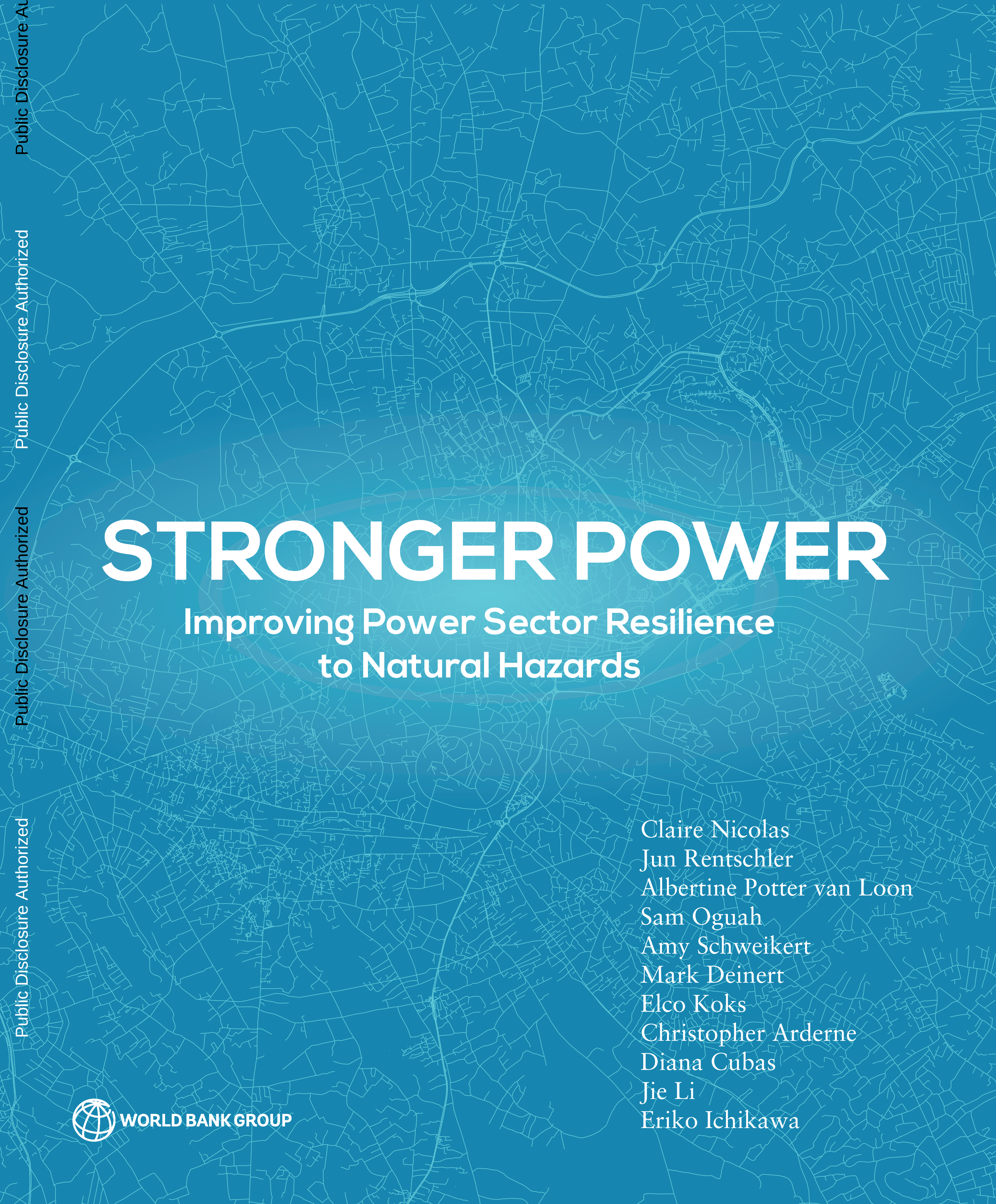
LIFELINES: The Resilient Infrastructure Opportunity



STRONGER POWER

Improving Power Sector Resilience to Natural Hazards

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Summary

The power sector is both highly vulnerable to natural hazards and a priority for any country's recovery and reconstruction. After Hurricane Maria in Puerto Rico in 2017, most of the power grid was down. One year and tens of billions of dollars later some customers were yet to be reconnected to the main grid. This type of long and widespread power outage has major consequences on people's health and well-being, for instance through lacking access to refrigeration for food and medicine, and on the ability of firms to produce and provide people with goods, services, jobs, and income

In most countries, the power system is designed to cope with high-frequency but relatively low-impact events. Low-frequency, high-impact events – such as many natural disasters – are rarely considered fully, and the implementation of planned management measures is often patchy. Furthermore, the power system is a special kind of infrastructure due to the heterogeneity of the generation assets and its wide spatial distribution. The latter means that power systems are often exposed to natural hazards and sometimes to more than one hazard, leading to high repair costs when disasters strike.

This paper, prepared as a sectoral note for the *Lifelines* report on infrastructure resilience, investigates the vulnerability of the power system to natural hazards and climate change, and provides recommendations to increase its resilience. It first describes how power outages are often the consequence of natural disasters and outlines the main vulnerabilities of the power sector. It then proposes a range of approaches and solutions for building a more resilient power sector – from increased robustness to greater flexibility – showing that the additional cost of resilience is not high if resources are well spent. Finally, it describes how emergency preparedness and disaster recovery encompass not only technical aspects, like asset strengthening or criticality analysis, but also "softer" skills, like governance, regulatory or capacity building, and education.

Contents

1. Introduction

Natural hazards are among the leading causes of power outages around the world. For instance, after Hurricane Maria in Puerto Rico in 2017, most of the power grid was down. One year and tens of billions of dollars later, some customers had yet to be reconnected to the main grid (Central Intelligence Agency 2018). Similarly, when Cyclone Sidr hit Bangladesh in November 2007, it not only caused the deaths of around 3,400 people, but also led to one of the largest blackouts ever recorded: 75 million people lost access to power, which translated into 1.9 billion customer-hours of lost electricity services. Long and widespread power outages such as these have major consequences for people's health and well-being. Among other effects, they impede access to refrigeration for food and medicine, as well as the ability of firms to provide people with goods, services, jobs, and income.

The cost of power infrastructure disruptions is substantial in developing countries. Rentschler et al. (2019) estimate that electricity outages in developing countries cause firms capacity utilization losses of $32 billion a year and sales losses of $82 billion a year. In addition, firms in developing countries are forced to spend an additional $65 billion a year on self-generating electricity to cope with outages. For households, the impact of power outages is also large; it can affect cooling and heating (which in turn may have health implications), economic activities and income, children's educational outcomes, social and leisure activities, and regular household tasks, such as cooking and cleaning (World Bank 2019). By analyzing studies that assessed the willingness of households to pay to prevent power outages, Obolensky et al. (2019) found that the cost of power outages to households in low- and middle income countries could lie anywhere between $2.3 and $190 billion a year.

In addition to the impact on consumers, disaster damages to power infrastructure and the resulting losses can weigh heavily on government balance sheets. After Hurricane Irma, restoring the grid in Florida took weeks, required more than 16,000 workers, and cost around US$1.3 billion (Florida Power & Light Company 2018) – all despite the $3 billion that had been invested over the past 10 years to improve the resilience of the Floridian grid. The project had included efforts to underground the main power lines, strengthen the lines serving critical services, and upgrade the power poles. In countries with less advanced power systems, the power grid and generation facilities are often even more vulnerable.

In most countries, the power system is designed to cope with high-frequency but relatively low-impact events. Low-frequency, high-impact events – such as most natural disasters – are rarely considered fully, and the implementation of planned management measures is often patchy. As climate change is likely to increase the frequency and intensity of this type of events, improving the resilience of the power sector to natural disaster is becoming essential for economic well-being and quality of life. This is particularly the case for developing countries with a lack of disaster risk management capacities, ageing and poorly maintained assets, and poorly designed networks without adequate level of redundancy.

For many developing countries, power spending represents a high share of the GDP. Between 2018 and 2030, developing countries are estimated to spend between US$45 billion and US$58 billion annually on new power infrastructure. With maintenance and variable costs, total spending could reach approximately US$88 billion to US$118 billion per year (Nicolas et al. 2019). Hence, natural hazards and climate change are urgent factors considering the large investments that will take place in the power sector in the next decades.

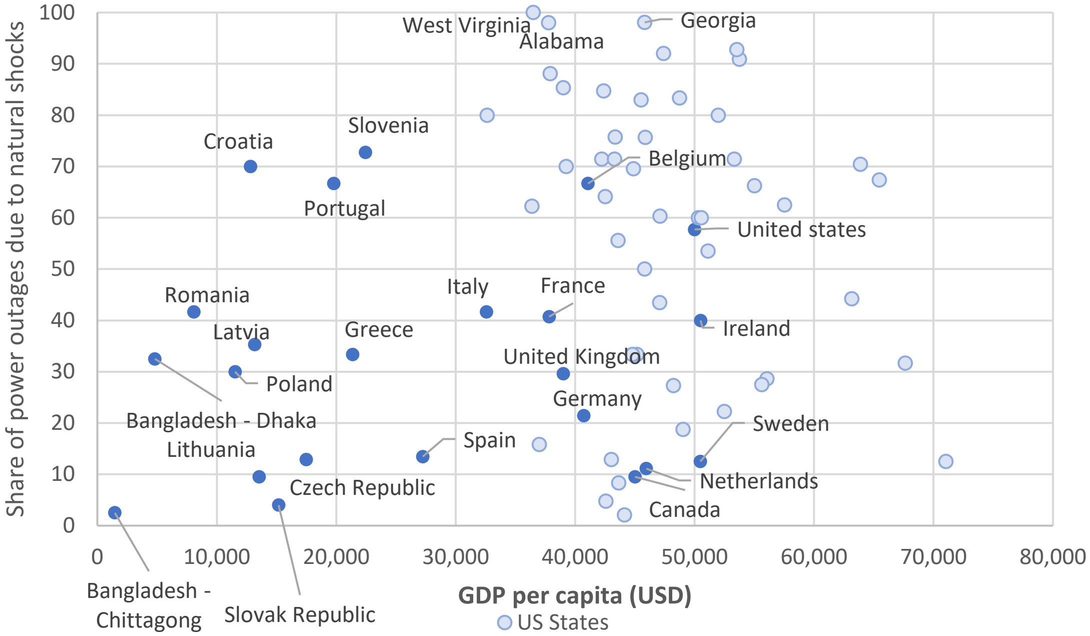
This paper, prepared as background material for the *Lifelines* report on infrastructure resilience, investigates the vulnerability of the power system to natural hazards and climate change, and provides recommendations to increase its resilience. It first describes how power outages are often the consequence of natural disasters and outlines the main vulnerabilities of the power sector. It then proposes a range of approaches and solutions for building a more resilient power sector – from increased robustness to greater flexibility – showing that the additional cost of resilience is not high if resources are well spent. Finally, it describes how emergency preparedness and disaster recovery encompass not only technical aspects, like asset strengthening or criticality analysis, but also “softer” skills, like governance, regulatory or capacity building, and education.

2. Power sector infrastructure is heterogeneous. So is its vulnerability to natural disasters.

1.1. Severe weather events, particularly storms, are among the main causes of power outages around the world

Rentschler, Obolensky, and Kornejew (2019) found that the share of power outages due to natural shocks can vary from anywhere between zero and 100 percent, though most country-level estimates fall in a range between 10 to 70 percent (Figure 1). Between 2000 and 2017, 55 percent of all recorded power outage events in the US were caused by natural shocks, compared to 44 percent by non-natural causes.[1] In the US, power outages caused by natural shocks lasted on average 2.5 days, making outages due to natural shocks more than twice as long as outages due to non-natural causes, and three times as long as outages due to vandalism. This means that 74 percent of the total recorded outage duration between 2000 and 2017 was caused by natural shocks. In Europe, between 2010 and 2017, climate-induced outages lasted 409 minutes on average, making them almost four times as long as outages caused by non-natural external causes. Over the period, natural shocks were responsible for 37 percent of the total outage duration in the considered European countries.

Figure 1. The share of power outages that are caused by natural shocks varies significantly across countries. The light markers represent federal states of the US.



Source: (Rentschler, Obolensky, and Kornejew 2019)

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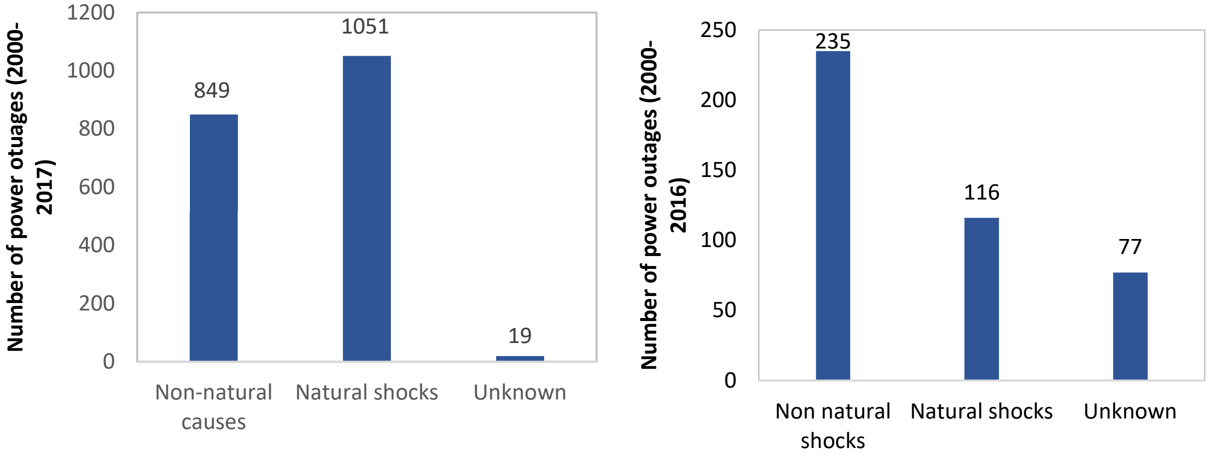
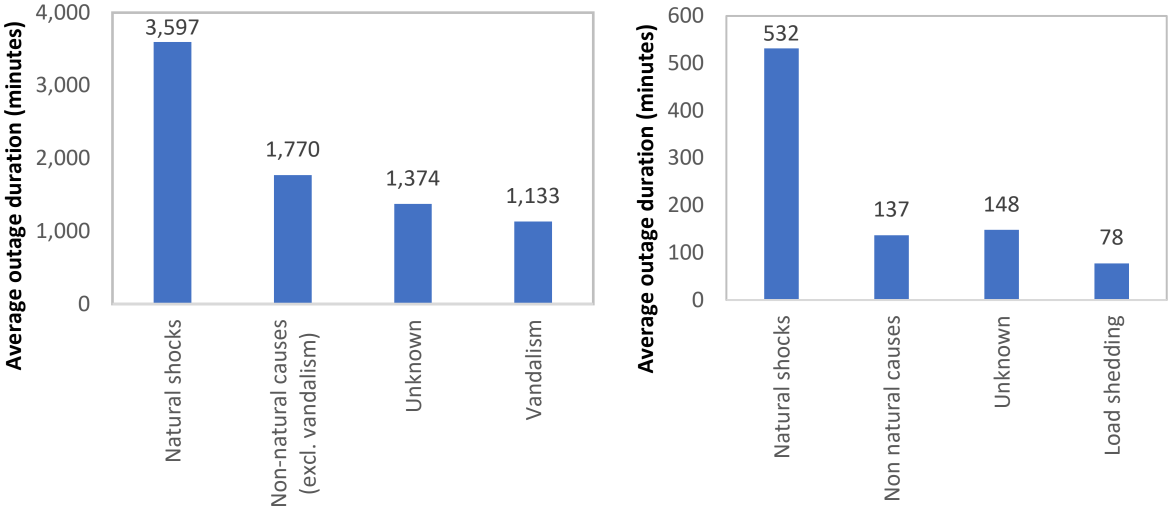
[1] The cause for the remaining 1% of outage events is unknown.

