan 2014). 13,406 km of power lines damaged	Contributed to long duration of power outages (IBON Foundation 2015)
New Zealand	Earthquake	2011	Liquefaction	Equipment met then current standards, but was aging (Giovinazzi et al. 2011). 15% of 11 kV cables, 50% of 66kV cables, 0.6% of LV cables, and 4 substations were damaged (N. Watson 2013), largely due to liquefaction.	Took 14 days to restore power to 90% (Giovinazzi et al. 2011) 248 MWe demand lost (N. Watson 2013)
California, U.S.	Wildfire	2015			Power lines caused the burning of 149,241 acres (Penn 2017)
California, U.S.	Wildfire	2017		Power turned off for ~33 hours to prevent power lines from starting fires (Daniels 2017)	
California, U.S.	Wildfire	2007	High wind speeds led to power line failures (Mitchell 2018)	Power line failures listed as cause of Sedgewick, Canyon, and Grass Fires (McCall, Macknick, and Macknick 2016)(U.S. Forest Service 2012)	Power lines caused fires that resulted in 1,300 homes destroyed and 2 deaths (Daniels 2017)

California, U.S.	Wildfire	2007	Transmission lines destroyed due to wildfires (U.S. Forest Service 2012)	Griffith Park Fire burned 817 acres in LA (U.S. Forest Service 2012)	Power outages to local neighbors (U.S. Forest Service 2012)
East Coast, U.S.	Hurricane Sandy	2012	Post-Tropical Cyclone: Storm surge, flooding, high winds	Transmission grid, distribution system damages (Hoffman and Bryan 2013)	Outage duration ranging from 2507 minutes - 20280 minutes Outage affected a total of 8.6 million customers (Hoffman and Bryan 2013)
Puerto Rico	Hurricane Maria	2017	Category 4: High winds, flooding	636 230 and 115 kV poles damaged, 252 substations damaged (New York Power Authority et al. 2017)	1,569,796 (100%) customers at peak (U.S. Department of Energy 2018a)
Puerto Rico	Hurricane Maria	2017	Category 5: High winds, flooding	Approx. 80-90% of transmission and distribution systems damaged (Clark, Campbell, and Austin 2018)	46,496 customers (U.S. Department of Energy 2018a)
Texas, U.S.	Hurricane Harvey	2017	Category 4	Hundreds of high-voltage transmission lines, including six 345 kilovolt (kV) lines and more than two hundred 69 kV–138 kV lines experienced storm-related forced outages; flooding force power plants to shut down (U.S. Energy Information Administration 2017; U.S. Department of Energy 2018a)	306,058 customers affected (U.S. Department of Energy 2018a)
Florida, U.S.	Hurricane Wilma	2005	Category 3 Hurricane	Damage to transmission poles, wires, and substations; includes high voltage transmission lines; substantial damage to distribution system (Department of Energy 2005)	1080 minutes, 10,000 MW 3.2 million customers affected (Mukherjee, Nateghi, and Hastak 2018b)

Virginia, U.S.	Thunderstor m	2012	High winds	Strong winds from storm knocked down power lines (Sinclair Broadcast Group 2012)	6787 minutes, 5000 MW 880,000 customers affected (Mukherjee, Nateghi, and Hastak 2018b)
Michigan, U.S.	Ice Storm	2013	Ice, winds	Ice coated power lines and trees; cold temperatures kept ice from melting (Stanglin 2013)	350 MW 140,735 customers affected (Mukherjee, Nateghi, and Hastak 2018b)
Oklahoma , U.S.	Ice Storm	2010	Ice, winds, cold weather	Ice weighing down trees and power lines (Lusby 2010)	148 minutes, 30 MW (Mukherjee, Nateghi, and Hastak 2018b)
California, U.S.	High winds	2011	High winds	225 kph wind gusts; reports of 460 downed power lines (Thompson 2011) Ice weighing down trees and power lines (Lusby 2010)	2016 minutes, 300 MW 100,000 customers affected (Mukherjee, Nateghi, and Hastak 2018b)
South Carolina, U.S.	Winter Weather	2014	Ice, wind	Half an inch of ice accumulation and snow weighed down poer lines causing them to go down (Bell and Lyttle 2014)	4177 minutes, 700 MW 120,124 customers affected (Mukherjee, Nateghi, and Hastak 2018b)
California, U.S.	Heavy Rain	2015	Rain, wind	Record rainfall from Tropical Storm Delores, 1.03 inches; lightning strikes in the area sparked wildfires and contributed to the outages (Robbins and Sifuentes 2015)	166 minutes, 160 MW 78,164 customers affected (Mukherjee, Nateghi, and Hastak 2018b)
Minnesota , U.S.	Thunderstor m	2015	Strong winds	250 transmission poles destroyed, trees fell onto power lines causing damage 100 transformers damaged (Dispatch 2015)	1740 minutes, 250 MW 250,000 customers affected (Mukherjee, Nateghi, and Hastak 2018b)

APPENDIX C – CASE STUDY FINDINGS: DETAILED FACILITY IMPACT INFORMATION

This appendix contains a table (C-1) the details specific facility damages incurred from natural hazard events.

