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Power grid recovery after natural hazard impact

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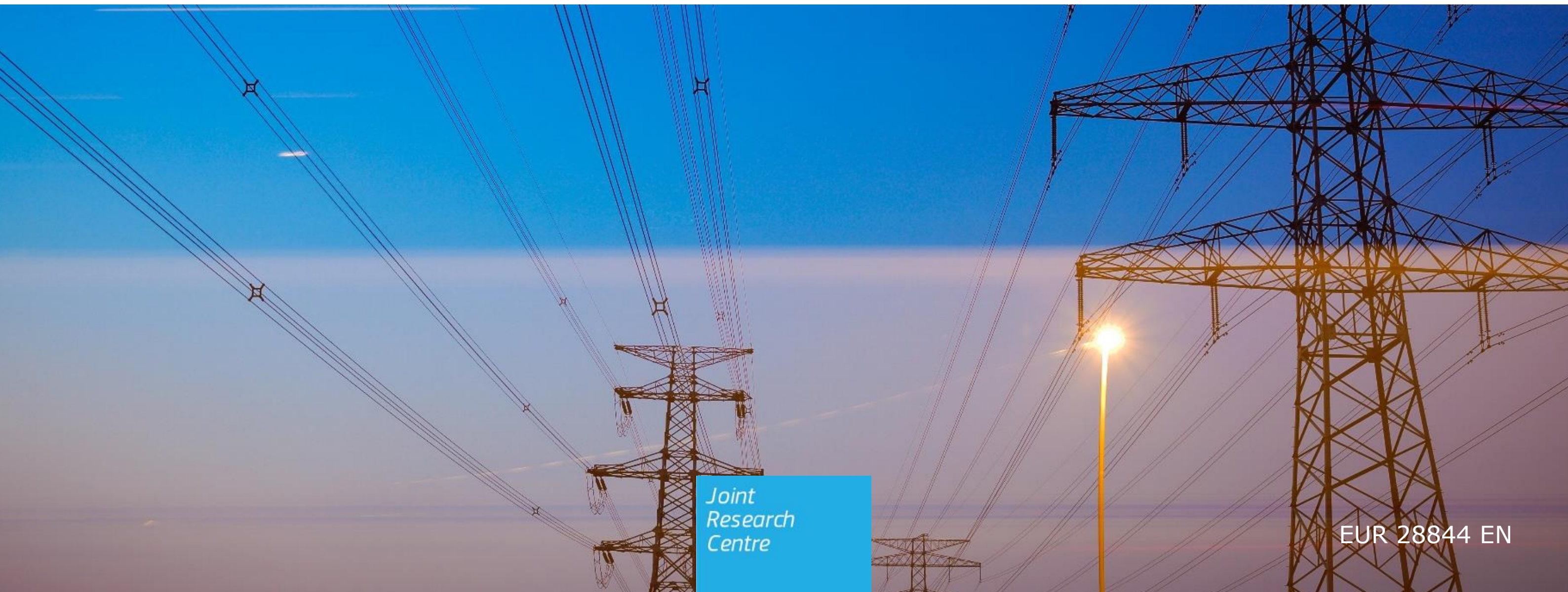

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Title *Power grid recovery after natural hazard impact*
Abstract
Natural hazards can affect electricity infrastructure, leading to power outages and affecting the resilience of society during disaster. This study analyzed the effects of earthquakes, floods and space weather on the power grid to identify vulnerabilities and to understand how these natural hazards influence the recovery time of electric utilities.

Contents

Executive summary

Electricity is the backbone of modern society. It is ubiquitous in the daily lives of European citizens and all critical infrastructure systems depend on the reliable delivery of electricity. This sector's regulatory framework spans across energy, civil protection and critical infrastructure policies.

Natural hazards can affect the electricity supply and result in power outages which can trigger accidents, bring economic activity to a halt and hinder emergency response until electricity supply is restored to critical services. This study aims to elucidate how the characteristics of earthquakes, space weather and floods influence the power grid recovery time. For this purpose, forensic analysis of the performance of the power grid during 16 earthquakes, 15 space weather events and 20 floods was carried out.

The study highlighted that different natural hazards affect the power grid in different ways. Earthquakes cause inertial damage to heavy equipment (such as generators and transformers) and brittle items (for example ceramics), and ground failure and soil liquefaction can be devastating to electric infrastructure assets. Equipment anchoring was the most effective mitigation strategy we identified, and site selection can arguably reduce the exposure to ground failure. Recovery time is driven by the balance of repairs and capabilities. Poor access to damaged facilities, due to landslides or traffic congestion, can also delay repairs. In this study the time to restore power supply ranged from a few hours to months, but more frequently from 1 to 4 days.

Floods are commonly associated with power outages. Erosion due to the floodwaters and landslides triggered by floods undermine the foundations of transmission towers. Serious, and often explosive, damage may occur when electrified equipment comes in contact with water, while moisture and dirt intrusion require time-consuming repairs of inundated equipment. In contrast to earthquakes, early warning is possible, and enables electric utilities to shut off power to facilities in flood zones, therefore minimizing damage. The most effective mitigation strategies included elevation, levees and locating critical facilities outside the flood zone. Recovery time was driven by the number of needed repairs, and site access as repairs cannot start until floodwaters have receded. In this study, power was back online from 24 hours up to 3 weeks after the flood. However, longer restoration times (up to 5 weeks) were associated with floods spawned by hurricanes and storms.