Figure 2. Total power outage durations in the US and 26 European countries by different causes. The European countries represent the EU-28 (without Hungary, Denmark, and Bulgaria) plus Serbia.



a. Power outages, United States (2000–2017)

b. Power outages, Europe (2000–2016)



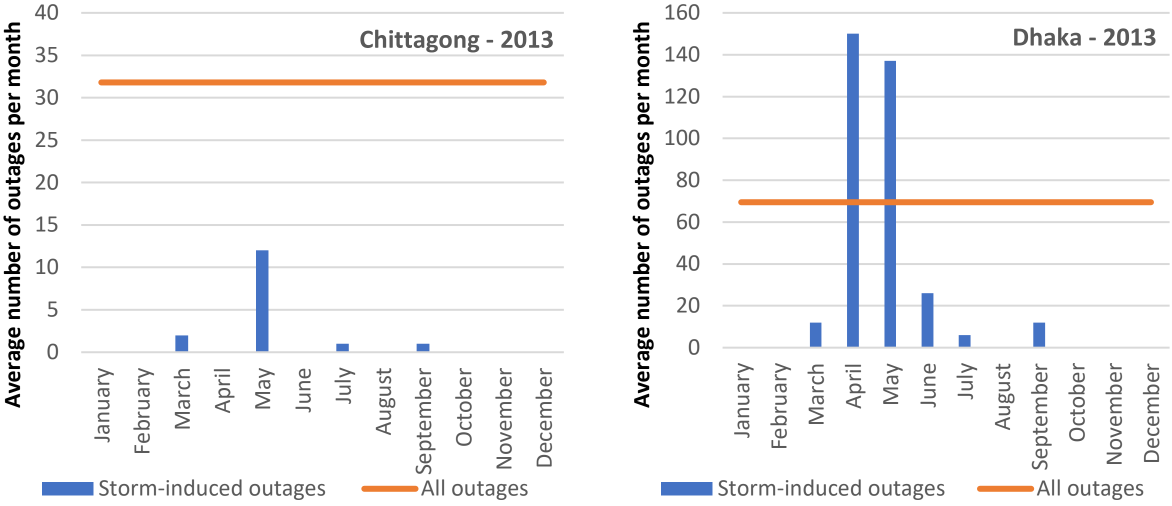
c. Average outage duration, United States

d. Average outage duration, Europe

Source: Rentschler, Obolensky, and Kornejew (2019)

Fragile energy systems are vulnerable to a wide range of shocks – not only natural ones. Evidence shows that natural hazards – in particular, storms – are the most frequent cause of electricity supply disruptions in the US, and a major cause in Europe. In contrast, in Bangladesh, natural shocks account for a far smaller share of power outages – not because energy systems are more resilient, but because system failures and non-natural factors are so frequent that energy users experience daily outages. In Chittagong, a major coastal city in Bangladesh, storms are estimated to cause only four percent of all outages (Rentschler, Obolensky, and Kornejew 2019). In Dhaka, the World Bank's Enterprise Survey suggests there are about two outages per day on average throughout the year; only during the storm season in April and May are outages significantly more frequent.[2] In other words, a fragile system is vulnerable not only to natural shocks, but also to a host of other stressors and shocks that include unmet demand, equipment failure, and accidents.

Figure 3. The number of storm-induced outages in Chittagong and Dhaka (Bangladesh), compared to average monthly outages (all causes) reported in the World Bank Enterprise Surveys.



Source: (Rentschler, Obolensky, and Kornejew 2019)

Still, natural hazards can be responsible for a large number of disruptions. Though limited data availability makes it difficult to quantify the link between power outages and storms, power systems in developing countries are more vulnerable to natural shocks than those in richer countries. Aging equipment, lack of maintenance, rapid expansion of the grid, and insufficient generation capacity are all factors that reduce the reliability of service in general – but also increase the system's vulnerability to natural shocks. For example, storms of the same intensity are more likely to cause outages in Bangladesh than in the United States (figure 4). On a day with wind speeds exceeding 35 kilometers per hour, electricity users in Bangladesh are 11 times more likely to experience a blackout than U.S. consumers.

The higher vulnerability of power systems in developing countries means that even frequent events have large, disruptive impacts. In Bangladesh, severe cyclones damage power plants, renewable resource infrastructure, and power distribution networks. Even relatively frequent storm events, such as the nor'westers occurring around April each year, significantly increase the incidence of power outages (Figure 5). These storms, known for their localized but violent gusts and lightning strikes, tend to significantly damage power transmission and distribution systems, as illustrated by a recent event in March 2019, after which 6,000 communication towers lost access to power (Dhaka Tribune 2019).

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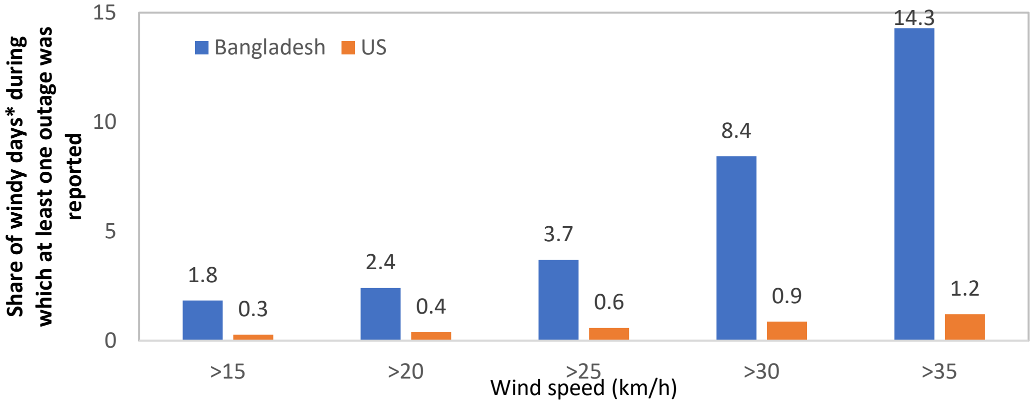
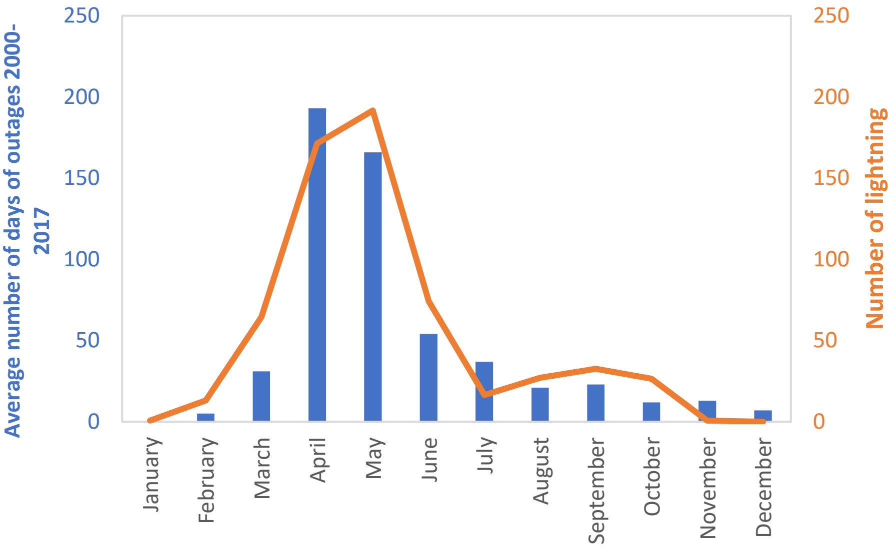
[2] Though these outages may affect different districts of the city.

Figure 4: Vulnerability of the power network to wind.



Note: Windy days are defined using different thresholds, relating to average recorded wind speeds.
Source: Rentschler, Obolensky, and Kornejew (2019)

Figure 5 Power outages caused by natural shocks are closely associated with Nor'wester storms that typically occur in April and May each year – proxied by lightning strikes. An increase in outages in September is explained by the monsoon season.



Source: Rentschler, Obolensky and Kornejew (2019).

1.2. Power sector vulnerability to natural disasters

This section describes the main vulnerabilities to natural disasters of generation facilities and transmission and distribution infrastructure. Table 1 presents a summary of those vulnerabilities; it categorizes the importance of considering a given disaster when designing an asset to avoid physical damages or service interruptions (e.g., droughts for hydropower). During a natural hazard, three main types of incidents can lead to system breakdowns: transmission and distribution grid failure, generation plant failure, and fuel and maintenance supply chain failures (Schweikert et al. 2019).

Type	Earthquake	Cyclone	Flood	Tsunami	Wildfire	Drought	Extreme Heat
Thermal plants	High	High	Medium	High		High	Medium
Hydropower plants	High	Low	Medium	Low		High	Medium
Nuclear plants	High	Medium	Medium	High		High	Medium
Solar (PV)	Low	High	Medium	Medium		Medium	Very low
Wind	High	Medium	Low	Medium		Very low	Very low
T&D lines	Medium	High	Low	Medium	High	Medium	Medium
Substations	High	High	High	Medium	High	low	Medium

Source: authors

Nuclear and hydropower plants are different that other power infrastructure since their failure can lead to catastrophic situations and casualties. Hence, their safety is considered with great care and their design is already subject to high standards in most countries.

1.2.1. Thermal generation (oil, coal, gas, and diesel generators)

Thermal plants are generally quite robust, yet, as illustrated by Table 1, they can sustain damages during cyclones and earthquakes if not designed with sufficiently high standards. Cyclones pose a risk because high winds are a danger for high cooling towers (Miyamoto 2019). Liquefaction during earthquakes can be quite damaging for power plants without deep foundations. When well designed and well located, thermal plants are not highly vulnerable to floods. However, a 2016 study in Bangladesh noted that the historical guidelines for flood design are likely to be inappropriate for future conditions, meaning this vulnerability will increase (Chattopadhyay et al. 2016).

Droughts and extreme temperatures can also cause service interruptions, because thermal plants rely on intake water for circulation in the cooling system. Generation may be curtailed by the reduced availability of cooling water as a result of droughts, very cold temperatures, or high temperatures that prevent water from cooling enough to be discharged (Galbraith 2011). Moreover, droughts and heat waves often coincide and may exacerbate the severity of both events. During the 2011 heat wave in Texas, water usually allocated to farmers had to be directed to power plants to avoid plant shut down, which also illustrates how the power sector is interconnected with other sectors (Faeth 2013). High air temperatures also decrease the efficiency of thermal power plants.

Diesel generators, which are much smaller than other thermal plants, have different vulnerabilities.[3] The most widely observed damages to small diesel generators found by Schweikert et al. (2019) was due to flooding. Oftentimes, back-up diesel generators are stored in the basement of a facility or at the ground level. When flooding, storm surges, or other natural events 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 window for a response effort (Srinivasan and Gopi Rethinaraj 2013).

Another vulnerability arises from the supply of fuel. Fuel is delivered by roads, rail lines, or pipeline, or through ports' terminals. If these interdependent infrastructures are damaged, plant operation is reduced or shut down completely. In the United States, between 2000 and 2016, 35 percent of all outages related to a fuel supply emergency affected coal-powered generation facilities, the largest of any fuel type. In Puerto Rico, following Hurricanes Irma and Maria, 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 2018). During Hurricane Sandy, it was noted that *"[d]ue 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 function"* (Comes and Van de Walle 2014). When it comes to diesel generators, fuel is stored on-site. However, in the event of longer outages or poor planning – for example, if fuel and generators are not co-located – on-site storage can result in limited operation and have a significant impact on other critical facility operations that rely on electricity, such as hospital equipment or communication infrastructure (Powell, Hanfling, and Gostin 2012).

1.2.2. Nuclear generation

Given the potentially large impact of a failure, nuclear power plants are built to robust design standards, reducing the impacts of most events. Nuclear plant curtailments or shut-downs can be observed but are generally due to pre-emptive closure or issues with the intake water used for cooling. Schweikert et al. (2019) found that the primary cause for pre-emptive closures were hurricanes, while issues with intake water used for cooling were caused by droughts, heatwaves, and winter weather.

For nuclear power plants, fuel can be stored on site and refueling is far less frequent than for other power sources (in the timescale of years), making them robust in the face of supply-chain issues. This was particularly evident in Texas following Hurricane Harvey, when nuclear power plants were able to operate at full capacity throughout the event. This allowed for continuous electricity supply despite the supply deficit resulting from reductions in generation facilities located on the coast, which were more affected by storm surge and flooding for longer time periods (Conca 2017).

The largest vulnerability of nuclear power facilities is the intake water used for cooling. A study

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[3] Utility-scale internal combustion engines have the same vulnerabilities as other thermal plants.

on water-related curtailments in the United States between 2000 and 2015 found that the majority of curtailments occur due to water intake and/or discharge issues related to water temperature (more than 90 percent) with many of these (79 percent) occurring during heatwave/drought conditions (McCall et al., 2016). Winter weather caused one curtailment when snow and ice restricted the amount of intake water available. In France, in August 2018, four nuclear reactors were shut down because high river temperatures prevented water discharge (Shugerman 2018).