Table C-1: Detailed facility impact information from case study assessments

Plant	Generation Type	Location	Event	Class	Date	Reason	Detail	Effect
Leyte Geothermal	Geothermal	Philippines	Hurricane	Cat 5	2013	Water damage (Rappler.com 2013)	Generation slowly brought back online over a few months: 120 MW on Dec. 9 (Rappler.com 2013) Total capacity of 650 MW and typically supplies about a third of the power for the region	Part of the reason for power outages in the Visayas restored to ~90% as of March 2014 (IBON Foundation 2015); Not fully repaired until a year after the event (IBON Foundation 2015)
Estancia Oil Barge	Oil	Philippines	Hurricane	Cat 5	2013	Strong winds and storm surge	Power barge ripped off moorings and slammed onto shore (Joint UNEP/OCHA Environment Unit 2013)	Caused an oil spill that threatened the environment, human health, and local livelihoods (Joint UNEP/OCHA Environment Unit 2013)
Philippines Transmission Network	Transmission	Philippines	Hurricane	Cat 5	2013	Strong winds	Damaged 248 towers, 318 poles, and 7 substations mainly in the Visayas (Jagnarine-Azan 2014)	Contributed to long duration of power outages restored to 90% as of March 2014 (IBON Foundation 2015)

Solar Panels - Enkindle Projct	Photovoltaic	Philippines	Hurricane	Cat 5	2013		Temporary solar panels lent to hardest hit areas to provide emergency power (Ranada 2014a)	Temporary relief
Diesl Generators	Diesel Generators	Philippines	Hurricane	Cat 5	8-Nov-13		164 generators deployed by the Department of Energy to the Visayas (NDRRMC 2014)	Temporary relief
Diesl Generators	Diesel Generators	Christchurch, NZ	Earthquake	6.3 mag	2011	Heavy shaking	Christchurch Hospital had 6 backup generators that experienced failures due to shaking distributing sump sludge within the diesel tanks (Ardagh et al. 2012)	Temporary relief
New Zealand Distribution Network	Distribution	Christchurch, NZ	Earthquake	6.3 mag	2011	Liquefaction	Damage to 66 kV, 11 kV, and LV cables and 4 substation (N. Watson 2013)	Took 14 days to restore power to 90% (Giovinazzi et al. 2011)
ERCOT Grid	Power Grid	Texas	Drought/ Heatwave	D4 - Exceptional Drought (NOAA 2011)	Summer 2011	Lack of water for cooling limiting generation and high temperatures increasing demand (NOAA 2011)	Limited interconnection with North American grid reduces ability to handle generation limiting events like extreme weather (EIA 2011)	No power outages due to drought, but price spikes (EIA 2011)

Thermoelectirc Power	Nuclear, coal, natural gas, oil	Texas	Drought/ Heatwave	D4 - Exceptional Drought (NOAA 2011)	Summer 2011	Lack of water for cooling	24 MW of generation lost due to drought conditions; as of Dec. 2011, 11,000 MW of supply was in areas of water at historically low levels and 15% of generating capacity were cnsidered at risk of shutting down (Harto and Yan 2011)	No power outages due to drought, but price spikes (EIA 2011)
Wind Power	Wind	Texas	Drought/ Heatwave	D4 - Exceptional Drought (NOAA 2011)	Summer 2011	Aggressive installation prior to summer of 2011 (Faeth 2013)	On average 10% and a max of 18% of Texas power was supplied by wind generation (Faeth 2013)	Without the wind power, rolling blackout woulds have been likely (Faeth 2013; Scanlon, Duncan, and Reedy 2013)
California Transmission Lines	Transmission	California	Wildfire		2007			
Power Lines	Transmission	California	Wildfire		2015			Power lines caused the burning of 149,241 acres (Penn 2017)

Power Lines	Transmission	Riverside County, CA	Wildfire	2017		Power turned off for ~33 hours to prevent power lines from starting fires (Daniels 2017)	
SDG&E Electric Utility	Utility	California	Wildfire	2007	High wind speeds led to power line failures (Mitchell 2018)	Power line failures listed as cause of Sedgewick, Canyon, and Grass Fires (McCall, Macknick, and Macknick 2016)(U.S. Forest Service 2012)	Power lines caused fires that resulted in 1,300 homes destroyed and 2 deaths (Daniels 2017)
Transmission Network	Transmission	Los Angeles, CA	Wildfire	2007	Transmission lines destroyed due to wildfires (U.S. Forest Service 2012)	Griffith Park Fire burned 817 acres in LA (U.S. Forest Service 2012)	Power outages to local neighbors (U.S. Forest Service 2012)
Malawi Hydro	Hydropower	Malawi	Drought/ Heatwave	2017	Low water levels at country's largest hydro plant (Alvaro 2018)	Capacity dropped from 300 MW to 150 MW (Alvaro 2018)	Country gets 98% of it power from hydro; rolling blackout enforced, some lasted 24 hours (Alvaro 2018)
Tanzania Hydro	Hydropower	Tanzania	Drought/ Heatwave	2015	Low water levels at all hydro plants (Alvaro 2018)	Forced to close all hydropower plants (Alvaro 2018)	Tanzania only able to generate 12% of power regularly consumed (Alvaro 2018)

Cahora Bazza	Hydropower	Mozambique	Drought/Heatwave		2016	Two years of drough conditions (Alvaro 2018)	Generation down to 34% of full dam capacity (Alvaro 2018)	Africa's largest hydropower plant(Alvaro 2018)
Salem Unit 1	Nuclear	New Jersey	Hurricane Sandy	Post Tropical	2012	High water levels (Steve Mufson 2012)	Manually shut down because water circulating pumps weren't working (Steve Mufson 2012)	
Nine Mile Point 1	Nuclear	New York	Hurricane Sandy	Post Tropical	2012	Electrical disruption (Steve Mufson 2012)	Automatically shut down due power disruption (Steve Mufson 2012)	
Nine Mile Point 2	Nuclear	New York	Hurricane Sandy	Post Tropical	2012	Loss of power (Steve Mufson 2012)	Loss of power from off site power lines, operations resumed as soon as diesel generators kicked in (Steve Mufson 2012)	
Indian Point 3	Nuclear	New York	Hurricane Sandy	Post Tropical	2012	Electrical disruption (Steve Mufson 2012)	Automatically shut down due to electrical disturbance (Steve Mufson 2012)	