Space weather affects transmission and generation equipment through geomagnetically induced currents (GICs). In contrast to earthquakes and floods, GICs have the potential to impact the entire transmission network. Based on the cases examined in this study, during geomagnetic storm conditions some form of abnormal operations conditions or equipment damage is likely. Although some early warning is possible, warning lead times are typically very short and existing forecasting capabilities need to be improved to provide transmission system operators all the information they need for preparing for a severe event. Delayed effects and the potential for system-wide impact were the main drivers of recovery time in this study. When damage is limited to tripping of protective devices, restoration time is less than 24 hours. However, repairs of damaged equipment may take up to several months.

Other factors affecting the power grid recovery time in the aftermath of natural disasters include the resilience of electric power utilities, and the disruption of other critical infrastructure (mainly transportation and telecommunications), either as a direct result of the natural event, or because of the loss of power supply.

The following recommendations related to policy, hazard mitigation and emergency management emerged from the findings of this study:

— Whenever possible, risk assessments across different EU policy areas directly or indirectly affecting electricity infrastructures should use a consistent set of scenarios.

— Risk management efforts should be integrated to maximize efficiency.

- There should be a transition from hardening system components and facilities to building resilience into the power grid to enable the system to function even under disaster conditions or recover more quickly.
- The resilience of the European power grid to extreme space weather should be assessed.
- TSOs/DSOs should develop, implement and exercise outage management plans. These plans should be updated when gaps are identified, e.g. in case of climate change.
- Spare items should be stockpiled to expedite the repair or replacement of key assets and equipment.
- Interoperability among neighboring TSOs/DSOs, and between TSOs/DSOs and emergency management organizations should be ensured.
- Repairs to critical electricity customers should be prioritized.

Future JRC work will focus on expanding this study to other hazards, including storms. Future studies should also take into consideration the potential effects of climate change on the frequency of occurrence and intensity of natural hazards, and the cumulative effect of natural disasters on ageing critical infrastructure assets.

1 Introduction

Disasters create overwhelming demands to affected communities and pose unique problems that complicate response efforts. The impact of disasters includes human losses (death and injury), widespread destruction of property and livelihoods, environmental damage and disruption of infrastructure. Critical infrastructure includes *systems or assets which are essential for the maintenance of vital societal functions, health, safety, security, and economic or social well-being of people*[1]. Experience from recent disasters has demonstrated that damage to infrastructure adversely affects community resilience.

The disruption of critical infrastructure systems by natural phenomena may have direct or indirect effects. For instance, damage to water and wastewater systems often poses a direct threat to public health in a disaster-affected area. Moreover, the disruption of critical infrastructure undermines resilience indirectly, by reducing the capability of affected communities to respond and recover. For example, the temporary loss of cellular telephone service slows down incident response, because many emergency services use cell phones for routine and emergency communications. The complex interdependencies among critical infrastructure systems often cause cascading disruptions of multiple systems and aggravate the post-disaster situation.

Among critical infrastructure, electric power is a cornerstone of modern economies. Electricity is ubiquitous in the daily lives of European citizens and spans across all sectors of the European economy. Electricity consumption in the European Union increased by 25% between 1990 and 2014 (EEA, 2017). In addition, all critical infrastructure systems depend, to a greater or lesser extent, on the reliable delivery of electricity. Conducted pursuant to a directive by President Franklin Roosevelt, the United States Strategic Bombing Survey estimated that the air raids would have been more effective if they had targeted electric generating plants instead of urban and industrial areas (Air University, 1987). More recent research has highlighted the potential consequences of long-term power outages (Petermann et al., 2011; Schmidthaler & Reichl, 2016; OSCE, 2016). Furthermore, energy is one of the two critical infrastructure sectors for which Member States are required by the European Critical Infrastructure Directive[2] to designate critical assets and facilities, develop Operator Security Plans and appoint Security Liaison Officers.

The purpose of this study is to improve the understanding of the impact of natural hazards on the power grid. It endeavors to elucidate how the characteristics of certain types of natural hazards influence the power grid recovery time. It is intended to inform policy-making and strategic and operational disaster risk management planning in the European Union Member States.

This report focuses on three types of natural hazards, earthquakes, space weather and riverine floods. These hazards were selected based on their prevalence and their potential for disrupting the power grid. Floods affect more people than any other hazard. Of the 34 Union Civil Protection Mechanism (UCPM) Participating States, 30 have included floods in their national risk assessment (EC, 2017). Riverine floods are prevalent in Central, Eastern and Northern European Countries, while flash floods are common in Southern European countries. Both types can result from extreme weather events, which are likely to be exacerbated due to climate change. Nineteen UCPM Participating States have identified earthquakes in their National Risk Assessments (NRAs). Earthquakes are a major risk in South-Eastern Europe, spawned from the subduction zone between the Eurasian and African tectonic plates. In addition, 6 countries have included space weather scenarios in their NRAs. Despite being more of a threat to Northern European countries and other countries in the North, extreme space weather can potentially affect electricity transmission networks also at lower latitudes.

([1]) Council Directive 2008/114/EC of 8 December 2008 on the identification and designation of European critical infrastructures and the assessment of the need to improve their protection (OJ L 345/75, 23.12.2008, p. 75-82).

([2]) Idem

Although these natural hazards are highly critical for the power grid, further research is warranted to address the vulnerability of electricity networks to other hazards. Future research will focus on hazards which affect the power grid either directly, by damaging critical components (e.g. storms) or indirectly, by altering the patterns of electricity consumption (e.g. heat waves and cold spells).