The best-known example of a nuclear power plant that sustained damage due to a natural disaster is the infamous Fukushima Daiichi Plant in Japan, which failed following a magnitude 9 earthquake and tsunami. In 1999, in France, a conjunction of hazards almost led to the failure of the Blayais nuclear plant. A combination of an exceptionally high incoming tide and unusually high winds due to Storm Martin caused a sudden rise of water in the estuary, flooding parts of the plant. The plant was built to sustain 4.5 meters of flooding; on this day, the combination of tide, storm surge, and storm wave over-topped the coastal dyke around the plant, with the water reaching levels between five and 5.3 meters (16.4–17 ft). The flooding caused widespread damage, including the loss of one of the two redundant service pumps of one of the four generators, and the loss of the low-head safety injection and containment spray pumps of the Emergency Core Cooling System. In the following days, more than 90000m^3 of water were pumped out of the flooded facility. In the aftermath of this event, a new method of evaluating flood risk was developed and the Blayais sea walls were raised to eight meters.

1.2.3. Hydropower generation

Hydropower generation is mostly vulnerable to droughts, as the streamflow it requires to function cannot be maintained with low water availability. In 2017, Malawi saw capacity reductions of 50 percent (from 300 MWe to 150 MWe) due to low water levels, which required rolling blackouts lasting over 24 hours (Alvaro 2018). Similar issues were seen in Tanzania in 2015, when the country was forced to shut down all hydropower plants due to two years of drought conditions. Van Vliet et al. (2012) quantify the relationship between water scarcity and power generation at the global level between 1981 and 2010, finding that droughts and warm years decrease hydropower utilization rates by 5.2 percent compared to the average.

While droughts are an issue for service continuity, they do not have lasting impacts on infrastructure. Earthquakes and floods are the two hazards that do threaten the plant integrity. During an earthquake, the most vulnerable parts of a hydropower plant are the base of the dam, the lift joins, the spillways, and the intake towers (Miyamoto 2019). The 2015 earthquake in Nepal damaged hydropower plants corresponding to 34 percent of the country's capacity.

Floods are another threat to dams, as they can cause considerable damages if the flood overtops the dam. Flooding caused a recent hydropower plant failure at the Oroville dam in California. In 2017, after a particularly wet winter, a series of storms forced the operations team to open the dam spillway. Soon, the engineering team realized that the spillway was breached and was forced to use the emergency spillway as well as the damaged spillway. As the hole in the regular spillway continued to grow and debris were carried downstream, causing damages, the engineering team feared that the emergency spillway would also break (because of erosion). These concerns led to the evacuation of 180,000 people. As the water inflows slowed down, the emergency spillway stopped overflowing. Two days later, the evacuation order was lifted (Vox 2017).

1.2.4. Solar photovoltaic and wind generation

Solar photovoltaic (PV) generation facilities are unique in that they can operate at almost any size, from a single panel to large, utility-scale plants.[4] Solar is mainly vulnerable to high winds that can damage the panels and to hail storms. Earthquakes also can impact solar farms, particularly if the attachment of the PV panels to the support structure is not properly designed (Miyamoto 2019). Solar facilities are generally not vulnerable to floods, but the landslides that sometimes follow floods can damage foundations, electrical substations, and connections. Droughts and the dusty conditions they generate lead to dust build-up on the panels, which causes efficiency and functioning issues.

Wind turbines are vulnerable to earthquakes and cyclones. In the case of earthquakes, wind turbines are mostly vulnerable to the vertical component of ground motion. Examples in Japan and New Zealand show a complete collapse of the tower because of high seismic forces. In other cases, the loss of strength in the soil has caused residual tilts in the tower, which considerably affect energy production (Asareh 2015). During a hurricane, both wind force and flying debris are a threat to the structural integrity of the turbine. Turbines have built-in mechanisms to lock and feather the blades when wind speed is too high (generally above 55mph) to reduce the surface area pointing into the wind (Hartman 2018). But when winds are too strong, the blades can be ripped off and towers can fall – as was the case for the Punta de Lima wind farm in Puerto Rico during the category-five Hurricane Maria (Conca 2017).

1.2.5. Power grid: transmission and distribution infrastructure

As stated above, transmission and distribution network failures are responsible for most outages. Transmission infrastructure is usually more robust than distribution infrastructure and hence more resilient to natural disasters. Tower-based transmission systems typically consist of truss or lattice designs that support the conductors, while distribution systems are based on poles, often wooden ones. Transmission lines are vulnerable to many natural disasters, including wildfires, high winds, freezing rain, heavy snow, earth movement (liquefaction, earthquake, landslides) or even extreme heat (Schweikert et al. 2019). Damages occurred most commonly from storm events. These damages may be a result of flying debris, falling trees, or lines breaking during winter storms because of the combined impact of ice and wind – factors that topple lines and poles. Grid infrastructure is also vulnerable to liquefaction in earthquake-prone areas (Watson NR. 2013). During very high temperatures, sagging of the lines has also been observed, sometimes leading to failures.

Wildfires present an interesting and unique case, in which distribution assets are the source of risks (sparks causing ignition). Various case studies illustrate that during high risk conditions

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[4] Wind and hydropower generation can also be small-scale and for individual use, but this practice is more common for solar.

(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 in 2017 when transmission lines were identified as a likely cause of fire start.[5] In these cases, the distribution infrastructure is both a culprit and a victim of wildfires. It is worth noting that transmission corridors, when well maintained, also provide a positive effect by creating firebreaks in the landscape.

Transmission infrastructure is also dependent on other infrastructure for its recovery – for example, transportation, because equipment, materials, and repair crews must be brought to each site for repair. As a result, the time required to restore the lines is usually the main reason for the lag in recovery time. Restoring Puerto Rico’s entire grid took nearly a year, while most generation facilities’ recovery time was quite fast (Schweikert et al. 2019).

Substations are highly vulnerable to floods, earthquakes, and cyclones. If their components are not properly anchored, earthquakes can cause substantial damages to substations. Tall components (such as disconnect switches) of electrical substations are susceptible to damage from wind, while floods can damage expensive components and lead to extensive service interruption. Extreme heat events can affect transformer performance, but they do not cause long-lasting damages.

1.2.6. Climate change will increase the power system’s exposure to natural disasters

Several climate change–induced phenomena are likely to increase power sector vulnerability. With increased drought frequency and higher temperatures, the efficiency of nuclear and thermal power plants is likely to decrease. Research suggests that a 1°C temperature increase could reduce power output by 0.45 to 0.8 percent (Mideksa and Kallbekken 2010).

At the same time, these events will impact substation equipment and the current rating of cables and lines, and are also likely to increase system stress because of additional demand for air conditioning. Extreme weather events could disrupt infrastructure, affecting the delivery of electricity; higher temperatures may also result in greater transmission losses because of the increased resistance of power lines.

In most regions, wind speed is likely to increase with climate change, while atmospheric icing (which negatively impacts wind turbine performance) should decrease. However, there is not enough evidence to conclude that wind-generated power output will increase, because incidents of extreme wind speed frequency (i.e., occasions at which the wind speed exceeds operational boundaries) are also likely to increase (Mideksa and Kallbekken 2010).

Climate change will also affect flood frequency and hydrological outputs by changing not only river flow and evaporation, but also the frequency of erratic river flow, which impacts dam safety (Döll and Schmied 2012).

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[5] 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).

Climate change is likely to increase temperature but decrease solar radiation. These projected changes will decrease the potential for solar energy: the efficiency of photovoltaic modules could drop by about 0.5 percent for every 1 °C increase in temperature (Patt, Pfenninger, and Lilliestam 2013).

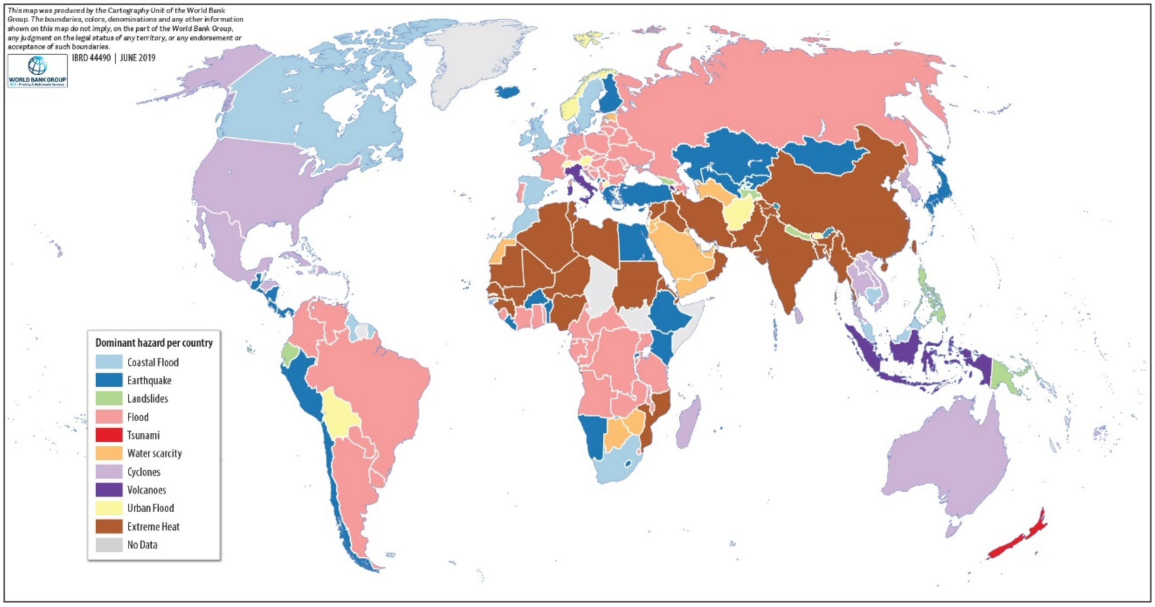
Finally, climate change–induced sea level rise could cause power plant relocation. Sea level rise will not only be responsible for increased flooding of coastal assets – combined with higher wind speeds, sea level rise will lead to greater corrosion of these assets due to saltwater sprays. A study on potential climate change impacts on Bangladesh power sector found that around a third of power plants should be relocated by 2030 to avoid inundations caused by sea level rise. Another 30 percent of Bangladesh power plants will likely be impacted by the increased salinity of cooling water and increased flooding frequency, while the northern region plants will probably see a yield decrease because of droughts (Khan, Alam, and Alam 2013).

3. Global power system exposure to natural hazards and risk

3.1 Exposure and risk for power generation infrastructure

An analysis conducted for this report demonstrates the significant exposure of power-generation infrastructure to natural hazards (Nicolas et al. forthcoming). The georeferenced power plants in this analysis come from the World Resources Institute's global power plant database (World Resources Institute 2018). Exposure of the plants is assessed for a large range of hazards: cyclones, earthquakes, floods, extreme heat, droughts, volcanic eruptions, tsunamis, and wildfires. The asset risk is assessed only for the most frequently recorded and costliest disasters: cyclones, earthquakes, surface flooding, river flooding, and coastal flooding. While extreme heat days and droughts also are high-frequency events, they mostly impact service continuity during the event and very rarely impact the integrity of the asset. The exposure analysis makes use of the ThinkHazard database (ThinkHazard 2019): assets are considered to be exposed to a hazard if the hazard level is "High" in ThinkHazard and if the asset is vulnerable to this hazard (e.g., a wind farm in a drought-prone area is not considered exposed to drought).

Figure 6 Dominant hazard per country. This figure presents the hazard causing the highest generation infrastructure exposure in each country (in MW).

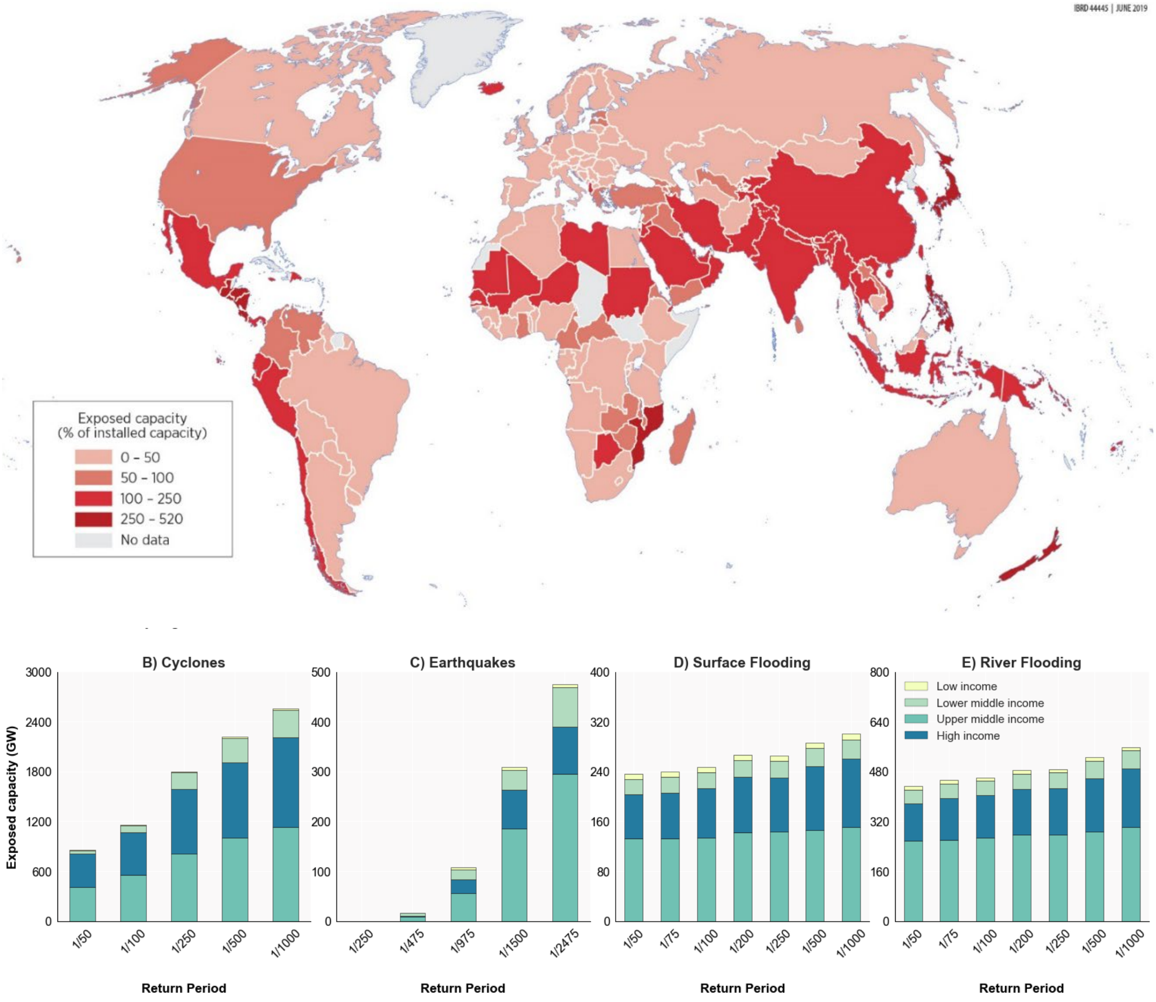


Note: Plants are considered exposed to a hazard if it can create outages/service interruption and even though the hazard does not impact the asset integrity.