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APPENDIX D - PUERTO RICO DAMAGES AND COST ESTIMATES

This appendix provides detailed damage assessment information available from multiple sources specific to Puerto Rico following the 2017 Hurricane season. There are two sections: first, detailed damages as reported from several sources are summarized to provide an overview of the system damage; second, the authors provide estimates of incremental resilient design investments. The latter section focuses on component-specific design standards for building power infrastructure to withstand Category 1-5 hurricane events, and the incremental costs associated with different design decisions. This includes specific information, for example, on the cost of a distribution pole built to withstand category 1 winds and the cost to withstand a category 4 storm (and the incremental unit cost of choosing a more resilient design). It also includes information on multiplicative factors specific to different terrain and weather considerations, such as whether a system is being constructed on flat, rural land, mountainous terrain, or urban areas.

This information can be analyzed along with Appendix E to understand the probabilistic risk and associated design costs for different levels of resilient infrastructure investment choices. A key finding in this research effort is the diversity of components and design choices available for a power grid; future work into this area will improve the generalization and estimation possibilities for different design thresholds.

Section K-1: Puerto Rico, Detailed Damages to Power Grid Infrastructure

As repairs and rebuilding are occurring, PREPA - and Puerto Rico in general - is evaluating rebuilding resilience options (and has been the subject of several reports, including New York Power Authority et al. (2017), Rossello (2017), and Bloodgood and Martinez (2018)). Table D-1 provides a summary of the damages to the power grid in Puerto Rico, emphasizing the systemic nature of damages. Drawing on these and other sources, Table D-2 provides asset-level estimates of costs for rebuilding damaged power grid transmission and distribution infrastructure, the recommendations (where given) for rebuilding to a more resilient design standard, and the estimated incremental costs of doing so. Table D-3 provides this information for generating facilities.

Table D-1 – Power Grid Damages, Summary of Assets
All data from New York Power Authority et al. (2017) unless otherwise noted

Transmission & Distribution	**Component**	**kV**	**Number damaged**
	Transmission Lines	115	84 Line Segments
		230	17 Line Segments
	Transmission Structures	115	530 Towers/Poles
		230	106 Towers/Poles
	Substations	38/115/230	252 Substations
	Distribution Circuits	4-13	900 Circuits
Generating Facilities	**Fuel Type**	**Number damaged**	**Total MW Generating Cap.**
	Oil	8	4,159
	Coal	0	N/A
	Natural Gas	1	820
	Solar	2 (Limperis 2017; Smith 2017)	68 (Limperis 2017; Smith 2017)
	Wind	1	26 (Siciliano 2017)
	Hydro	1	22.5)
Electricity Outages	**Metric**	**Time**	**Value** (*Source unless noted*: U.S. Department of Energy 2018)
	Percent Customers	1 week	100%
		1 month	81.50%
		6 months	6.60%
		1 year	0% (Sullivan 2018)
	Number of Customers	1 week	1,569,796
		1 month	1,279,384
		6 months	97,000
		1 year	0 (Sullivan 2018)

Where available, Table D-2 and D-3 take costs directly from these reports and, where not provided, are estimated using US-based engineering design standards and unit costs applied to known damaged components. Other resilience options are being explored; for example, Siemens Industry, Inc. (2018) presents a vision for mini-grid based systems designed to withstand outages better than an existing island-wide grid.

Results show that the cost of building back better, when compared to baseline estimates, varies greatly in magnitude based on the component. For example, hardening of the transmission grid (lines, poles, circuits) are generally relatively low incremental costs (~10%) based on estimates made in Puerto Rico.

However, one note here is that the estimates from New York Power Authority et al. (2017) for repairing distribution circuits are inconsistent with other estimates; the estimated costs of rebuilding to a more resilient design standard are lower than baseline estimates made by nearly a factor of four. While this source does not provide detailed information on specific construction and asset costs by component, estimates using US-based design standards indicate these costs may be higher.

Table D-2: Baseline and Build Back Better Component Estimated Costs - Transmission and Distribution
Unless otherwise noted, all information from New York Power Authority et al. (2017)

Component	Transmission Lines and Structures					Distribution Circuits	Substations		
kV	38	115		230		4-13	38 [6]	115	230
Number damaged	N/A	84 Line Segments	530 Towers/ Poles	17 Line Segments	106 Towers/ Poles	900 Circuits[7]	252 Substations[8]		
Est. Total	N/A	291 miles [9]		59 Miles[10]		2,250 miles[11]	84 Substations [12]	84 Substations [13]	84 Substations[14]
Baseline Repair Detail	N/A	Single circuit, lattice tower (PG&E 2018)		Single circuit, lattice tower (PG&E 2018)		New construction of suburban distribution (Hall 2012) [15]	Repair substation equipment	Repair substation equipment	Repair substation equipment
Baseline Repair Unit Cost (USD	N/A	$1.4 / mile (PG&E 2018)		$1.6 / mile (PG&E 2018)		$0.91 / mile (Hall 2012)	$5.50/ substation (PG&E 2018)	$7.50/ substation (PG&E 2018)	$9.50/ Substation (PG&E 2018)

[6] Using 60/70 kV prices estimated from PG&E chart as 38 kV prices could not be found (PG&E 2018)

[7] From NY report, know that 75% of 1,200 distribution circuits need repair

[8] From NY report, know that 38 kV, 115 kV, and 230 kV substations were damaged; assume that an equal number of each were damaged; from NY report (Table 3-4), know that 121/252 substations had minor damage and are in need of repair and 131/252 substations have major damage and need to be replaced. Thus, assume half of substations need repair and half need replaced. Assume this is true across 38 kV, 115 kV, and 230 kV substations. So, 42 38 kV need repair, 42 38 kV need replaced, 42 115 kV need repair, 42 115 kV need replaced, 42 230 kV need repair, and 42 230 kV need replaced.