This report is structured in five parts. The next chapter sets the context for the study, by outlining the profile of the electricity critical infrastructure subsector, including policy and regulation in Europe. Chapter 3 describes the methodology used in this study. Chapter 4 discusses the impact of earthquakes, space weather and floods on the power grid, and how the type and extent of damage affects recovery time. Chapter 5 describes the impact of the power grid's resilience and of the disruption of other critical infrastructure sectors on recovery time. Last, chapter 6 presents recommendations for policy, hazard mitigation and emergency management.

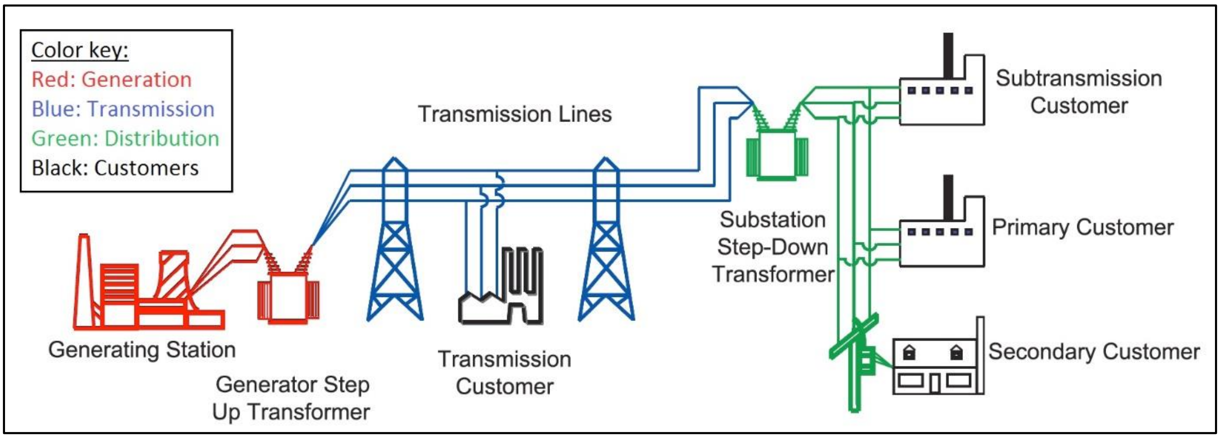
2 Electricity in Europe

According to the European Critical Infrastructure Directive, electricity is a subsector of the Energy Sector, along with oil and natural gas. Electricity assets and components are owned by private and public entities, including some energy consumers. This chapter describes the key characteristics of the electricity industry, the extensive public/private partnerships involved in the subsector, and relevant policies in the European Union.

2.1 Electric Power Subsector Profile

Traditionally, the Electricity Subsector includes the generation, transmission and distribution of electric power (Figure 1). Although fossil fuels have historically been the main electricity generation source, the fraction of electric power produced from these traditional power plants has steadily decreased in recent years in favor of renewable energy sources. Fossil fuels provide about 50 percent of the total electricity generated in the European Union, as shown in Figure 2. Hydroelectric power production plants are concentrated in the transalpine range, the Carpathians and the Scandinavian countries, and accounted for 12% of total generation in 2016. In the same year, nuclear power plants produced 26% of the total electric power. A growing percentage of the EU's electricity generation is coming from wind and other renewable sources, such as geothermal and solar. The EC has recently proposed in its Clean Energy for all Europeans package a binding EU-level minimum of at least 27% for the share of renewable energy consumed in the EU by 2030. This translates into 50% of electricity consumed in the EU coming from such sources.

Figure 1. Overview of the traditional electric power system



Source: Adapted from US-Canada Power System Outage Task Force (2004)

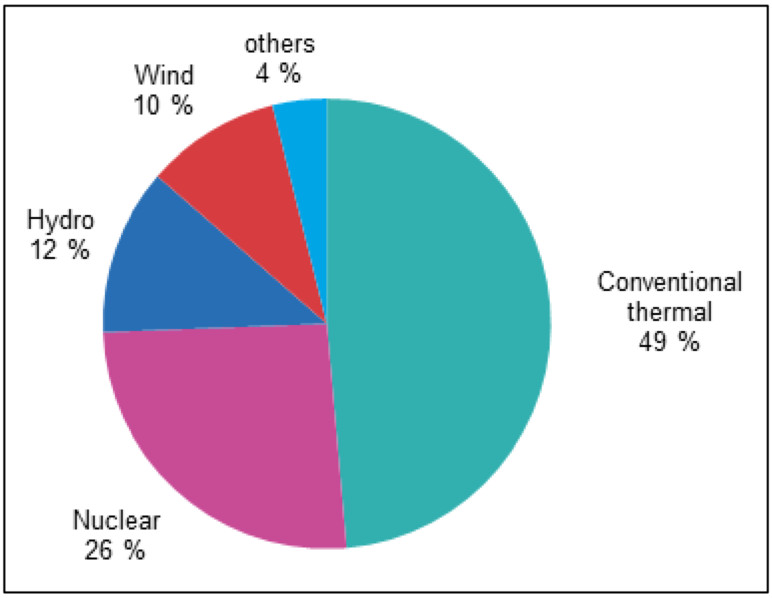
Electricity critical infrastructure assets and facilities are owned by public and private entities. In addition, some types of consumers, such as large industrial complexes and other critical infrastructure facilities, operate cogeneration plants or generators, usually to maintain backup electricity capabilities. A proliferation of distributed energy sources, mainly photovoltaics (PV), was recorded during the last decade, even to the low voltage level of residential consumers. This trend is expected to continue due to technology cost reductions and combined with the electrification of transport, progress in storage technologies, and the digitalization of energy (e.g. smart meters coupled with smart household appliances and Energy Management Systems). Overall, the electric power subsector faces a paradigm change to a much more horizontal (and complex) system where end-consumers will play a much more active role. It is noted that consumer empowerment is at the core of the EC energy policy as expressed in the Clean Energy Package for all Europeans.