Exposure levels for distinct natural hazards vary geographically, as illustrated in Figure 6, which indicates the predominant natural hazard per country. At first glance, most natural hazard types are represented across the globe. For example, Chile and Japan are strongly exposed to earthquakes. On the other hand, floods are Brazil's and Russia's chief natural disaster type, while the area stretching from Northern Africa to Myanmar and China is mainly exposed to extreme heat. From Thailand to New Zealand, countries are mainly exposed to tsunamis, floods, coastal floods, and cyclones. However, countries in Sub-Saharan Africa are exposed to a more counter-intuitive mixture of extreme heat, wildfires, water shortages, and floods.

Figure 7 Global multi-hazard power generation infrastructure exposure. Panel A represents the sum of exposed capacity for all hazards divided by the total installed capacity in the country.[6] Panels B to E present the exposure for four income groups per hazard and per hazard return period (the asset is considered exposed if the hazard intensity is higher than a threshold that differs between income groups to reflect the different design standards and maintenance efforts).

A)



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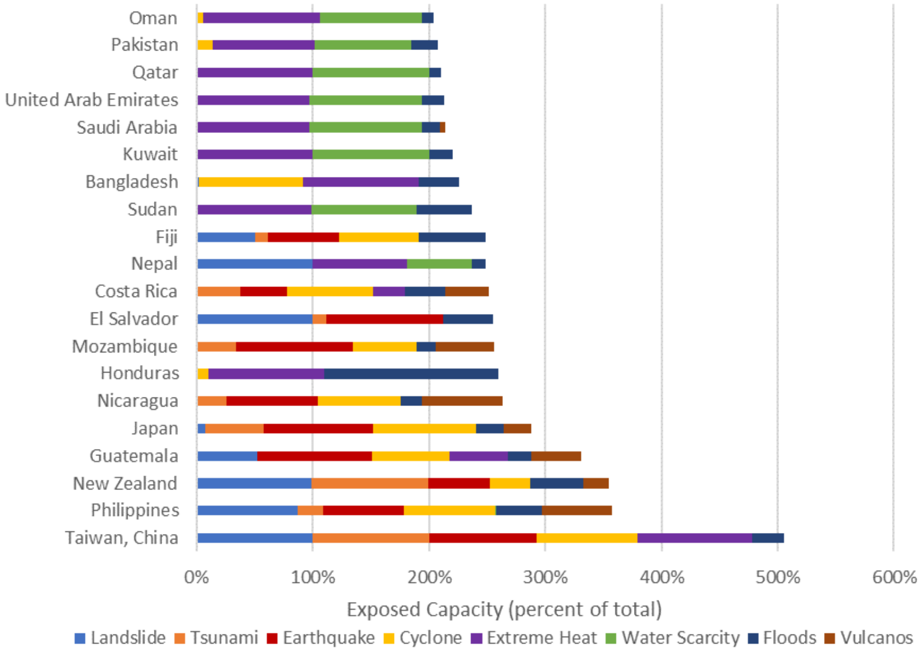
[6] Exposed capacity is divided by total installed capacity in the country. The value can be above 1 because one power plant can be exposed to various hazards. Power plants are considered to be exposed to a hazard when they are in an area where the hazard level is "High" in ThinkHazard!. Hazards considered are: Coastal Flood, Earthquake, Cyclone, Flood, Water Scarcity, Cyclones, Vulcanic eruptions, Tsunamis, Extreme heat, and Wildfires.

Figure 7 presents the multi-hazard exposure of power generation infrastructure by country. The indicator sums the capacities that are exposed to different hazards (and can exceed 100 percent if assets are exposed to more than one hazard). It shows that a large number of countries are exposed to more than one hazard. At first glance, the generation capacity in Europe, Canada, the eastern part of South America, and Australia is relatively protected from natural hazards. On the other end of the spectrum, generation capacity in countries such as Nepal, New Zealand, Japan, Mozambique, the Philippines, and most of Central America is heavily exposed to various natural hazards. Most of the Middle East and South Asia face between 100 and 250 percent generation capacity exposure. The most exposed countries (the Philippines, New Zealand, Guatemala, Japan and Taiwan, China) are highly exposed to cyclones, earthquakes, tsunamis, and landslides (Figure 8).

Figure 8 Countries with the highest multi-hazard exposure indicator and their dominant hazard



Based on this exposure analysis, Nicolas et al. (forthcoming) estimated Expected Annual Damages (EAD) by considering different generation infrastructure types, hazard intensities, the building standards used in the country, fragility curves, and infrastructure investment costs. This process enables estimates of the global average annual repair costs for damages caused to power generation infrastructure by cyclones, earthquakes, surface flooding, and river flooding.

The total global EAD from all hazards amount to about US$ 15 billion per year, representing around 0.2 percent of the value of power generation infrastructure installed worldwide (Figure 9). Of these damages, about 84 percent are caused by cyclones, 12 percent by surface and river flooding, and 4 percent by earthquakes. Most of these damages are suffered by China (Figure 10).

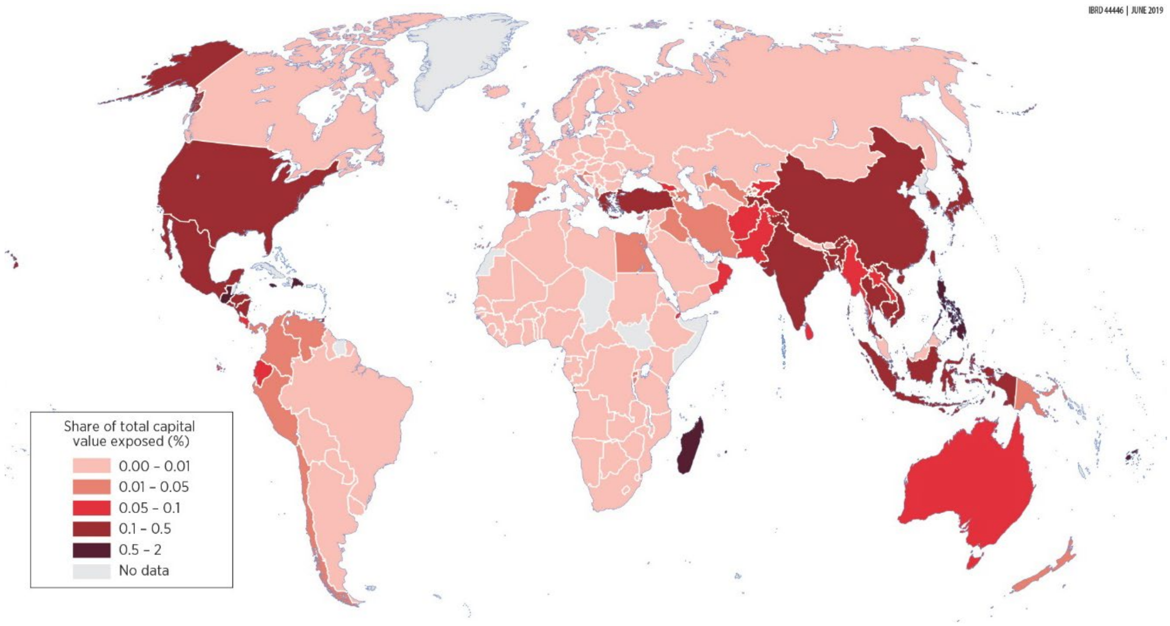
Globally, losses are driven mainly by thermal plants in the case of cyclones, and by hydropower plants in the case of earthquakes.

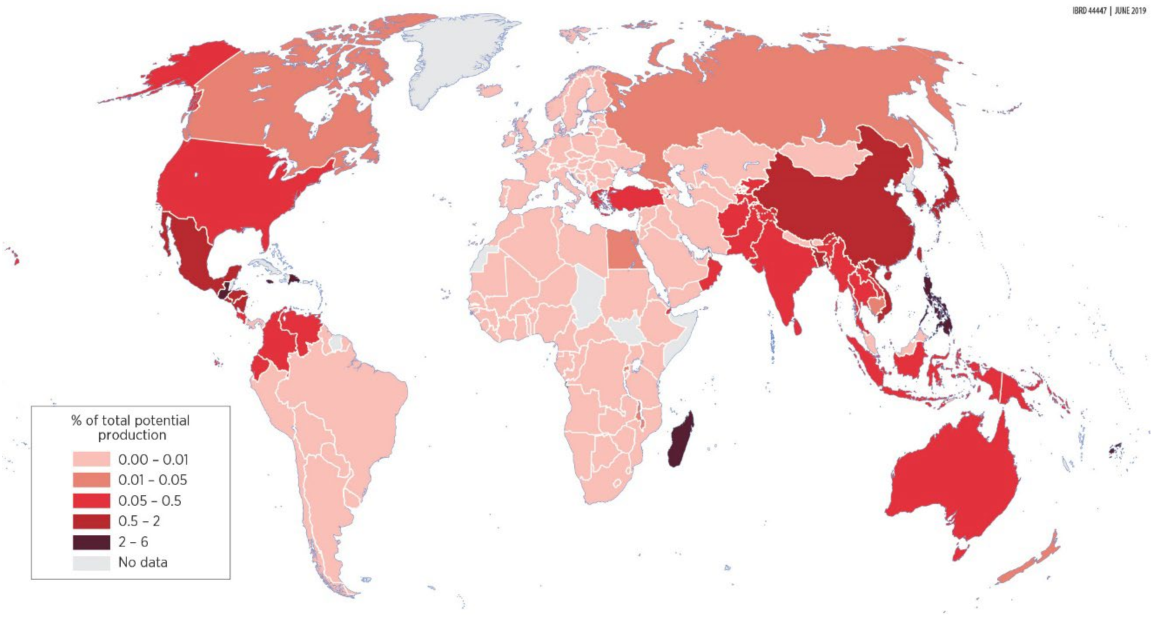
In addition, Figure 9 (panel B) presents expected annual generation losses, which can represent up to five percent of the total generation of some countries. Those losses have been calculated by taking into account the expected damage for each plant as well as the restoration time, which varies between country groups. Countries with the highest production risks are those whose power system is often already constrained because they are not totally electrified or because electricity demand is growing quickly.

The difference between panels A and B in Figure 9 demonstrates that looking at assets is insufficient to understand the impacts that disasters have on power systems and its users. Ultimately, the reliability of generation is what matters. In addition, it is important to note that expected annual losses can hide the devastating cost that individual disasters can cause.

Figure 9 Multi-hazard risk indicator for capacity, capital expenditure and energy produced. Panel A) presents the asset risk divided by installed capex in country, while Panel B) presents the output risk (in MWh) divided by the total potential generation of the country.

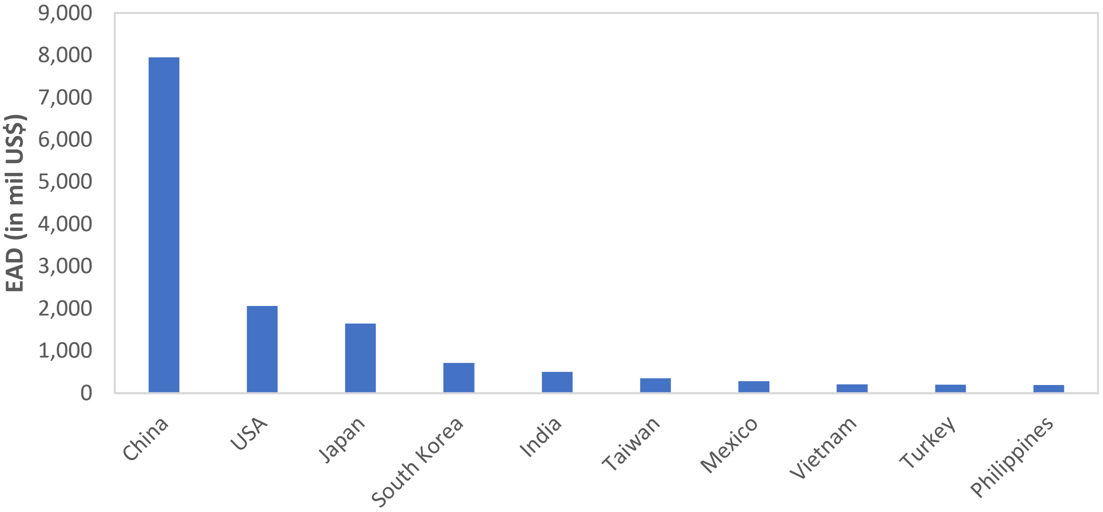
A) Share of total capital value exposed (%)





B) % of total potential production

Figure 10 Top 10 countries in terms of Expected annual damages to power generation infrastructure



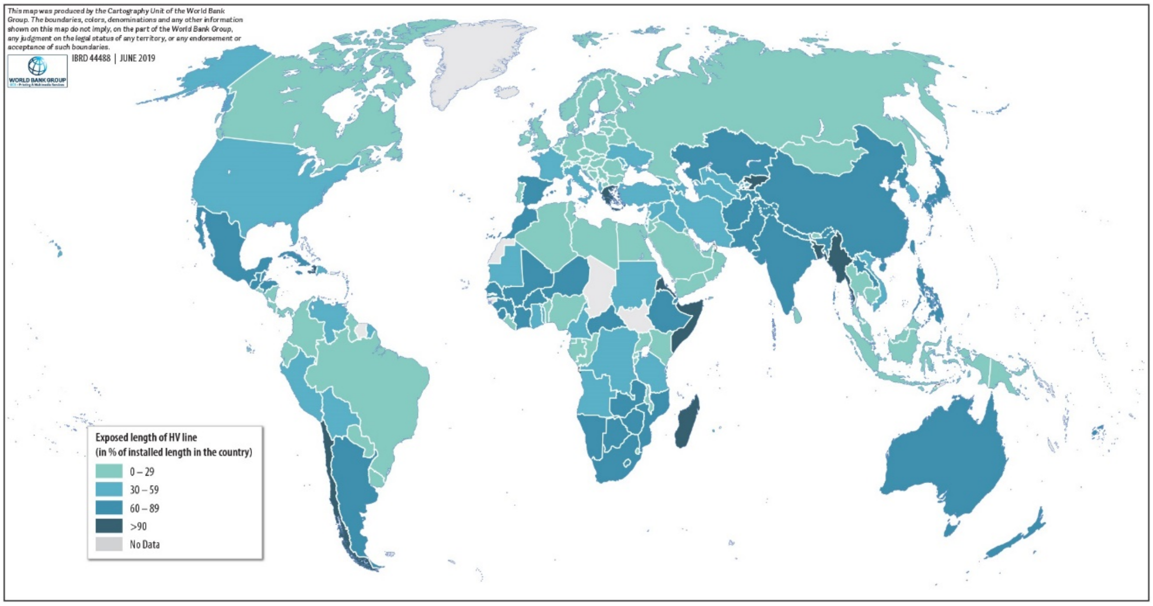
3.2 Exposure of transmission and distribution infrastructure

A similar multi-hazard exposure and risk analysis has been performed for grid infrastructure. Since no global database of grid infrastructure is available, the data used is that presented in Arderne et al. (forthcoming). The high-voltage (HV) line infrastructure data comes from OpenStreetMap, while the medium-voltage (MV) infrastructure is estimated using nighttime light data, road and topology data, and population data (Arderne et al. forthcoming).