[9] Miles estimated from NY Report; know 350 miles of line need repaired and 84/101 segments (Table 3-1) are 115 kV, so estimate miles by 350*(84/101)

[10] Miles estimated from NY Report; know 350 miles of line need repaired and 17/101 segments (Table 3-1) are 230 kV, so estimate miles by 350*(17/101)

[11] From NY report, know that 75% of circuits need repair and there are 30,000 miles of overhead and underground lines. So, assume 75% of 30,000 miles of circuits need repair. Also assume 10 miles/feeder per Puerto Rico "Build Back Better" report

[12] Information taken from "Replacement Substation Equipment" in PG&E; costs were added up from circuit breakers, disconnect switches, and line protection relays. Five units/terminals assumed for each piece of equipment.

[13] Information taken from "Replacement Substation Equipment" in PG&E; costs were added up from circuit breakers, disconnect switches, line protection relays, and wave trap. Five units/terminals assumed for each piece of equipment.

[14] Information taken from "Replacement Substation Equipment" in PG&E; costs were added up from circuit breakers, disconnect switches, line protection relays, and wave trap. Five units/terminals assumed for each piece of equipment.

[15] Since rural is cheapest and urban is most expensive, and PR has both mix of urban and rural, take "middle" suburban distribution construction cost

Millions)							
Baseline System Repair Cost (US millions)	N/A	$411	$98	$20,430	$231	$315	$399
Better Repair Detail	Hardware upgrade on 1000 poles (Rossello 2017)	Single circuit, tubular steel pole (PG&E 2018)	Single circuit, tubular steel pole(PG&E 2018)	* Add automation(Rossello 2017) * Reconstruct and harden all 1200 circuits (Rossello 2017) [16]	Replacement control building, flooding protection, substation relocations, upgrade structures and insulators to 158 mph, replace end of life circuit breakers, harden and upgrade relay protection systems, T/D SCADA, and security (Rossello 2017)		
Better Unit Cost	$20,000/ Pole (Rossello 2017)	$1,553,000/ mile (PG&E 2018)	$1,878,000/ mile (PG&E 2018)	$2,000,000/ mile (Rossello 2017)	$15,000,000/ substation (Rossello 2017)		
Better System Repair Cost (US millions)	$20 (Rossello 2017)	$452	$111	$2,400 (Rossello 2017)	$5,100 (Rossello 2017) [17]		
Incremental Better Cost (US millions)	N/A	$41	$13	$357	$4,155		

Table D-3 provides estimates on damages, baseline repair costs and resilient repair design and costs for generating facilities in Puerto Rico, including eight petroleum facilities, one wind farm and one hydro-electric facility. Solar information is provided for four plants in Table 15 in the main body of the text.

[16] Per Puerto Rico "Build Back Better" report: "1200 feeders * $200k/mile * 10 miles/feeder = $2.4 billion"

[17] Cost for replacement of 340 substations or all the substations in Puerto Rico.

Detailed plant information was not available for all facilities but provides an estimate of the range of damages and different design and cost options for rebuilding.

Table D-3: Baseline and Build Back Better Component Estimated Costs - Generating Facilities Unless otherwise noted, all information from New York Power Authority et al. (2017). All costs in USD Million							
Fuel Type	Oil					Wind	Hydro
Number damaged	8					1	1
Facility	San Juan	Aguirre	Palo Seco	Cambalache	Daguao	Punta Lima (26 MW)	Dos Bocas
Facility Component	Cooling Towers		Entire Facility	Roofing and Doors	Fuel Storage Tanks[1]	Wind Turbines	Westinghouse Unit
Baseline Repair Detail	Cost to replace cooling tower system (All Kote Lining 2018)		New unit build	Base repairs	Base repairs	Cost of commercial-scale turbines (Haggerty 2017)	Base repairs
Baseline Repair Unit Cost	$0.2 (All Kote Lining 2018)		$1,300	N/A	N/A	$2 / MW (Haggerty 2017)	N/A
Baseline System Repair Cost	$0.4 (All Kote Lining 2018)		$1,300	$10	$2.7	$52	$30[18]
Better Repair Detail	N/A [19]		New unit build and storm hardening[1]	Base repairs, replacement of damaged spares, and storm hardening	Base repairs, replacement of damaged spares, storm hardening	N/A [20]	N/A [21]
Better Unit Cost	N/A		$1,300	N/A	N/A	N/A	N/A
Better System Repair Cost	N/A		$1,300	$30.8	$130	N/A	N/A
Incremental Better Cost	N/A		$20	$20.8	$10.3	N/A	N/A

Section D-2: Estimated Costs and Design Choices for Hurricane Events

This section includes information based on U.S. electricity grid design focused on the incremental costs between design choice to withstand heavy wind loads. It also includes information about cost factors related to terrain and geographic design. The information presented here is collected from multiple

[18] Repair data an estimate for all seven hydro facilities. Two of the plants were in service as of Nov 29, 2017. Dos Bocas is by far the largest facility and had extensive damage, so most of the repair cost is assumed to be for that plant alone.

[19] Build Back Better costs unavailable for cooling towers.

[20] Build back better costs unavailable for wind turbines.