Electricity generated at bulk power plants is moved using high-voltage transmission lines. Transmission substations located inside generation plants use Generation Step-Up (GSU) transformers to increase the voltage. These substations link each generation station with one end of a transmission line. Increasing the voltage decreases power loss due to resistance, therefore allowing electric power to be carried efficiently over long distances. In Europe, the voltage of transmission lines ranges between 110 and 750 kV. At the other end of a transmission line, another substation uses step-down transformers to reduce transmission voltages and links the transmission line with the electricity distribution system.

The transmission network also links adjacent national grids, creating interconnections which span across multiple countries. Europe, especially in the North-West forms a highly interconnected meshed Grid. Interconnections increase the opportunity for trade of electricity, increasing the overall socio-economic benefit, and enhance security of supply by enabling sharing of resources in cases of system stress. On the other hand, the highly meshed grid in Europe necessitates close collaboration between the Transmission System Operators (TSOs), since a fault in a part of the network can quickly propagate throughout the system and lead to cascading failures. The EC has set an obligatory goal to reach an interconnection level in each EU Member State of at least 10% by 2020 and 15% by 2030.

The distribution system runs at lower voltages (down to 240V in continental Europe) and delivers electricity to individual customers. It includes distribution lines and distribution substations, which use transformers to gradually step down the voltage before it reaches the end customers. Medium and low voltage distribution circuits are often used as an economical way of connecting distribution lines with transmission lines. They include substations which step down the voltage from transmission lines and send it to distribution substations located in towns and neighborhoods. Some consumers who require higher voltages than the domestic power supply, such as large industrial facilities, may plug directly in the subtransmission system.

Figure 2. 2016 EU-28 Electricity Generation Profile



Source: Eurostat (2017)

Transmission and distribution system operators use sophisticated monitoring and control systems to ensure safe and predictable operation of the power grid. Control centers are staffed on a 24/7 basis and accomplish several key functions, including matching electricity production with the load, maintaining synchronization of the grid, and maintaining the reliability of the grid by bringing online or taking offline key components of the system in response to anticipated or present threats. These centers use Supervisory Control and Data Acquisition Systems (SCADA) and Distributed Control Systems (DCS) to remotely monitor the flow of electricity and control equipment such as switches, circuit breakers, transformers and generators. Smart grid technologies are being increasingly employed to improve the reliability, flexibility, efficiency and sustainability of the electric power grid.

2.2 Policy and regulation

2.2.1 Current legal context at the EU level

Currently, risk reduction and crisis management regulations in the electricity subsector at the EU level are scattered over different legal acts. Following is a short discussion of the most important points.

At the pan-European level, the European Network of Transmission System Operators for Electricity (ENTSO-E) produces seasonal outlooks (6-month periodicity – summer & winter outlooks) according to the requirements of Article 8 of the Electricity Regulation[3]. These assessments explore the main risks identified within the seasonal period and the Member States that could be affected, and highlight the capabilities of neighbouring countries to contributing to the generation/demand balance in critical situations. Moreover, ENTSO-E analyses retrospectively electricity crises affecting many Member States, such as the cold spell of January 2017 (ENTSO-E, 2017). It should be noted, however, that the seasonal outlooks in their current form are mainly focused on generation adequacy, i.e. whether there will be adequate available generation capacity to cover the forecast demand. They do not cover a full vulnerability analysis that fully accounts for extreme weather conditions, natural hazards, simultaneous failures in the grid or man-made hazards (e.g. fuel shortages and malicious attacks).

At the Member State level, risk preparedness is only implicitly set in Article 4 of the Electricity Directive[4] and Article 7 of the Security of Supply (SoS) Directive[5] which impose the general obligation to Member States to monitor security of supply and to publish every two years a report outlining their findings, as well as any measures taken or envisaged to address them. Crisis management is set by the SoS Directive and Article 42 of the Electricity Directive. Finally, regarding cybersecurity, an increasingly important issue given the digitalisation of the power system, the NIS Directive[6] provides the horizontal framework to boost the overall level of network and information security across the EU.

The success, especially in terms of harmonisation, of the above legal frameworks is rather debatable. A review of the state of risk preparedness in the area of security of electricity supply (VVA Europe and Spark Legal Network, 2016) showed significant discrepancies among Member States in a number of issues, including the competent authorities that undertake the national risk assessments, the types of risks assessed and the time-horizon examined, the development (or not) of comprehensive risk preparedness plans, the responsibilities and the strategies for dealing emergency situations. Most importantly cross-border effects and the possibility of simultaneous scarcity of generating capacity in the neighbouring Member States are rarely taken into account in the national plans.