The analysis takes into consideration the three most devasting hazards for power lines: earthquakes, cyclones and wildfires.[7] Figure 11 presents the multi-hazard exposure of HV and MV line infrastructure by country and shows that, as is the case for generation, a large number of countries are exposed to more than one hazard. At first glance, the grid in Europe and northern Africa is relatively protected from natural hazards. On the other end of the spectrum, HV infrastructure in countries such as Greece, New Zealand, Myanmar, Somalia, and Chile is heavily exposed to various natural hazards. MV infrastructure is highly exposed in many small island developing states (for example, Vanuatu, Bermuda, and Tonga) as well as in Madagascar, Greece, and Mexico (see Figure 12).

Figure 11 Global multi-hazard HV and MV line infrastructure exposure. Panel A represents the sum of exposed length of line for all hazards divided by the total installed line length in the country. Panels B to D present the exposure for four income groups per hazard and per hazard return period (the asset is considered exposed if the hazard intensity is higher than a threshold that differs between income groups to reflect the different design standards and maintenance efforts).

A) Exposed length of HV lines (% of installed length)



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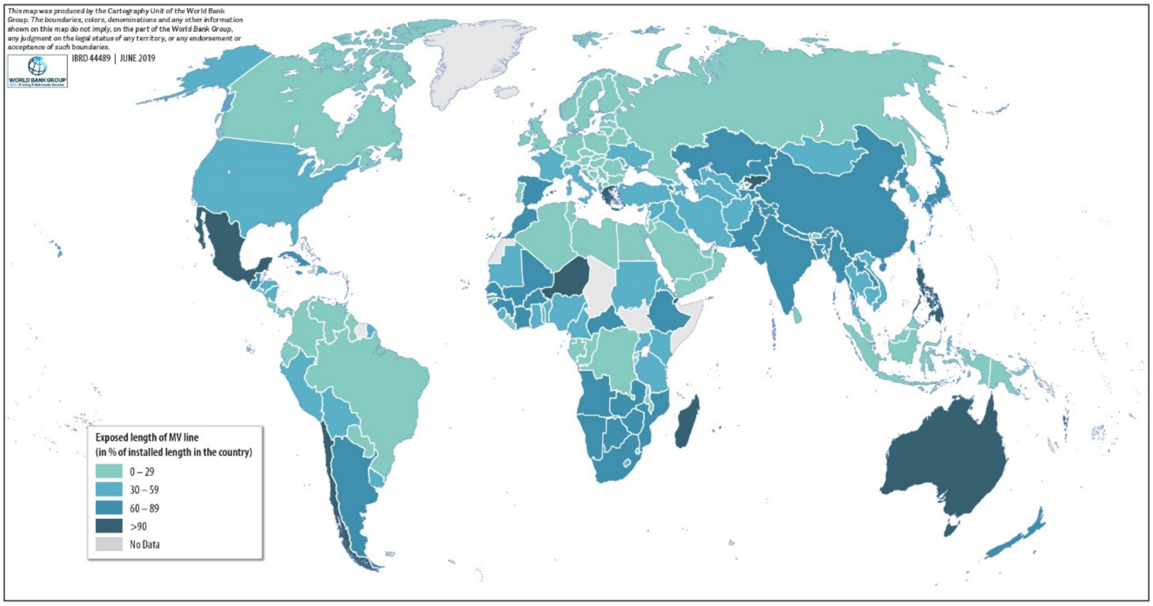
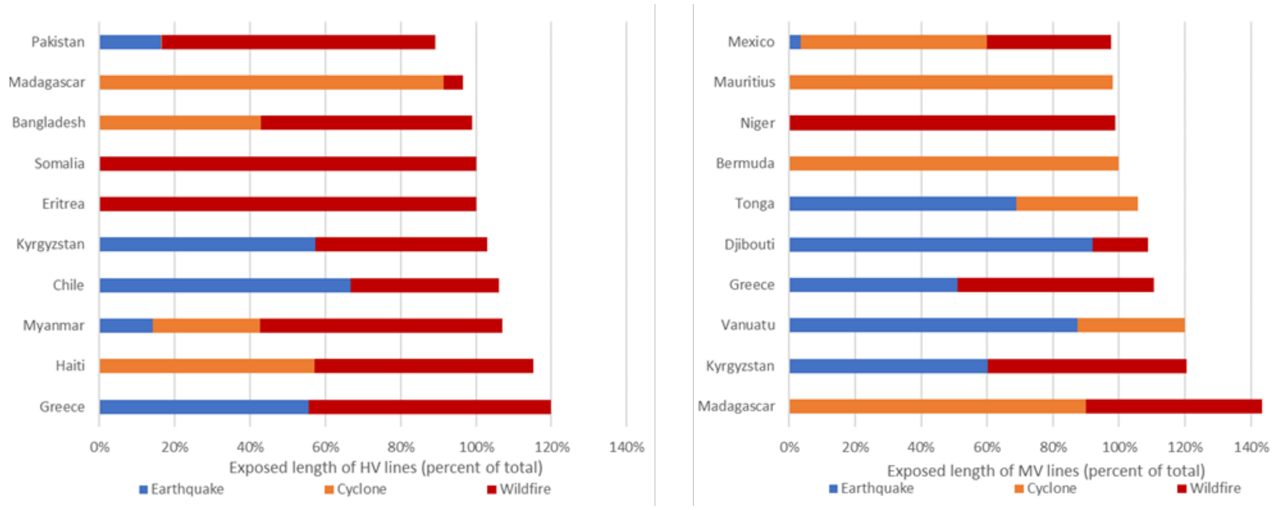
[7] Thunderstorms are also a threat for transmission and distribution assets, but hazard maps for thunderstorms are not available.

B) Exposed length of MV lines (% of installed length)



Source: (Nicolas et al. forthcoming)

Figure 12 Countries with the highest multi-hazard exposure indicator and their dominant hazard (HV lines left, MV lines right)



Source: (Nicolas et al. forthcoming)

4. Improving power sector resilience

Because of its networked nature, the vulnerability of the power sector cannot be calculated by simply summing up the vulnerability of its individual components (Carlotto and Grzybowski 2014). In interconnected power grids, power utilities have to maintain a dynamic balance between load and production. When disruptions occur, the balance needs to be quickly re-established to prevent generators and load breakers from tripping. Otherwise, the result can be cascading outages that can lead to total blackouts, as it was the case in the 2009 blackout in Brazil, which followed the shutdown of the Itaipu hydroelectric facility (*Reuters* 2009). Researchers also suspect that transmission and distribution systems experience what is called self-organized criticality: they evolve by their own means to a critical state in which even a minor event can lead to major failures (Carlotto and Grzybowski 2014). As such, it does not necessarily make sense to consider the resilience of individual parts of the system. A network-based approach is necessary.

This section focuses on strategies that can increase power sector resilience. The first set of strategies are intended to increase the robustness of infrastructure by hardening it and by improving its design – via power sector planning, for example. The second set of strategies aims to improve network flexibility and adaptability to ensure that the system will be able to react as smoothly as possible when disasters strike. Finally, the third set of strategies concerns the way that operations can be improved to better cope with natural hazards and minimize their consequences.

4.1 The costs of increasing power system robustness

Improving the robustness of power infrastructure seems like an obvious, albeit sometimes costly, way to increase the resilience of the power sector. Building more robust infrastructure with higher design standards would allow the system to withstand bigger shocks while reducing repair costs, system interruption costs, and maintenance costs. This section describes how power sector infrastructure can be hardened, and assesses the costs of robustness.

4.1.1 Hardening infrastructure

Measures to harden infrastructure depend on the type of hazard that most threatens a country's grid. For instance, Tonga, which is highly exposed to cyclones, began to upgrade its grid by replacing its low-voltage overhead network with aerial-bundled conductors (ABCs), installing underground service cables to customer premises, and installing new smart meters. The project was undertaken for its technical benefits (to reduce losses and outages) as well as to improve resilience to hazards (Tonga Power Limited 2016). An estimated 54 percent of the network had been upgraded (GoT 2018) when Tropical Cyclone Gita made landfall in Tongatapu, Tonga. The cyclone damaged 45.9 percent of the portions of the power grid that had not been upgraded, compared to only 4.7 percent of the upgraded segments of the grid (ADB 2018).

Cyclone-proofing is necessary for thermal, wind, and solar plants as well as for the grid. To protect thermal plants against structural damages during high-wind events, the stacks and cooling tower components need to be anchored using wind-rated mechanical attachments: cooling towers need bracing, while stacks need cross-wind mitigation (Miyamoto 2019). Increasing wind turbines' robustness to high winds is often done by using shorter blades. This downsizing has a cost, however, since the turbine size is not optimal for the average wind speed; the result is a lower production rate than could be obtained in an area not prone to cyclones. Other parts of the plant also must be reinforced, including the turbine tower, which can be made with thicker steel – sometimes adding as much as a third or half again the initial weight.

Similar solutions can be used to improve power lines' wind performance. Structural interventions include using concrete or steel poles instead of wooden poles; using more stay wires with modified pole or tower foundations; and modifying tower designs. For transmission lines, the aluminum structures can also be upgraded to galvanized steel lattice or concrete structures (Miyamoto 2019). For suspended lines, introducing more dead-end towers (which are stronger than suspension towers) along the transmission lines will reduce the risk of cascading tower collapse. Aerial bundled cables/conductors and underground cables can also help reduce outages during storms. ABCs offer better resistance to winds and to growing trees and shrubs compared to exposed conductors, but are multiple times (2–15 times) more expensive than overhead conductors. Using underground lines also improves resilience of the grid, as they are shielded from the elements of nature. However, burying overhead wires costs between $300,000 and $1.25 million per kilometer (compared to $80,000-$240,000 for suspended wires), plus expenses for coolants and pumping stations (White House 2013). Additionally, underground cables take longer to restore in the event of a fault, and repair costs are also higher. The advantages therefore need to be balanced carefully against the disadvantages.

Finally, improving wind performance of solar panels can be done most effectively by improving the design of panels, particularly their anchorage (to ensure they will be designed for the uplift due to wind loading), and installing the panels horizontally when necessary (at the cost of efficiency).

In the case of earthquakes, higher design standards for improved performance are quite similar across different types of power infrastructure: they often involve deeper foundations in liquefaction-prone areas, better anchorage of both electrical and mechanical components, or using seismic protection devices to reduce demand on the components or buildings.

One straightforward way to improve power system performance during floods is to elevate solar panels, or to locate plants or substations in an elevated area that will not be flooded – and, when possible, far enough from the coastline to avoid coastal flood. For existing plants that cannot be moved, elevating critical components is an option (particularly for substations), as is building dikes or flood protection walls. In the Tonga Ha'apai Islands, for example, following Tropical Cyclone Ian in 2014, the government decided to move transformers above the maximum possible sea-flood level. Similarly, following Hurricane Sandy in 2012, Con Edison installed flood walls and flood doors, and raised one substation control room above storm-surge levels (Brown 2016). Installing flood monitoring devices to notify operators during a flood event can also help mitigate the inundation (Miyamoto 2019). Finally, diesel generators are mostly vulnerable to floods, so the primary recommendation to make them more resilient is to avoid the usual practice of storing them in basements. Keeping the fuel stored next to generators should also mitigate the second vulnerability of these generators – the supply chain issue.

Droughts may primarily cause impacts to hydropower assets, but they also threaten thermal and nuclear power. In the latter cases, replacing the water-cooling system with air cooling, dry cooling, or a recirculating system can improve the plant's performance during droughts. For hydropower, increasing storage capacity may help mitigate the impact of a drought, but only if the drought is not too lengthy. Otherwise, the solutions have to be system wide (e.g., operational complementarities with other sources, or regional integration through interconnections).

4.1.2 The incremental cost of hardening infrastructure remains limited

The cost of hardening power infrastructure depends heavily on the hazard and the infrastructure involved. Miyamoto (2019) estimated this cost for power sector infrastructure for floods, earthquakes, and cyclones (see Table 2), linking the cost of hardening the infrastructure with the change in damage probability.