[21] Data unavailable for a "build back better" cost for this specific facility.

sources, most notably utility company unit cost estimates and peer-reviewed literature. This analysis highlighted the complexity of power grid design and number of components. While the methodology used here builds on similar work looking at the cost increments of different climates on design and cost estimates (see: (Schweikert et al. 2015)), future work in this area should focus on identifying categorical design choices to simplify this analysis. This information is not intended to guide design decisions but inform to the methods and value of continued work in this area.

Section D.2.1: Design Comparisons and Cost Estimates

In a simplified approach to understanding the resilient design considerations and incremental costs required to build to different design categories, this analysis focused on two main elements: distribution and transmission poles and the wiring. Table D-4 provides the costs of construction for distribution poles designed to withstand specific wind loading, from “light” duty baseline amounts to 150 mph sustained wind loading. These wind loadings are estimated from Jurgemeyer and Miller (2014). An incremental cost is provided for each category, relative to the baseline cost estimates. This data shows that the incremental cost of upgrading a Class 6 wood poles, design Category B (suitable for intersections and crossings) from a baseline design to Category 1 (100 mph sustained winds) incurs no incremental cost, as the baseline design is suitable to withstand wind loading at this speed. However, upgrading to a Category 2 storm (110 mph sustained winds) results in a savings for Class 6, Grade B poles, while a cost of $112,000 (19%) is incurred. Upgrading to Category 4 storm (design basis of 150 mph sustained winds) incurs a cost between 25-70% of the baseline, depending on the pole class and grade. Both Grade B and C poles can be used in a single transmission segment, depending on the design. The main considerations of cost are the number of poles required per mile (Jurgemeyer and Miller 2014).

Table D-4: Construction cost per mile, estimated. Incremental cost increases calculated as difference between baseline and more resilient design criteria cost. Baseline costs are estimated using design guidelines from Jurgemeyer and Miller (2014) and cost information for wood poles for 60 kV and 115 kV transmission lines from PG&E (2018) unless otherwise noted. No incremental costs are provided for Category 5 hurricanes (defined as sustained winds exceeding 155 mph) due to baseline and resilient design comparison availability. ***Note:* Costs are estimated costs per mile including pole, ASCR transformer and calculated as an estimated standard construction cost. These estimates are based on NSIC guidelines and will require geographic-specific design, along with permitting, right of way, and other engineering considerations. All costs estimated from data in Jurgemeyer and Miller (2014) unless otherwise noted.					
Category	**Category Design Detail**	**Pole Design**	**Cost (USD thousands)**	**Incremental cost from baseline**	
				Dollars (USD thousands)	**%**
Baseline* costs from 1,2	9 lb per sf (430 Pa wind pressure), no ice and a conductor rating of -1 C	Wood pole, class 6, Grade C construction	$ 604		
		Light duty steel poles	$ 629		
		Single circuit lattice tower	$ 1,411		
		Single circuit lattice tower, 230 kV	$ 1,660		
		Double Circuit Lattice Tower	$ 2,243		
		Double Circuit Lattice Tower, 230 kV	$ 2,649		
1	Sustained winds of 74-95 mph (Costs estimated to withstand 100 mph sustained winds)	Wood pole, class 6, Grade C construction	$ 604	$ 0	0%
		Wood pole, class 6, Grade B construction	$ 604	$ 0	0%
		Wood pole, class 4, Grade C construction	$ 604	$ 0	0%
		Wood pole, class 4, Grade B construction	$ 604	$ 0	0%
2	Sustained winds of 96-110 mph (Costs estimated to withstand 110 mph sustained winds)	Wood pole, class 6, Grade C construction	$ 604	$ 0	0%
		Wood pole, class 6, Grade B construction	$ 604	$ -	0%
		Wood pole, class 4, Grade C construction	$ 641	$ 37	6%

		Wood pole, class 4, Grade B construction	$ 716	$ 112	19%
3	Sustained winds of 111-130 mph (Costs estimated to withstand 130 mph sustained winds)	Wood pole, class 6, Grade C construction	$ 622	$ 18	3%
		Wood pole, class 6, Grade B construction	$ 750	$ 146	24%
		Wood pole, class 4, Grade C construction	$ 726	$ 122	20%
		Wood pole, class 4, Grade B construction	$ 848	$ 244	40%
4	Sustained winds of 131-155 mph (Costs estimated to withstand 150 mph sustained winds)**	Wood pole, class 6, Grade C construction	$ 750	$ 146	24%
		Wood pole, class 6, Grade B construction	$ 970	$ 366	61%
		Wood pole, class 4, Grade C construction	$ 848	$ 244	40%
		Wood pole, class 4, Grade B construction	$ 1,026	$ 422	70%
Unknown wind strength * Costs from 2	Specific sustained wind speed was not provided for these design and cost parameters. Puerto Rico assessments state better performance in 2017 events for steel poles over lattice structures.	Tubular steel pole, single circuit	$ 1,553	$ 142	147%
		Tubular steel pole, single circuit, 230 kV	$ 1,878	$ 218	199%
		Double Circuit, Strung on both sides, Tubular Steel Pole	$ 2,507	$ 264	299%
		Double Circuit, Strung on both sides, Tubular Steel Pole, 230 kV	$ 2,979	$ 330	374%
Undergrounding costs, withstand all wind speeds	Placing transmission wires underground	Rural costs* (minimum and maximum). Cost includes labor and materials *Costs from: Hall (2012)*	$1,400 (minimum) $27,000 (maximum)		
	Placing distribution wires underground		$297 (minimum) $1,840 (maximum)		

Additionally, information is provided in Table D-4for steel lattice, steel pole and double circuit designs. Findings from Puerto Rico suggest that tubular steel poles fared better in the 2017 Hurricane season when compared to lattice structures, although in this preliminary assessment, no specific wind loading criteria including unit costs were available (PG&E 2018; California ISO 2012). The incurred costs when a tubular steel pole, single and double circuits, are compared with baseline light-duty steel poles are between 150%- 374%.