Cooperation between Member States is established only at the technical level between TSOs, with the notable exceptions of the Nordic countries and to a lesser extent of the Pentalateral Energy Forum. However, political decisions, such as market suspension,

(3) Regulation (EC) No 714/2009 of the European Parliament and the Council of 13 July 2009 on conditions for access to the network for cross-border exchanges in electricity and repealing Regulation (EC) No 1228/2003 (OJ L 51/15, 14.8.2009, p. 15-35).

(4) Directive 2009/72/EC of the European Parliament and of the Council of 13 July 2009 concerning common rules for the internal market in electricity and repealing Directive 2003/54/EC (OJ L 211/55, 14.8.2009, p. 55-93).

(5) Directive 2005/89/EC of the European Parliament and of the Council of 18 January 2006 concerning measures to safeguard security of electricity supply and infrastructure investment (OJ L 33/22, 4.2.2006, p. 22-27).

(6) Directive 2016/1148 of the European Parliament and of the Council of 6 July 2016 concerning measures for a high common level of security of network and information systems across the Union (OJ L 94/1, 19.7.2016, p. 1–30)

export bans and load-shedding activation, are still taken to a significant extent unilaterally. This can have substantial negative effects especially under simultaneous electricity crisis conditions, as was demonstrated by the cold spell of January 2017.

Overall, the evaluation of the current legal framework concluded that it has proven ineffective in improving the security of supply in Europe (EC, 2016). Given the increased interconnected nature of the European power systems, purely national approaches for prevention of, preparation for and managing of electricity crises become ineffective. There is the need for a harmonized framework for defining the necessary level of security of supply per country, to compare the expected level of security of supply between countries, to assess risks and to define measures for their mitigation taking fully into account cross-border impacts or simultaneous crisis situations.

On cybersecurity, the NIS Directive provides only a general legal framework. A detailed and harmonized approach specific to the electricity sector is still lacking.

2.2.2 Policy initiatives

The ongoing regulatory effort on the Internal Energy Market relates with risk preparedness. Three network codes are of main importance on the subject: the CACM Guideline[7], the SO Guideline[8], both already in force, and the Network Code on Emergency & Restoration[9], still in Comitology. These codes establish a harmonized framework of technical procedures and the interoperability of rules at the EU level regarding the basic structure of the electricity markets, the allocation of interconnector capacity in both normal and emergency situations, the rules that should be followed by TSOs for the secure operation of the System, the interoperability between the Member States of the System Defense Plans, and the remedial actions followed in emergencies and in the restoration of the system. In addition, they provide for the creation and the allocation of specific responsibilities to Regional Security Coordinators (RSCs) that should cover geographically the whole European Union. In the Clean Energy for all Europeans package, it is proposed that RSCs are further delegated with more tasks and become Regional Operational Centers (ROCs).

Even though these network codes contribute to the creation of a harmonized framework for assessing security of supply and coordinate remedial actions in both emergency and system recovery situations, there is still a gap in both their scope and content. First, they essentially remain at the technical level, leaving room for disparities when highly political decisions, such as market suspension, export bans and load shedding are to be made. Second, even though the codes provide for periodic assessments of security of supply in different time-horizons, these remain basically within the context of generation adequacy, and are not a full vulnerability analysis.

Due to the above regulatory gap, the European Commission has proposed a Regulation on risk-preparedness[10] in the context of the Clean Energy for all Europeans package. The Regulation aims for the creation of a general legislative framework for the prevention, preparation for and management of electricity crisis situations. A short description of the main provisions of the Regulation on risk-preparedness is given in Box 1.

([7]) Commission Regulation (EU) 2015/1222 of 24 July 2015 establishing a guideline on capacity allocation and congestion management (OJ L 197/24, 25.7.2015, p. 24-72).

([8]) Draft Commission Regulation establishing a guideline on electricity transmission system operation (final), https://ec.europa.eu/energy/sites/ener/files/documents/SystemOperationGuideline%20final%28provisional%2904052016.pdf (accessed July 14, 2017)

([9]) Draft Commission Regulation establishing a network code on electricity emergency and restoration (final), https://ec.europa.eu/energy/sites/ener/files/documents/nc_er_ener_vs_13_ecbc_on_24_25-10-2016finalasvotedfor_publication.pdf (accessed July 14, 2017)

([10]) Proposal for a Regulation of the European Parliament and of the Council on risk-preparedness in the electricity sector and repealing Directive 2005/89/EC (COM/2016/0862 final – 2016/0377 COD), http://eur-lex.europa.eu/resource.html?uri=cellar:1d8d2670-b7b2-11e6-9e3c-01aa75ed71a1.0001.02/DOC_1&format=PDF (accessed July 14, 2017)

Box 1. The proposal for a Regulation on risk-preparedness in electricity sector

Creation of a Competent Authority

First, the proposal provides for the creation of a competent authority on risk preparedness in each Member State, which should be either a national governmental or a regulatory body.

Risk Assessments

At the regional level, ENTSO-E is delegated with the task to develop a methodology and identify electricity crisis scenarios every three years or sooner if needed. The latter task can be delegated by ENTSO-E to the Regional Operational Centers. The assessment should cover at least the following risks (Article 5 of the Regulation):

- Rare and extreme natural hazards
- Simultaneous accidental hazards
- Consequential hazards including fuel shortages
- Malicious attacks (including cyber-attacks)

The risks should be ranked according to impact and probability, and the developed methodology should take into full account the interaction and correlation of risks across borders as well as simultaneous crisis scenarios.