Table 1 Cost of power infrastructure hardening

	Earthquakes		**Cyclones**		**Floods**	
	Cost increase	Damage probability is reduced by	Cost increase	Damage probability is reduced by	Cost increase	Damage probability is reduced by
Thermal plants	20%	10	10%	3	2%	Risk very low
Nuclear plants	5%	10			2%	2
Hydropower plants	20%	2			5%	1.3
Solar plants	5%	5	15%	2.5		
Wind farms	5%	1.2	5%	2		
T&D lines	15%	Residual risk very low	20%	2		

Source: Miyamoto 2019

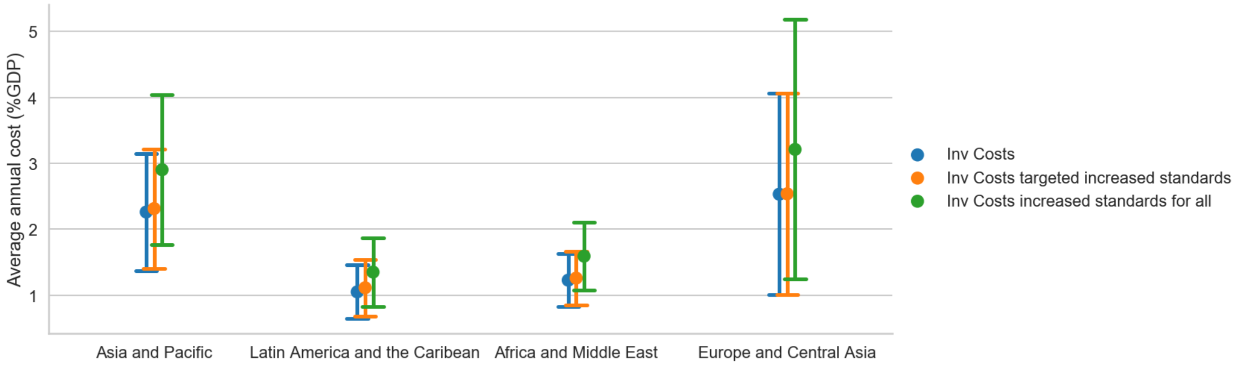
Nicolas, Rozenberg, and Fay (2019) estimate how much LMICs (low- and middle-income countries) will need to spend on infrastructure to achieve their access goals. Their results provide a baseline to examine how those estimates would change if power plants were built with better robustness standards.

Without accounting for resilience, investment needs in the power sector range from 0.9 percent to three percent of gross domestic product (GDP) annually (US$298 billion to US$1 trillion per year), depending on the desired level and quality of service, the technologies deployed, and their deployment timing and energy efficiency. An additional 0.32 to 0.85 percent of GDP will be needed for maintenance.

If all new power plants are built to the highest standards to increase their wind, flood, and earthquake performance, investment needs could increase by as much as 30 percent in some scenarios.[8] This would raise the investment need to between 1.2 and 3.9 percent of GDP annually. The cost increase is in the range of what is spent annually on maintenance for the generation side of the power sector.

If only those assets that will be located in flood-, cyclone-, or earthquake-prone areas are built with higher protection standards, then the additional cost would represent only between 0.03 and 0.08 percent of GDP annually (see Figure 13 for results detailed by regions). This is a total investment cost increase of around 2.5 percent, which is quite low compared to the impact of the other investment cost drivers (e.g., level and quality of service, demography, technology evolution, spending efficiency). Such an investment would reduce the risk to new asset by a factor 2.5 to 3.1.

Figure 13 Investment needs in the power sector and the incremental cost of increasing the robustness of future powerplants (average annual cost of investment in the power sector in LMICs, 2015-2030)



Note: LMICs = low- and middle-income countries; the results shown are for a 2C scenario. The base scenario is the investment scenario presented in Nicolas et al. (2019). "Targeted increased standards" is the scenario where only infrastructure in exposed areas are hardened; the percentage of hydro, thermal, nuclear, wind, and solar plants in flood-, earthquake-, or cyclone-prone areas is calculated by region, and, depending on the asset type and the hazard, the cost is increased accordingly. In the "increased standards for all" scenario, it is supposed that the exposure is not known and that all power plants are hardened.

These results show that it is important to target infrastructure hardening when the hazard exposure is high, and that hardening all infrastructure "by default" can be quite costly. It also shows that having good data on the probability and spatial distribution of natural hazards, as well as on their potential evolution due to climate change, is essential to improve power sector resilience.

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[8] This refers to the future scenarios described in (Nicolas, Rozenberg, and Fay 2019). These scenarios are derived from six global energy-economy modeling frameworks, each of which depicts a uniquely evolving energy investment landscape in futures spanning a continuation of today's trends to those that are dramatically more transformative.

Box 1. Build Back Better: Improving the grid in Puerto Rico

Hurricane Irma, a Category 5 storm, made landfall in Puerto Rico on September 6, 2017, leaving 70 percent of electricity customers without power and damaging critical infrastructure (Campbell, Clark, and Austin 2017; New York Power Authority et al. 2017). On September 20, 2017, a second hurricane, Maria, made landfall in the island as a Category 4 storm with wind speeds of over 250 km/h. The consecutive storms caused catastrophic damage, especially to the electrical grid. Damage was so extensive that even undamaged generators could not supply power (U.S. Energy Information Administration 2018). The disaster resulted in electrical power outages to 90 percent of the island, as well as loss of housing and infrastructure and contamination of potable water. The cost of the damage is estimated in the tens of billions of dollars (Central Intelligence Agency 2018).

Much of the Puerto Rico'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). Because of poor maintenance and vegetation management, transmission lines and towers in the center of the island were severely damaged by high winds: approximately 101 transmission line segments, 636 poles, and 673 conductors/insulators were damaged by the storm.

In early October 2017, only 20 percent of all transmission lines in Puerto Rico were functioning (Ferris 2018). Virtually 100 percent of Puerto Rico Electric Power Authority (PREPA) customers were without power for over a week following the storm, and the slow pace of recovery meant that many customers were left without power for several months (U.S. Department of Energy 2018). Generating facilities were repaired quite fast, and most renewable generating facilities sustained only modest amounts of damage; however, none of these facilities were able to connect to the power grid for several months because of the state of the grid and because the operator feared that the grid would not be able to deal with renewable energy variability. Small amounts of solar and hydropower were able to reconnect to the transmission system in late 2017, but the first wind farm did not reconnect until February 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 later in 2019 (U.S. Energy Information Administration 2018).

As repairs and rebuilding continue, PREPA has evaluated resilience options. Results show that the cost of building back better, when compared to baseline estimates, varies greatly based on the component. For example, hardening the transmission grid (lines, poles, circuits) generally has relatively low incremental costs (around 10 percent) while hardening the distribution system (replacing wood poles with tubular steel poles) has much higher incremental costs (around 100 percent). In Puerto Rico, upgrading transmission and distribution infrastructure to withstand Category 3 hurricanes would increase costs by three to 40 percent, while upgrading to withstand Category 4 hurricanes (210-250 km/h sustained windspeeds) would increase costs by 24–70 percent.

Source: (Schweikert, et al. 2019)

4.1.3 Good maintenance can reduce costs and increase resilience

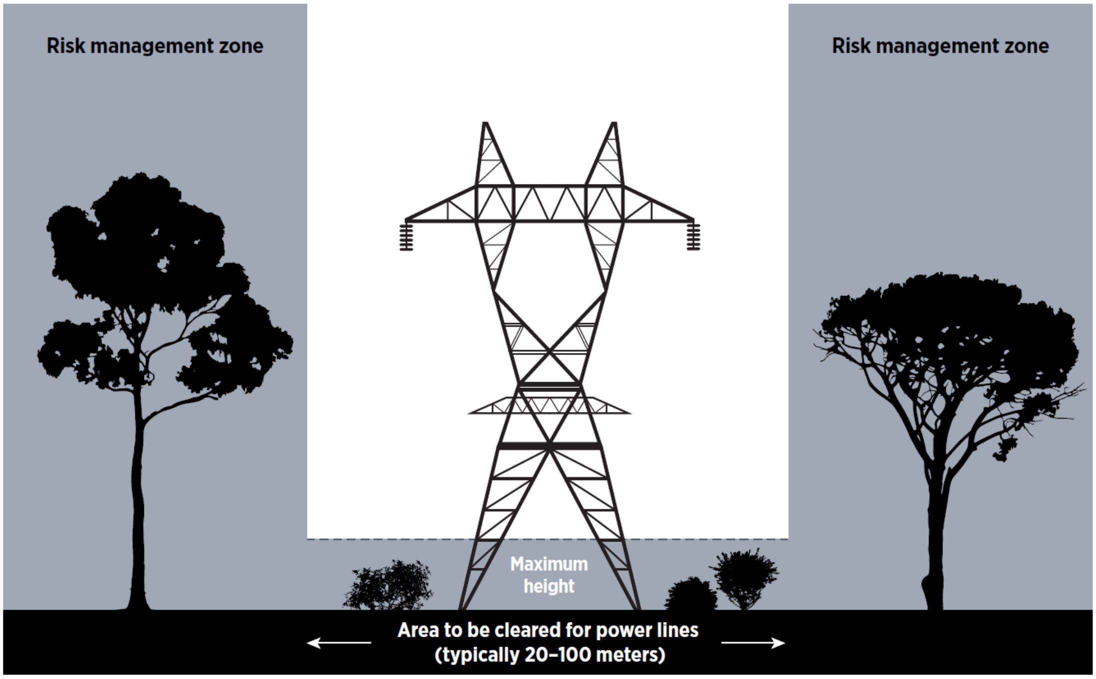
Power system infrastructure maintenance is essential for increasing power sector resilience. Unfortunately, because of a lack of funds, maintenance is often performed poorly – when it is performed at all.

For generation plants, maintenance encompasses visually inspecting the state of the asset, as well as cleaning debris and obstructions from dam sluice gates and drainage channels, periodically servicing standby generators and painting metal surfaces to prevent corrosion, and replacing rotting wooden distribution poles (Brown 2016). Good maintenance is particularly essential for hydropower plants, as this type of infrastructure can last up to 100 years. Lack of maintenance was identified as the cause of the Oroville dam failure in 2017, which led to the evacuation of 180,000 people (Vartabedian 2017).

When it comes to the power grid, tree contact with power lines is a leading cause of outages and has caused several regional blackouts, including the August 2003 blackout that affected 50 million people in the northeast U.S. and parts of Canada (Hansen 2017). Sometimes, contact with vegetation will "just" trip the line, while in other cases it can lead to wildfires or to fallen lines. During storms, flying debris and vegetation, not strong winds, are the primary causes of pole damage; reinforcing poles is thus less efficient than trimming trees, as tree-related failures increase exponentially when wind speed reaches 100km/h.

Traditionally, vegetation management around power lines has been based on maintaining a clearance zone (see Figure 14). A buffer of between six and 15 meters is usually used on both sides of medium-voltage lines, while a low-growth zone is delimited around transmission lines (between 10 and 50 meters on both sides). Vertical limits are also considered for all line types. In the US, the North American Electric Reliability Corporation (NERC) sets vegetation clearance requirements for transmission, while California and Oregon are two of the few states that have strict clearance requirements for electric distribution systems (2018c). Vegetation management is often outsourced by the utility companies, and in the absence of standards and rigorous methodology for identifying vegetation hazards "outside" of required clearances, it is often based on the contractor's expertise and knowledge. For most utility companies, vegetation management tends to be one of the largest expenses associated with maintaining the grid. California's Investor-Owned Utilities spend more than $250 million a year on vegetation management around distribution lines alone.

Figure 14 Easement profile - Vegetation clearance at transmission and sub transmission electricity networks



Source: (Energy Queensland Limited 2019)

4.2 Better planning and understanding of system effects can reduce the cost of resilience

The 2010–2011 earthquakes in New Zealand highlighted the value of pre-emptive investment in infrastructure. Estimates show that the $6 million spent to harden transmission and distribution infrastructure resulted in $30-50 million reduction in direct asset replacement costs (Fenwick and Hoskin 2011). Yet, as discussed previously, hardening all assets is not necessary, and a careful cost-benefit analysis should be performed. Indeed, if the asset is not critical, its failure may be acceptable if few or no customers experience service interruptions. Since the power system consists of networked infrastructure, its redundancy usually allows some elements to fail without sacrificing service to all customers. Hence, improving the reliability of the service for electric utility customers requires an understanding of which asset(s) to harden and how increasing network diversity and redundancy could help. In this section, we will discuss measures to increase the resilience of the power sector. Emergency preparedness measures will be detailed in the following section.

4.2.1 Criticality analysis: Targeting investment where it matters most

Outages cannot be avoided completely; attempting to do so would incur significant costs. This section therefore describes how planning can minimize the impacts of hazardous natural events on transmission and distribution.

Transmission and distribution networks are typically designed with some level of redundancy to reduce the risk of outages from planned and unplanned events. These considerations are included in the planning and construction standards of most utilities. For example, the system planning criteria might specify maximum line loading limits under normal conditions, so that in the event of an outage, the components remaining in service (e.g., circuits or lines, or transformers or generators) can support the system load (called n-1). Depending on the sensitivity of the load center, the supply network in a particular area may be designed to operate within limits in the event of a double or even triple outage (n-2 or n-3).

Considerations of natural hazards can be included in transmission and distribution system planning, but usually are not. These considerations may, for example, require improving the reliability criteria for vulnerable or critical parts of the network from single-element contingency (n-1) to double-element contingency (n-2). These types of analyses can help identify which are the critical assets in the network and what their failure would mean for the system – and, most importantly, for the customers (Mitra et al. 2016). The same is true of the n-1-1 contingency analyses that utility companies are asked to perform in order to plan for cascading outages and not only simultaneous outages or failures (unlike the classical n-k contingency analyses). Depending on the hazard probability and the consequences of the critical asset failure, the utility can then make the decision to reinforce the grid.

But with this type of classical contingency analysis, the impact of a large shock (one that would impact more than two elements of the network) is not accounted for. And the impact will depend on the characteristics of the shock: for instance, Ouyang, Dueñas-Osorio, and Min (2012) find that the expected annual resiliency of the power transmission grid in Harris County, Texas, USA, is higher when planning for random (frequent) shocks than when planning for hurricanes. If data on the full distribution of possible events is not available, it might be more robust to invest in changes that will improve the resilience of the network to a wide range of random events.

Unfortunately, given the complexity of power-flow models and how time consuming it is to solve them, even the n-2 contingency analysis is often very difficult to perform. Hence, studying how the system would behave if *p* elements were to fail is only possible in a designated area, or for a selection of those *p* elements. An n-*p* contingency analysis at the system level is rarely possible.

However, this type of study can reveal high-return interventions. For example, Veeramany et al. (2018) performed a network criticality analysis for seismic risks in Washington State. Working on a subset of the transmission network that was assumed to be vulnerable to seismic hazards, they considered 40 potential seismic events (four different earthquake magnitudes for 10 epicenters) and ran 200,000 scenarios (10 epicenters x 4 magnitudes per epicenter x 5,000 simulation iterations per initiator) to assess the behavior of the system during an earthquake. For each scenario, they used the seismic data to identify which asset would fail and then performed the load-flow study to identify if and where there would be unserved energy in the system. They then computed the expected service interruptions by considering the likelihood of seismic scenarios, including asset failures, the extent of load lost, and the post-event recovery duration. They were able to identify the most critical combination of assets; in this case, they realized that hardening one asset or adding redundancy to “double” it could reduce risk by 88 percent.