Finally, costs for undergrounding transmission and distribution infrastructure is provided in Table D-4 for reference. Numbers provided are for rural construction in the United States and range from under half a million (for distribution wires) per mile to over $27,000 (for transmission lines) per mile. Costs provided in Hall (2012) also include estimates for suburban and rural construction. These costs are higher than rural construction and, for distribution lines, range from $528,000 (minimum value, distribution lines, suburban) to $4.5 million per mile (urban, distribution lines, maximum value). For transmission lines, these costs increase significantly to $2.3 million per mile (minimum value, suburban construction, transmission lines) to $30 million (maximum value, suburban/urban construction, transmission lines). Costs are also provided for the conversion of overhead lines to underground lines. In Florida (USA), these costs for actual projects in 2007 are provided and average a cost of $975,000 per mile (costs estimated from four projects, with costs ranging from $414,000 to $1.6 million per mile). In all of these costs, estimates are that labor accounts for approximately just over 50% of the cost, which would vary geographically and affect prices of construction.

In this analysis, no design standards for above ground transmission were found for sustained winds exceeding 157 mph (Category 5 hurricane speeds). One alternative, though significantly more expensive than above ground options, is upgrading to composite poles (capable of withstanding 200 mph sustained winds) or undergrounding key transmission lines (see text above). Specifically relevant to the Puerto Rico context, the U.S. Virgin Islands, following the 2017 Hurricane season, are undergrounding many of their transmission lines, installing composite poles, upgrading substation infrastructure and enhancing metering infrastructure (FEMA 2018). These upgrades will mean that approximately 50% of the U.S.V.I. population will receive their power from underground facilities (Rao 2018). The design decisions between composite poles and undergrounding infrastructure is dependent on terrain, specifically mountainous and marine areas will be relocated underground. The total estimated project cost exceeds $620 million with FEMA paying approximately 91% as part of the storm recover and resilient upgrading considerations (Rao 2018).

Section D-2.2: Multiplication Cost Factors

The cost estimates presented above are for flat terrain in non-densely populated regions. Many utilities use cost multiplication factors in their initial project estimates. Estimates are provided in Table D-5 and D-6 is an example of multiplication factors from Southern California Edison utility company (California ISO 2012). Similar factors were found with other utilities including Florida Power and Electric and Pacific Gas and Electric. Both have baseline design focused on "light" loading considerations (guidelines not requiring additional wind or ice loading considerations).

Table D-5: Description of key multiplication factors for cost estimating. *Source*: California ISO (2012)	
Terrain	Going from flat to mountainous terrain increases the cost of a transmission line. Terrain influences where structures are located, how many structures will be required and which type (strength) of structures will be required. As terrain becomes more rugged, access to the site and construction also gets more complex.

Population density	Population and land use effect the cost of a transmission line. Structure quantities may be increased and/or made taller in more populated areas for aesthetic purposes, EMF mitigation efforts or due to crossings. Construction activities may also be impacted by physical constraints and work hour restrictions.
Weather study	Transmission line costs increase as weather loading conditions increase. Wind and ice increase the loading on transmission structures which may require stronger structure types or an increased number of structures to reduce the span lengths.

Table D-6: Cost Multiplication Factors
Source: Curry and Wilson (2012)

	Low	High	Average Multiplier (Multiple Utilities)
Desert	1	1.1	1.05
Scrub/Flat	1	1	1
Farmland	1	1.1	1
Forested	1	3	2.25
Rolling Hill (2-8% slope)	1	1.5	1.4
Mountain (>8% slope)	1	2	1.75
Wetland	1.2	1.2	1.2
Suburban	1	1.33	1.27
Urban (population density)	1	1.67	1.59
Weather	1.35	1.6	N/A

When the cost estimates for components (Table D-4) and multiplicative cost factors (Table D-5) are combined with the storm recurrence interval probabilities (Appendix E), this information can provide insight into the costs and benefits of specific design investments over the lifetime of an asset, and could be used as inputs for a probabilistic risk assessment model. These preliminary findings suggest that design-specific cost estimates merit further investment as a method for analyzing the costs and benefits of investing at different design standards.

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APPENDIX E – DETAILED DATA FOR HISTORICAL OCCURRENCES OF WIND EVENTS IN PUERTO RICO, 1901-PRESENT

This appendix provides data on the probability of no event occurring in a thirty-year time period (Figure E1) and of at least one event occurring in a thirty-year time period (Figure E2).
These probabilities were calculated using a Poisson distribution (Formula E-1) for historical windspeed data from local wind stations in the geographic region of Puerto Rico (National Centers for Environmental Information 2018). The windspeed data is recorded at an approximate height of 10 meters, meaning the data is only an approximation of the actual wind speeds occurring closer to the ground (the approximate height of infrastructure estimated in this study sits between 10-30 meters above the ground level). The wind speed data is recorded in knots and is the one-minute sustained wind speed measured in a location. Table E-1 provides a summary of the recorded events.

Formula E-1:

$$\frac{(\lambda t)^k e^{-\lambda t}}{k!}$$

$where:$
$k \ = occurrences\ within\ a\ specific\ storm\ category\ in\ years\ since$ 1901
$\lambda \ = \left(\frac{1}{\Delta t}\right) * k$
$\Delta t \ = time, in\ years. for\ which\ data\ is\ available\ (1901 - present)$

Table E-1: Summary statistics for windspeed events occurring in Puerto Rico, 1901-Present. Data for windspeed recorded in one-minute sustained wind speeds at approximately 100 meters above ground elevation.