On a national level, Member States are obliged every three years, or sooner if needed, to identify the most relevant electricity crisis scenarios, which should be consistent with the respective regional scenarios. In addition, Member States will inform the Commission and the Electricity Coordination Group (ECG) about possible risks they see in relation to the ownership of infrastructure relevant for security of supply (Article 7.3 of the Regulation).

Apart from the 3-year risk assessments, short-term adequacy assessments (seasonal, week-ahead and intraday) have to be done with a more limited scope of covered risks. Specifically, the minimum requirements for these short-term adequacy assessments are (Article 8.1 of the Regulation):

- Covering the uncertainty of inputs in respect to grid and generation capacity, demand, and weather induced phenomena including the variability of production from Renewable Energy Sources (RES)
- The probability of occurrence of a critical situation
- The probability of occurrence of a simultaneous crisis situation

The methodology for all short-term adequacy assessments will be developed by ENTSO-E, which will also conduct the seasonal outlooks, possibly in collaboration with the ROCs. The latter will conduct the week-ahead and intraday adequacy assessments for their respective regions.

Risk-preparedness plans

Based on the 3-year regional and national electricity crisis scenarios, the competent authority of each Member State shall establish a risk-preparedness plan. The plan will be effectively divided in two parts, one consisting of national measures and one covering regional measures, i.e. measures with a cross-border impact. For improving harmonization, the plans should follow a specific template given in the Annex of the Regulation for risk-preparedness. It is noted that in the impact assessment of the proposed Regulation on risk-preparedness in the electricity sector it is contemplated that in practice the coordinated regional measures will most probably be designed by the Regional Operational Centers (EC, 2016)

Before adoption, each plan must be submitted to the competent authorities of the other Member States in the region and the Electricity Coordination Group for reviewing.

A basic principle that the risk-preparedness plans should follow is "market first", i.e. markets should be permitted to operate even under scarcity conditions where electricity prices spike. Market-suspension should be a measure of last resort. For all non-market measures, the trigger, conditions and procedures for their implementation should be clearly specified. Additionally, for the coordinated regional measures, legal and financial arrangements regarding mutual assistance must be predefined.

Management of electricity crisis situations

The national competent authorities are the main responsible parties for managing expected or actual electricity crisis situations. The Commission and the ECG should be informed in the case of an early warning, while the Commission and the neighboring Member States should be informed when a crisis is declared. The actions set out in the risk-preparedness plans should be followed to the fullest possible extent, with due respect to the functioning of the internal electricity market, both inside the Member State and in other Member States. Non-market measures should be activated only in a crisis situation and when all options provided by the market have been exhausted. If necessary and possible, Member States should offer assistance to each other in order to prevent or mitigate an electricity crisis, subject to compensation.

2.2.3 Natural hazards and electric power systems

In addition to the Proposal for a Regulation of the European Parliament and of the Council on risk-preparedness in the electricity sector discussed in Box 1, the resilience of electric power systems against natural hazards is addressed in several other EU policy areas. First, Article 6 of the Union Civil Protection Mechanism Decision[11] requires all Participating States (including all 28 EU Member States plus Iceland, Montenegro, Norway, Serbia, the former Yugoslav Republic of Macedonia and Turkey) to develop and regularly update a National Risk Assessment. The Commission’s disaster risk assessment guidelines (EC, 2010) require that National Risk Assessments should consider the impact of hazards on critical infrastructure. Specifically, each single- or multi-hazard risk scenario needs to describe the impact of hazards in terms of the costs of infrastructure recovery and disruption of economic activities. However, the guidelines leave the choice of methodology to Member States.

Several Member States have identified the potential for natural and man-made hazards and threats to disrupt critical infrastructure. Floods are the most prevalent hazard in the NRAs submitted until May 2017. Of the 30 Member States which have included flood scenarios in their NRAs, 10 have considered that floods may disrupt critical infrastructure. Furthermore, of the 19 Member States which have included earthquake scenarios in their NRAs, 4 have identified the potential of earthquake damage to critical infrastructure. In addition to the loss of critical infrastructure as a secondary effect of identified hazards and threats, 24 NRAs discuss primary scenarios of critical infrastructure disruption. These scenarios contemplate the potential for disruption to critical infrastructure systems irrespective of the underlying cause. Of those NRAs, 20 include scenarios of long-term power outage (EC, 2017; Krausmann et al., 2016).

Besides the requirement to conduct national or subnational disaster risk assessments under the UCPM, several other sectoral policies address the potential for critical infrastructure disruption resulting from natural hazards. The Floods Directive[12] requires Member States to develop flood-specific risk analyses considering, among others, the consequences of scenario floods to the economy and the environment. The Water

([11]) Decision No 1313/2013/EU of the European Parliament and of the Council of 17 December 2013 on a Union Civil Protection Mechanism (OJ L 347/924, 20.12.2013, p. 924–947)
([12]) Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks (OJ L 288/27, 6.11.2007, p. 27–34)

Framework Directive[13] advances the protection of water resources as a mitigation measure against floods and droughts. Floodwater damage to critical infrastructure systems can be a major contributor to the cost of floods. Droughts can reduce the output of hydroelectric power plants, but also of thermoelectric power plants, which require large quantities of water for cooling.