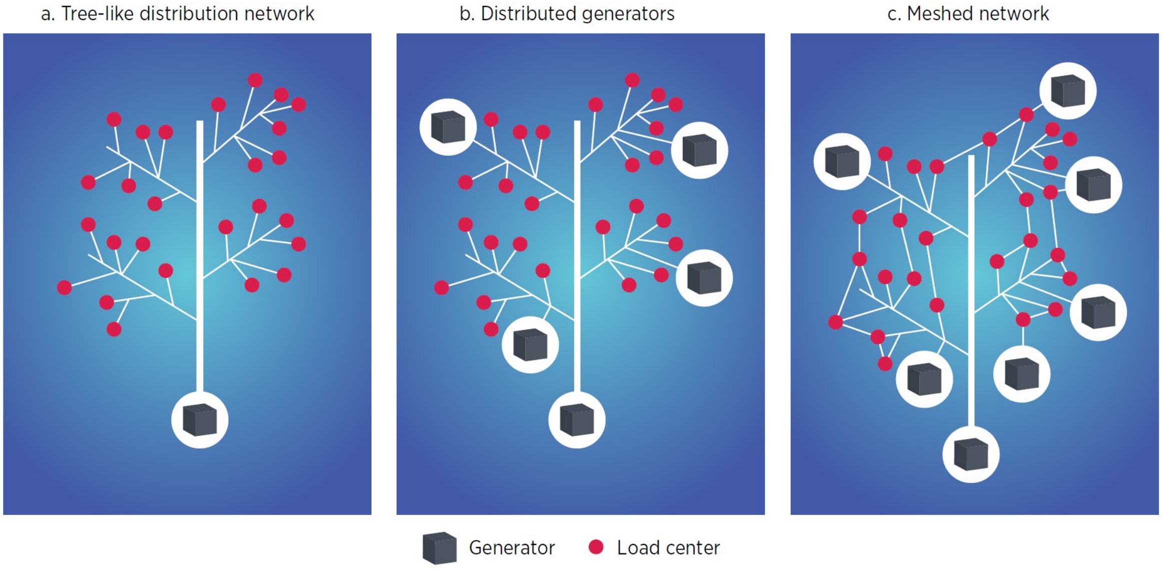
This type of analysis is important to understand how the network will behave should 1 to *p* elements fail, as the criticality of the remaining nodes change when the most critical node is removed. To overcome the difficulty presented by a n-*p* contingency analysis, Onetta, Carlotto, and Grzybowski (2014) propose working with the network topology as a first approximation. By assessing the impact of the removal of several nodes at once, this approach enables researchers to assess how additional links could improve the overall network connectivity.

4.2.2 Diversification and flexibility: increasing network versatility

Criticality analysis can highlight opportunities to increase resilience through redundancy. For transmission and distribution networks, identifying critical assets via an n-1 or n-2 contingency analysis does not necessarily mean doubling or tripling key components of the network (for n-1 and n-2 respectively) or undergrounding the lines. A more effective approach is usually to create “ringed” or meshed networks that provide multiple supply points to various nodes in the grid (see Figure 15). A meshed network reduces exposure to outages along corridors. It also provides the ability to quickly switch loads between feeders or supply points. This approach is being used more and more for distribution networks that were traditionally star shaped (radial distribution) and that are now becoming as meshed as most transmission networks. But redundancy also has some drawbacks. Costs increase due to the construction, operation, and maintenance of additional assets, and – counter-intuitively – redundancy can increase the risk of cascading failures.

An effective response to this risk is defensive or adaptive islanding, which is a mechanism to stop black-out propagation. During cascading failures, parts of the grid naturally become islanded. But if load and generation in the resulting islands do not match, there is a high probability that the islands will fail (particularly if load is higher than generation). Defensive islanding consists in splitting the system into stable and self-sufficient islands when there is a risk of cascading failures. The resulting islands can then operate, or fail, independently of the larger system. In the event of region-scale extreme events, this approach could be effective by isolating the affected area and preventing a disturbance propagation (Panteli et al. 2016).

Figure 15 Network topology can improve grid resilience



Source: (Stöcker 2018)
Note: The meshed distribution network contains distribution feeders that are linked by open switches during normal operations to maintain the radial characteristic of the distribution network. These switches are closed to provide alternative paths for electricity when a distribution feeder is disconnected.

Distributed energy resources (DERs) are another option to diversify and increase the grid flexibility. DERs increase resilience through embedded generation, microgrids, and mobile generating units by supporting load without the grid. During Superstorm Sandy, for example, the Co-Op city microgrid in New York successfully decoupled from the grid and supported consumers during outages on the wider network (Strahl et al. 2016). Distributed generation can enable more islanding mechanisms, as generation is located closer to the load, feeding directly into the distribution network and often bypassing the transmission grid. DERs usually include renewable generation, diesel generators, back-up power sources (e.g., small natural gas turbines) and batteries. Until recently, DER installation, and particularly renewable installation, has been driven by consumers and by environmental concerns; only recently has resilience become another driver of its development. If well planned, DERs can help the network operator not only increase system resilience, but in some cases also relieve congestion and avoid the construction of additional transmission infrastructure.

Storage solutions can also contribute to improving overall system resilience. First, storage mitigates islanding problems and facilitates the deployment of DERs, particularly in the case of variable renewable energies. Second, utility-scale battery storage has already been adopted by some utility companies for frequency regulation purposes (e.g. KEPCO in South Korea), preventing the propagation of disturbances and replacing traditional thermal methods of frequency regulation. The continuing development of Pumped Storage Powerplants (PSP) also offers the opportunity for very large-scale energy storage, and PSPs can compensate for the loss of generation facilities, albeit very temporarily.

4.2.3 Smart grids and innovations to improve power system operations

New technologies that offer effective ways to improve power sector resilience continue to emerge. Smart grids, advanced metering infrastructure, automation, drones, and remote sensing are all being employed to help improve reliability and mitigate the risks of natural hazards.

Smart grids and advanced metering infrastructure both improve situational awareness and facilitate rapid restoration of service. They also enable the operationalization of the solutions discussed previously: increasingly meshed distribution networks, DERs, and adaptive islanding. Intelligent electronic devices in power networks provide valuable information on the state of the power system. Phasor measurement units (PMUs), for example, have averted widespread blackouts even in normal operations. They rapidly assess and report the state of the transmission network, and, when employed in wide-area monitoring systems, automatically react to changes in the network. The information from PMUs and other intelligent electronic devices helps improve grid performance and resilience, and is vital to system operators, who are otherwise blind to rapid changes in the power system (The GridWise Alliance 2013; White House 2013). Meanwhile, advanced metering infrastructure provides two-way communication, which helps utility companies improve situational awareness. For example, the Potomac Electric Power Company (PEPCO) in the Washington, D.C., metropolitan area attributed its ability to rapidly restore power after Superstorm Sandy to AMI, because they received "no power" signals that allowed them to quickly locate outages (White House 2013).

Other forms of automation can not only improve resilience, but also decrease costs. Automated switches enable quick reconfigurations of the network and easy fault isolation, and prevent entire feeders from tripping. Since they do not require manual replacement, replacing traditional fuses with automated switches can greatly improve network adaptability while reducing costs.

Electric Power Board (EPB) a utility based in Chattanooga, Tennessee, discovered this firsthand. Between 2009 and 2011, EPB invested in distribution automation technologies, including the installation of over 1,200 automated circuit switches and sensors on 171 circuits. The total investment in grid automation distribution was around $48.4 million. Glass et al. (2015) demonstrated that this was a cost-effective investment: the cost analysis showed that, under normal conditions, EPB’s distribution automation saves their customers an estimated $26.8 million per year. When a severe weather event occurred, the project prevented $23.2 million in customer costs and more than 40,000 customer outages, representing 4.9 million customer outage minutes.

Remote sensing technology has benefits both in normal operations and in disaster situations. To manage vegetation and inspect transmission and distribution infrastructure, utility companies are increasingly turning to drones (Hansen 2017). After a shock, drones can also be used to assess the situation, particularly if the transport infrastructure is also disrupted. Light detection and ranging (LiDAR) and aerial imagery can help identify dangerous trees and vegetation encroachments. This data not only provides input for the predictive modeling of vegetation growth patterns, but also assists in identifying areas with high fire risk (Elizaveta Malashenko 2018). GIS systems, which are now seeing greater use, can help prioritize maintenance and dispatch teams by linking the classical SCADA (Supervisory Control and Data Acquisition) systems to a georeferenced asset management system; after a disaster, they can also be used by teams on the ground to tag and reference damages in real time.

Some solutions, however, are less high-tech. Demand response, for instance, can decrease network stress during unplanned events. As defined by the Federal Energy Regulatory Commission, demand response is when end-use customers change their normal consumption patterns of electronic usage in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use. During disasters, this mechanism could be critical to reducing stress on the network: Carlotto and Grzybowski (2014) show that the size and scope of blackouts in a network grow with its utilization rate, meaning that the closer the network is to its operational limit, the larger the blackouts. Demand response has already been used in Texas during a polar vortex event in 2014, when two power plants went down because of the cold, suddenly forcing 1800MW offline. Because of the extreme weather, the grid was already operating under constraints, and ERCOT (the Electric Reliability Council of Texas), the state's grid operator, had to call upon available demand response across the state to avoid rolling blackouts. At that time, ERCOT predominantly relied on large industrial customers for participation in demand response. Their reduction of electricity use, coupled with the use of all available power sources, mitigated the plant failures. Currently, automated demand response programs are implemented only in a few countries. But there are more traditional ways to implement this solution: TV, internet, radio, or newspapers, as well as automated phone text messaging, can be used to communicate the need for demand reduction to users when an extreme weather event is expected (Brown 2016).

These new methods, innovations, and technological developments, along with increased use of communication technologies, will help utility companies better operate their systems. But it will also make them dependent on more network infrastructure. Some utility companies, mostly in developed countries, have now installed their own closed-loop fiber optic system, which allows them to exchange data at a very high speed. Most also use their own dedicated telecommunication infrastructure to support critical communication and automation functions.

4.2.4 Dealing with uncertainties: Planning better, forecasting better?

There is a long history of planning in the power industry. But, as discussed previously, most planning is intended to ensure that the system will be optimally designed to operate reliably under normal conditions and during small shocks (low impact–high probability events), and disregards high impact–low probability events.

Planning criteria and methodologies will need to be revised to include resilience, because the design of resilient power systems starts with the overall planning of the system. Until recently, there had been little work on including climate considerations in planning. Although these issues are well understood in qualitative terms and practiced in the field, they are not systematically considered in producing a power system plan that finds a good balance between cost and risks.

Spyrou and Hobbs (2016) is a recent example that uses a two-stage stochastic planning model to analyze the impact of climate risks on the power system expansion plan for Bangladesh – one of the most vulnerable countries to climate change (Adams et al. 2013). Stochastic planning is not the only alternative, however, to deterministic planning. Indeed, the academic field concerned with decision making under uncertainty has been making significant progress this past decade. Methods like multi-scenario analyses, decision-making under deep uncertainty, and robust decision making (Rozenberg, Bonzanigo and Nicolas 2018) help identify a range of solutions that will perform well under a wide range of futures, instead of a single optimal solution that could fail if the future scenario does not unfold as envisaged. These approaches allow utility companies to deal with the sometimes very different climate futures that climate models are projecting.

To better account for resilience considerations, these companies will also have to adopt a holistic approach. Currently, planning exercises tend to be disconnected from each other. Most of the time, least-cost generation expansion plans are realized independently from transmission and distribution planning exercises. But since the power system is a network, the resilience of the whole system must be considered as a unit. An integrated approach that simultaneously considers both the resilience of individual assets and that of the system as a whole would be highly desirable – but likely difficult to operationalize.

Indeed, if the generation and network expansion plans have been heretofore performed separately, it is partly because those exercises are computation intensive and require a lot of data (which can be scarce, particularly in developing countries) and a great deal of modeling. Coupling the two analyses, and adding on top of that the need for detailed georeferenced hazard data and asset fragility curves, could be daunting for large systems. This is true particularly because the process would require utility companies and researchers to abandon the field of power system modeling and switch to interdisciplinary models that could simulate the behavior of the power system and its reaction to a natural disaster. An example of this type of work is the criticality analysis performed by Veeramany et al. (2018), which coupled a georeferenced transmission network model and georeferenced seismic risk data to assess Washington State network resilience to seismic events. Though this approach may be difficult at large scales, it may be effective for small systems like those of many small-island states.

4.3 An example: the Case of Orion

Orion is one of the largest electricity distribution companies in New Zealand, providing power in remote rural areas, regional towns, and the city of Christchurch. In 2011, approximately two-thirds of its consumers lost power after the Christchurch earthquake. By the end of the following day, Orion had restored power to 50 percent of the affected consumers; by the end of the week, to 86 percent; and within 10 days, to 95 percent. Planning and design made all the difference (Kwasinski et al. 2014; Fenwick et al. 2011).

Since 1996, Orion has had an ongoing seismic strengthening program designed to improve network resilience and minimize the economic impacts resulting from outages, including outages caused by earthquakes. The improvement program was initiated after the Christchurch Lifelines report, *Risks and Realities*. Since then, Orion has invested in increasing the resilience of its network, learning from events such as the 1987 Edgecumbe earthquake and from engineering and geotechnical assessments.

The risk-reduction measures taken by Orion to strengthen its network and better respond to earthquakes include the following:

- All new structural assets, together with existing strategic structural assets like sub-transmission lines and zone substations, are designed to withstand a 500-year seismic event with little or no service disruption.
- Improvements have been made at bridges, including strengthening the connections between superstructures and substructures, increasing column strength and ductility, strengthening or renewing retaining and approach structures, and strengthening lateral/longitudinal restraint mechanisms.
- Orion occupies a multi-building site in central Christchurch. It had invested in a nearby hot site[9] for immediate essential control functions, and also occupied an older but robust on-site building for general office use. This enabled Orion to start repair work within a day after the earthquake.
- Orion maintains a meshed electricity distribution system. This spider-web approach to the network greatly increased Orion's ability to restore power promptly after the 2010 and 2011 earthquakes. It meant that power stayed on unless all the multiple links into an area failed. If all the links were indeed damaged, the company could fix the link that was the easiest and quickest to repair.