	Top Windspeed for Category (miles/hour)	Top Windspeed for Category (km/hour)	Annual Prob. Of 1 event	Number of Storms since 1901
Tropical Storm	40-74	63-118	10.6%	14
Hurricane - Category 1	74-95	119-153	2.5%	3
Hurricane - Category 2	96-110	154-177	2.5%	3
Hurricane - Category 3	111-129	178-208	0.8%	1
Hurricane - Category 4	130-156	209-251	2.5%	3
Hurricane - Category 5	>156	>251	0.8%	1

Using the information summarized in Table E-1, Figures E-1 and E-2 show the probability of storm occurrence, by category, over a thirty-year time period. These probabilities are based on historical data for storms from 1901-2017. Because there were the same amount of Category 1, 2, and 4 storms (a total of 3 each) and of Category 3 and 5 storms (1 each), the graphs have only three lines. It should be noted that a changing climate may impact the frequency and severity of hurricane-force storms, although that falls outside the scope of this current analysis.

Figure E-1: Probability that no storm occurs, by category, in a thirty-year time period. Data is derived from historical values (see Table E-1)

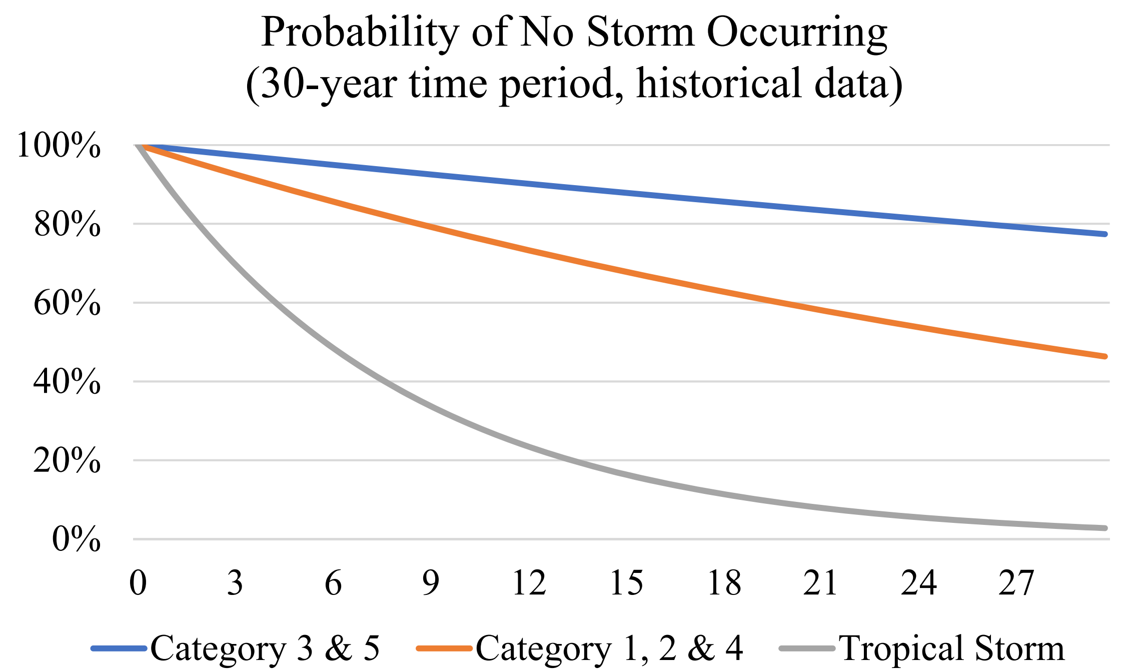
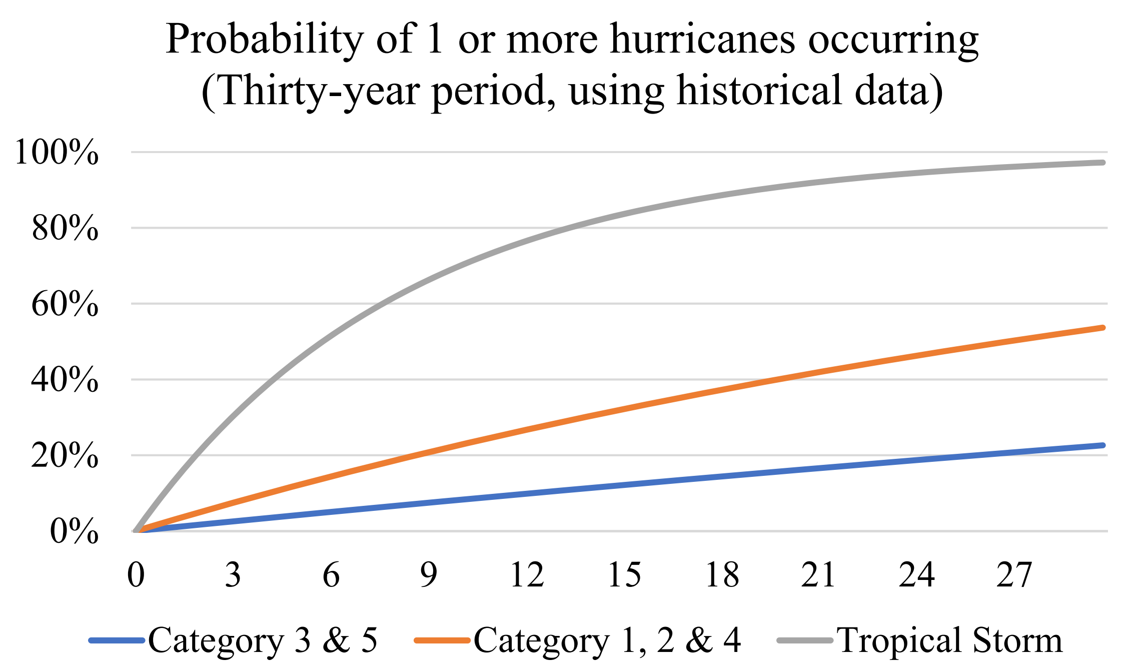