Two policy areas are explicitly related to power generation. The Seveso III Directive[14] deals with hazardous materials in fixed sites. Industrial facility operators are required to submit a safety report detailing the risk from hazardous materials releases from various scenarios. The Directive explicitly indicates natural hazards must also be considered as initiating events in the analysis of the risk from hazardous materials releases. Fuel storage depots are located adjacent to or inside thermoelectric power plants to ensure a steady supply to generators. When tank farms are inside a power plant, the facility may be subject to the Seveso III Directive, depending on the amount of hazardous substances stored onsite. The Nuclear Safety Directive[15] requires Member States to take measures to protect nuclear power plants from a wide range of hazards and threats, including natural hazards. Although risk analysis techniques used in industrial and nuclear facilities are nearly identical, safety requirements for nuclear facilities are generally much more stringent.

Last, the European Critical Infrastructure (ECI) Directive, focusing on energy and transport, explicitly requires Member States to designate ECIs based on the potential impact of the disruption of critical infrastructure systems, expressed in terms of casualties, and economic and public effects. Each designated ECI shall develop an Operator Security Plan (OSP), which needs to include an analysis of the risk of disruption from major threat scenarios and outline prevention and protection measures. Despite the multi-risk orientation of the ECI Directive, efforts have so far focused on threats from terrorist or other malicious attacks.

([13]) Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy (OJ L 327/1, 22.12.2000, p. 1–73)

([14]) Directive 2012/18/EU of the European Parliament and of the Council of 4 July 2012 on the control of major-accident hazards involving dangerous substances, amending and subsequently repealing Council Directive 96/82/EC (OJ L 197/1, 24.7.2012, p. 1–37)

([15]) Council Directive 2014/87/Euratom of 8 July 2014 amending Directive 2009/71/Euratom establishing a Community framework for the nuclear safety of nuclear installations (OJ L 219/42, 25.7.2014, p. 42–52)

3 Methodology and definitions

The research design for this study was predominantly purposeful. It focuses on disruptions of the critical electricity infrastructure subsector caused by selected natural hazards, and it explores the relationship between recovery time and hazard type. The study was data-driven, using an inductive approach based on the analysis of power grid disruptions due to earthquakes, space weather and floods.

Several databases provide information on disasters and their impact. Examples include GDACS (2017), a cooperation framework between the United Nations and the European Commission, and DMIS (2017), developed by the International Federation of Red Cross and Red Crescent Societies. These and other databases include near-real time data and archive records of disasters around the world, including information on lifesaving needs, critical infrastructure, critical services, risk from secondary/associated hazards and reports on the number of affected individuals. However, the information in these databases is intended for emergency managers and lacks the technical details required to assess the damage to lifelines.

Therefore, for the purpose of this study, data was collected from the open technical literature, field survey reports and research papers addressing the performance of lifelines in the face of earthquakes, space weather and floods. This exercise produced records of 16 earthquakes, 15 space weather events and 20 floods, listed in the Annex. Due to a scarcity of publicly available data, the impacts of floods caused by diverse events such as extreme rainfalls, storm surge etc. were included in this study. The dataset scope is worldwide, with a view to maximizing efficiency by capturing lessons from a wide range of events.

Electric power systems are designed and built after the architecture discussed in section 2.1, but they differ in configuration, output, frequencies and voltages. The power networks of most EU Member States are part of the European synchronous grid, which uses a frequency of 50 Hz. In the Americas and part of Asia, the power line frequency is 60 Hz. The output and voltage of the transmission and distribution grid vary among countries. Most European countries use 220 or 230 V for the Low Voltage distribution component of the grid, whereas most of the Americas use 110 or 120 V. The equipment and devices used by power grids depend to a large extent on the frequency, voltage and output of the network, as well as on their position in the network architecture. For instance, large power transformers are design-built based on their position in the transmission system.

Where applicable, this study took into consideration the effect of equipment design on earthquake, space weather and flood vulnerability, with a view to identifying the design characteristics which may affect the level of damage of critical equipment[16]. In addition, network design features, such as configuration, voltage and frequency, were accounted for in the analysis of the damage to individual components and the disruption of the power grid generated by natural hazards.

Nuclear power plants are a significant component of power generation in several EU Member States and other countries. Although civilian nuclear reactors are primarily used for research and electric power generation, they are typically not considered as part of the critical energy infrastructure sector. Because of their military implications and the potentially catastrophic consequences of nuclear accidents, nuclear power plants are part of a separate critical infrastructure sector and are subject to higher standards of safety and security. For instance, most countries require nuclear reactors to withstand much stronger earthquake loads than residential buildings or hospitals. However, non-safety related (NSR)[17] equipment and buildings may not be subject to these requirements. In this study, only damage to NSR equipment and buildings was considered, where available, and only

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([16]) Here, "critical equipment" refers to equipment and devices the failure of which may prolong recovery time.

([17]) In the nuclear energy sector, "safety-related" refers to equipment, systems or buildings which must remain functional during and following design-basis events. Examples of safety-related functions include shutting down a nuclear reactor and maintaining it in a safe-shutdown condition (US Nuclear Regulatory Commission, 2017).

to the extent that the equipment was comparable to that used in non-nuclear power plants. Examples include GSU transformers and switchyards located in or adjacent to nuclear power plants.

The systems-based visualization of the power grid discussed in section 2.1 was used as an initial abstraction to guide data collection and analysis. Information about the performance of the power grid to the events in our dataset was recorded in three tiers, each corresponding to another level of decomposition (Table 1).