Orion continues to apply lessons learned to strengthen its network and prepare for disasters. After the Christchurch earthquake, the company invested in a mobile center to house the sensitive computer systems needed to operate and control the network. This mobility allows them to move to offices throughout the city if the head office location is shut down.

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[9] A hot site is a work area recovery site. It is a duplicate of the original site of the organization, with full computer systems as well as near-complete backups of user data.

5. Before and after disaster: preparedness and recovery

Enhancing power sector resilience does not only mean strengthening its ability to anticipate and absorb shocks, but also improving its ability to recover from the effects of a hazardous event in a quickly and efficiently (Brown et. al 2016).

Utility companies, as well as their priority energy users, will be better prepared for power outages when a disaster strikes if they incorporate appropriate policies and tools into a disaster recovery framework. Such a framework should include contingency plans and institutional arrangements that clearly allocate responsibility during the recovery period. A good emergency preparedness plan, accompanied by strategic investments, can shorten restoration time and limit the impact of disasters.

5.1 The critical role of contingency plans

5.1.1 Emergency Preparedness Strategies for Power Utilities

Utilities in developing countries often struggle to keep up with existing standards, fail to conduct maintenance, have a poor awareness of their infrastructure exposure, and lack organizational capacity. These factors explain why disaster risk management (DRM) practices are often quite weak. To become more resilient, utilities should focus on a multi-step approach that includes technical, regulatory, operational, institutional, and financial aspects, as demonstrated in Figure 16.

Laws, Regulations, Guidelines, and Institutional Frameworks

Resilience depends on developing or sustaining the laws, regulations, and guidelines that require utilities to (i) apply appropriate safety standards to resilient power facilities, both in the installation/construction phase and during regular maintenance and operation; and (ii) prepare an emergency action plan to be submitted to the relevant authority. It is also crucial that governments create a clear legal structure or an institutional entity that will be responsible for coordination and enforcement of disaster risk management (DRM) provisions.

At the operational level, each power company may prepare an emergency action plan that involves emergency preparedness systems, including drills and training of staff as well as recovery operations. Recovery operations encompass not only specific steps for damage recovery and power restoration, but also internal institutional coordination and cooperation with other utilities, governmental institutions, and municipalities.

Asset Management

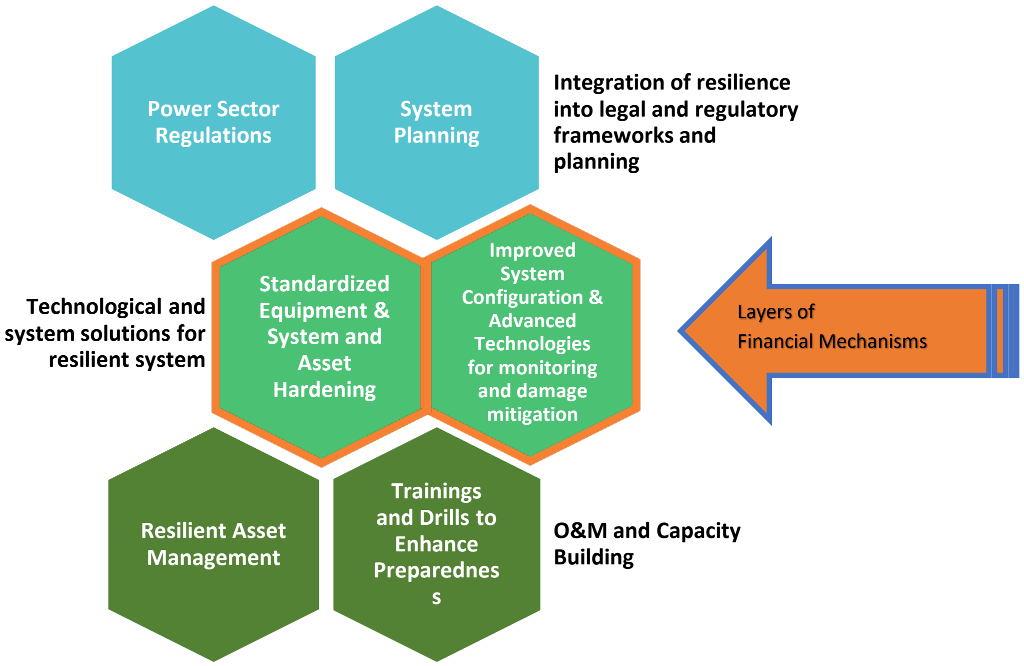
By integrating DRM into management and daily operations, utility companies will be able to quickly identify vulnerable assets and implement preventive measures. There are other essential steps that utilities can take to increase system resilience, including: regularly maintaining and updating their asset inventory and mapping energy infrastructure, regularly assessing infrastructure vulnerability, and improving operations based on lessons learned from past events. Standardizing equipment is also key: this process ensures that equipment can be used interchangeably, and shrinks the inventory of spares required for both routine operations and post-disaster recovery.

Technological/System Solutions

Geographic Information Systems (GIS) can enable visualization of damaged areas during a power outage. This was the case during New Zealand's successful public communication response after Christchurch earthquake. Through accurate maps, immediate data on network status and recovery times was available to the media. With the single-city overviews, residents could determine areas of the network that were damaged and where they could find power. The power sector's rapid, transparent information-sharing enabled customers to take appropriate action (Oguah et. al 2017).

Additionally, it is important for utilities to have back-up centers to resume system operations after failures at the main control center, as well as mobile substations and emergency restoration systems to reduce restoration time. These facilities should be supported by the creation of and good use of communication links with priority users to share information.

Figure 16 Key Factors of Pre-disaster Preparedness



Financial Instruments

In developed countries, power utilities rely on a diverse range of financial instruments, like insurance or credit-line instruments, but these instruments are rarely available in developing countries. Alternatives include reserve funds, which are trust funds held specifically for contingent events that affect the electricity sector. In Mexico, the FONDEN (Natural Disasters Fund) is a financial mechanism that provides federal agencies and Mexican states with immediate liquidity to finance recovery efforts. FONDEN has a mandate to: (i) finance post-disaster emergency assistance (through a revolving fund), and (ii) provide the 32 Mexican states and the line ministries (for example, the Ministry of Infrastructure, Ministry of Health, Ministry of Education, and Ministry of Human Development) with financial resources in the event that losses from natural disasters exceed their budget capacity (World Bank 2012). Contingent funds like these should be supported by subsidy programs for power assets that are critical for building system resilience and inclusive communities.

Other financial instruments of use to power utilities include catastrophe bonds that offer the power sector access to capital markets for protection against the impacts of natural disasters; and contingent credit financing, which provides loans negotiated by electricity retailers prior to weather events. These loans enable them to borrow money from a single financier or group of financiers, provided that the retailers operate within certain pre-arranged risk management parameters. In 2013, the World Bank executed a US$450 million weather and oil price insurance to Uruguay's state-owned public electric company, Administración Nacional de Usinas y Trasmisiones Eléctricas (UTE). The weather index insured the energy company against drought and high oil prices. When rainfall and/or accumulated water reserves fell, UTE had been forced to purchase alternative fuels (mostly oil and natural gas) for electricity production. When the price of oil is high, generation costs become very expensive, affecting UTE's bottom line, and creating problems for both consumers and the national budget. The weather index insurance created an important fiscal buffer, which was part of a wider risk-management strategy (World Bank 2014).

Capacity Building

Power utilities need to build, strengthen, and maintain their capabilities by conducting trainings, exercises, and periodic drills to prepare staff at all levels to respond to significant outages, or ready them to be sent to remote areas to provide services (including through mobile stations). After Cyclone Ian in Tonga, for instance, external technical field staff and contractors were needed, the additional staff helped transport equipment to the remote islands (Brown et al 2016).

5.1.2 Emergency Preparedness of Electricity Users

Damage to power infrastructure can cause power disruptions. Although power interruptions are inconvenient and lead to economic losses for all users, certain priority users are essential for the efficient and effective recovery of lifeline services and the mitigation of disaster impacts. The main priority users are listed below:

- **Hospitals and health facilities.** Power disruptions from natural disasters disproportionally affect health facilities, often rendering them unable to provide lifesaving or other medical care. To ensure care continuity, hospitals must have an updated inventory of assets to ensure that the number of backup generators and the amount of fuel stored will be sufficient should prolonged power outages occur.
- **Water sector.** Water service providers are dependent on electricity to provide reliable water services for pump-driven networks. Water utilities should focus their emergency preparedness efforts on pumping stations, reservoirs, and storage tanks – for example,

by installing an uninterrupted power supply at pumping stations to prevent service disruption during a blackout, or installing emergency shutoff valves at primary reservoirs (World Bank 2018).

- **Food sector.** For the food sector, refrigeration is critical. Warehouses need to review and upgrade their backup power generators and fuel supplies, and have emergency plans for replenishing their fuel quickly after a disaster (Jha 2013).
- **Transportation.** Power outages after a natural disaster can cause critical disruptions in transport systems, including the shutdown of airports, ports, and public transit systems. With the increasing use of 'Intelligent' Transport Systems (ITS), power supply has become even more important to maintaining the continuity of transport services. Transport agencies should have emergency plans and an emergency operation center.
- **Telecommunications.** After a natural disaster, system operations may not be able to maintain telephone, cellular, email, or dedicated broadband networks for communications. It is a common practice for telecommunication facilities to have reserve power (battery banks) for short-duration outages; in North America, these battery banks can store from three hours' to eight hours' worth of power. It is essential for key telecommunication facilities to also have backup power generators for prolonged power outages.

The use of data centers for financial services and other intangible services has also greatly increased the exposure of some sectors in the event of power failures. While power utilities are responsible for restoring power services after a disaster, each sector must individually raise awareness and enhance its capacity to take proactive actions to mitigate the risk of interruptions and to restore power as quickly as possible after shocks.

Priority users should focus their efforts on measures and contingency plans that will ensure effective coordination of recovery and reconstruction efforts and clearly allocate responsibilities among stakeholders. Contingency and business-continuity plans should include both the operational and the financial impacts of natural disasters. Key elements of contingency plans include:

- **Emergency plans and insurance policies**. The plan should identify business activities necessary for continued operation during a disruption. In doing so, it should consider the business' supply chain in order to assess which supply lines are essential for operation. Additionally, businesses should review and update their existing insurance policies to fully understand their business coverage, their deductibles, and the limits of their coverage.
- **Asset management.** Users should secure all utility assets, including water heaters, gas tanks, and heaters, and, if necessary, move them to elevated locations to avoid water damage. Additionally, users should fill emergency generators with fuel and contact fuel suppliers with their anticipated needs for post-storm deliveries. Users should also ensure the business emergency supply kit is fully stocked. For users seeking more information, the US Federal Emergency Management Agency (FEMA) has prepared comprehensive emergency preparedness materials to highlight the importance of preparedness before, during, and after a disaster.

- **Information and technology.** Users should develop a systematic process to back up records that are not easily reproduced, such as insurance documents, legal contracts, tax returns, and accounting statements. During a disaster, users can stay informed through technology, including Geographical Information Systems and even cellphones, which enable users to receive and respond to warnings from outside agencies and emergency responders.

5.2 After the disaster: quick and effective recovery

To achieve a quick recovery after natural disasters, deliberate measures should be taken to prepare *before* disaster strikes. As summarized in the section above, these measures are taken at both the policy and operational levels, and are to be improved upon after a disaster occurs in the region.

5.2.1 Policy-level interventions

After a disaster, the agency responsible for power sector recovery should communicate with utilities to determine: (1) the damage sustained by power facilities, including generation assets, transmission and distribution lines, transmission towers, and substations; (2) where power is available and where it is not; and (3) the situation of the power supply to shelters and priority facilities such as hospitals. Based on the information gathered, the ministry/agency in charge will lead the recovery process and coordinate with other actors to respond to observed needs. Under the instruction of the leading agency, utilities will carry out the recovery actions through (i) inspecting and fixing damaged power facilities, (ii) conducting rolling blackouts, (iii) securing cross-regional power supply, and (iv) bringing necessary materials, including self-power generation facilities, to priority facilities and shelters.

5.2.2 Operational-level actions

This section summarizes specific steps that can be taken by utilities companies to achieve quick recovery from disaster.

Information gathering
Once a disaster occurs, it is critical that utilities companies gather and share necessary information in a timely manner. This information includes: (1) the current status of the disaster, whether meteorological or terrestrial; (2) what damages have been sustained by power facilities; (3) if and where there are or will be blackouts; (4) the status of affected staff; and (5) traffic information. Much of this information should be publicized through television, radio, newspapers, and the Internet – especially information on blackouts, restoration of power, and further expected hazards. These actions would be taken in cooperation with the government and municipalities.

Internal coordination – securing staff
Staff who are assigned to deal with the disaster recovery should be present even during holidays and at night, unless there are dangers or difficulties in doing so. These staff oversee the disaster

recovery operations; they are responsible for deploying staff to the affected site, as well as cooperating with external organizations until normal operations are restored.

Securing materials/spare parts

Utilities should confirm whether the materials and/or spare parts they have on hand are sufficient for recovery, and, if they are not, seek the means to procure them, including from other utility companies. To ensure that the materials and/or spare parts are delivered in a timely manner, utilities could pre-select vendors for cars, ships, and helicopters. Further, it would be helpful for utilities to cooperate with municipalities in order to secure a place to put these materials once they have been delivered. It may be unrealistic for a utility to stock enough rapidly-deployable spare equipment to restore service following a major event, but the objective could be to stock enough spare equipment to restore service to predetermined critical loads.

Cooperation with external institutions

a) *Cooperation with the government, municipalities, and the military* includes information sharing and staff deployment. The military may offer staff as well as necessary tools to help restore facilities to the affected areas.

b) *Cooperation with other utilities companies - Mutual Aid Agreements.* Though utility companies are often business competitors, in the event of a disaster, cooperation is critical. Companies may cooperate to, among other actions, (i) deploy staff to the affected areas, (ii) supply materials and/or spare parts to restore damaged power facilities, and (iii) arrange power supply at the regional level. In order to ensure cooperation, it has become increasingly common for utilities companies to enter into Mutual Aid Agreements that describe possible ways to cooperate (Brown, et. al 2016). Under the Mutual Aid Agreements, utilities can mutually agree to pool interchangeable emergency stock and human resources to effectively respond to the disaster (Lindsey 2008).

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