Figure E-2: Probability that at least one storm occurs, by category, in a thirty-year time period. Data is derived from historical values (see Table E-1)



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Appendix F – Areas of Potential Future Work
This appendix provides a table with selected geographic regions that are vulnerable to the hazard events assessed in this study.

Table F-1: Selected list of severe global natural hazard events for future investigation			
Event	**Location**	**Classification**	**Date**
East Africa Drought [1]	East Africa (Kenya, Somalia, Ethiopia, Eritrea, and Djibouti)	Severe	2010-2012
Tropical Storm Delta [2]	Canary Islands, Morocco, Algeria	Tropical Storm	2005
Hurricane Fred [3]	Cape Verde	Category 1	2015
Cyclone Bondo [4]	Madagascar	Equivalent to a Category 4 hurricane	2006
Tropical Storm Chedza [5]	Madagascar, Malawi, Zimbabwe, Mozambique	Tropical Storm	2015
2013 Somalia Cyclone [6]	Somalia, Ethiopia	Weak system → deadliest in Somalia history	2013
Somali Flash Floods [7]	Somalia	N/A	Annual
2010 West African Floods [8]	Niger	N/A	2010
2017 Botswana Earthquake [9]	Botswana	6.5 mag.	2017
2014 Orkney Earthquake [10]	South Africa	5.3 mag.	2014
2017 Somalian Drought [11]	Somalia	Severe	2017
Hurricane Helene [12]	West Africa, Cape Verde	Tropical Storm/Category 2	2018
2010-2011 Southern Africa Floods [13]	South Africa, Mozambique, Zimbabwe, Namibia, Botswana, Zambia	N/A	2010-2011
2013 Sudan Floods [14]	Sudan	N/A	2013
2014-17 Brazilian Drought [15]	Brazil	Severe	2014-2017
2013 Argentina Floods [16]	Argentina	N/A	2013
2016 Ecuador Earthquake [17]	Ecuador	7.8 mag.	2016
2010 Chile Earthquake [18]	Chile	8.8 mag.	2010
Tropical Storm Bret (2017) [19]	Trinidad and Tobago, Guyana, Venezuela, Windward Islands	Tropical Storm	2017

Table F-2: Example geographic areas for consideration of natural hazard impacts on power grid infrastructure systems. This table details some of the identified stressors in specific geographic regions around the world, especially related to infrastructure gap and natural hazard events. All information from Rockefeller 100 Resilient Cities Program (Cities Archive, 2018)	
City/Country	**Shocks and Stresses**
Accra, Ghana	Aging infrastructure, costal/tidal flooding, disease outbreak, earthquake, environmental degradation, infrastructure failure, lack of affordable housing, rainfall flooding
Addis Ababa, Ethiopia	Disease outbreak, inadequate transportation systems, infrastructure failure, lack of affordable housing, rainfall flooding, terrorist attack, unemployment, water insecurity
Cape Town, South Africa	Climate change, crime/violence, cyber-attack, drought, drug/alcohol abuse, fire, informal housing, infrastructure failure, lack of social cohesion, poverty, rainfall flooding, civil unrest, traffic congestion, unemployment
Dakar, Senegal	Environmental degradation, informal housing, infrastructure failure, poverty, rainfall flooding, costal erosion/sea levels rise
Durban, South Africa	Drought, economic inequality, environmental degradation, fire, food insecurity, hazardous materials accident, homelessness, inadequate health systems, poverty, rainfall flooding, civil unrest, water insecurity
Kigali, Rwanda	Aging infrastructure, energy insecurity, environmental degradation, infrastructure failure, lack of affordable housing, landslide, rainfall flooding
Lagos, Nigeria	Disease outbreak, energy insecurity, inadequate public transportation systems, infrastructure failure, population growth/overpopulation, rainfall flooding, sea level rise/costal flooding
Nairobi, Kenya	Disease outbreak, environmental degradation, infrastructure failure, lack of affordable housing, rainfall flooding, terrorist attack, unemployment
Paynesville, Liberia	Crime/violence, disease outbreak, inadequate health systems, infrastructure failure, poverty, rainfall flooding, riot/civil unrest, water insecurity
Chennai, India	Aging infrastructure, economic inequality, hurricane/typhoon/cyclone, infrastructure failure, poverty, civil unrest
Pune, India	Disease outbreak, earthquake, lack of affordable housing, poor air quality, rainfall flooding, terrorist attack, water insecurity
Surat, India	Aging infrastructure, disease outbreak, drought, earthquake, sea level rise/costal erosion
Semarang, Indonesia	Costal/tidal flooding, disease outbreak, drought, rainfall flooding, sea level rise/costal erosion
Jakarta, Indonesia	Costal/tidal flooding, cyber-attack, earthquake, lack of affordable housing, poor air quality, rainfall flooding
Santiago De Los Caballeros, Dominican Republic	Aging infrastructure, crime/violence, disease outbreak, earthquake, environmental degradation, hurricane/typhoon/cyclone, lack of affordable housing, rainfall flooding

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