Table 1. Data recorded

Tier	Level of decomposition	Information recorded
1	The power grid as a system	Power grid behavior Effect on population Effect on other critical infrastructure sectors Response strategy Recovery time Lessons learned
2	Generation, transmission and distribution subsystems	Damage and recovery time for each subsystem
3	Individual facilities or major components	Facility/component designation Facility/component behavior Damage to structures Damage to equipment Damage to piping Local response Recovery time Lessons learned (not captured under Tier 1)

The majority of the records in the resulting dataset were categorical, but numerical data was considered whenever feasible and available. For instance, information about damage to individual facilities, such as substations (Tier 3), was correlated with the peak ground acceleration (earthquakes) or water level height (floods) to which the facility was exposed, whenever this information was available. When the location of the facility was available, shake maps or flood maps were overlaid on a GIS application to determine the peak ground acceleration or water level the facility was exposed to.

The level of detail varied across the reports used for this study. The information in most reports was sufficient to establish the type of damage and the failure mechanism. In addition, several sources included an indication of the consequences to the population and other critical infrastructure sectors, response strategy, as well as repair and/or recovery time. The affected population was typically reported as the proportion of customers or households where the hazard impacts were observed. However, the diversity in grid architecture made it difficult to establish cause-and-effect between the power grid recovery time and the severity of damage to specific subsystems or components.

In addition, there are inconsistencies in recovery time reporting. First, not all sources reported recovery time. Second, different definitions and indicators of recovery were used by each reporting source. Some sources defined recovery as the restoration of service to the population affected by a power outage, while others as the repair of the power grid or subsystems to its pre-disaster state. Last, most sources reported the time to achieve a different fraction of complete recovery, such as a percentage of the affected population with restored service, or a percentage of power generation.

Two power grid recovery thresholds were used in this study. The first threshold is the restoration of power supply to customers. Both domestic and industrial customers were considered, based on available information. This threshold includes efforts directed at temporary repairs or workarounds, as well as the use of backup generators. The progress of recovery in this case is usually reported in terms of the percentage or number of customers with power supply, or the quantity of power supplied, expressed in power units or as a percentage of pre-earthquake supply. **The second threshold is the complete repair of the network, so that temporary solutions, including generators, are no longer required.**

4 Impact of natural hazards on the electric power system

Natural hazards, such as earthquakes, floods and space weather events, cause many different types of damage to electricity lifelines. The recovery time may be prolonged compared to failures not generated by natural events, because multiple systems may be affected simultaneously. This chapter outlines the type of damage incurred to power grid components due to earthquakes, floods and space weather, and describes how the level and extent of damage affects recovery time.

4.1 Earthquakes

Power outages are a common occurrence during and after major earthquakes. Electricity is typically interrupted during or immediately after the shake. The epicentral area is affected, but adjacent areas may also suffer outages. The duration of the outages in any area is a function of the level of damage to the substations and power lines which serve the area. Following the earthquake, power is restored progressively. **Depending on the intensity of ground motion and the level of damage, the duration of the blackout for most customers may range from a few hours to months.** In this study, except for the most severe cases, it took between 1 and 4 days to restore full power. However, customers in remote or poorly accessible areas may experience longer blackouts. Rolling or intermittent blackouts are not uncommon, and aftershocks may also cause blackouts after power has been restored.

4.1.1 Effect of the level and type of damage on recovery time

Earthquakes cause widespread structural damage to power generation, transmission and distribution subsystems. Structural failures may result from earthquake loading or be secondary to ground failure. Structural damage results from the response of structures and equipment to strong seismic ground motion. The following is a discussion of the type and severity of damage to buildings, equipment, and transmission and distribution lines.

Buildings in electric power networks house control rooms and protect heavy equipment, such as turbines and transformers. Most *buildings* in this study were steel-frame, reinforced concrete frame or wall, masonry (reinforced or unreinforced), or mobile structures. Electricity utility buildings are relatively short, from one to three stories high, which improves their seismic performance. Multi-story buildings may not perform as well, especially if heavy equipment is located on the upper floors. Electricity utility buildings have performed quite well in earthquakes in this study. Of the 39 facilities (substations and power plants) included in this study, which were subjected to peak ground accelerations (PGA) between 0.15g and 0.97g, severe or catastrophic structural damage to buildings was noted in only 5 cases. In two of the cases, PGA was 0.69g and above. In the remaining three cases, building damage was caused by ground failure (landslide, liquefaction, slope failure). However, in other instances, well-engineered buildings exposed to higher PGAs without soil liquefaction suffered less damage. For instance, the Devers Substation was exposed to 0.97g during the Palm Springs, CA earthquake of 1986, the strongest ground motion in this study. The control building was designed to the Uniform Building Code of the late 1960s and suffered no structural damage (EPRI, 1988). **Severe or catastrophic structural building damage may increase recovery time as it affects critical equipment contained in or next to the affected buildings.** In addition, debris from collapsed buildings may damage adjacent equipment. Less than severe structural damage had no impact on recovery time in this study.

The *equipment contained in buildings* was often more vulnerable to dynamic horizontal loading than building structures in this study. Control buildings include computers, network racks, electrical panels, file cabinets, HVAC equipment and battery racks. These and other equipment items are heavy, have tall and slim shapes, and rest on small surfaces, which makes them particularly vulnerable to strong ground motion. Unanchored equipment frequently topples and/or falls from racks and tables. The risk of toppling or falling increases with the height and decreases with the base diameter. For example, several unanchored or partially anchored electrical control and instrumentation cabinets with an aspect ratio (H/D) greater than 3 overturned during the Spitak, Armenia earthquake of 1988 (EPRI, 1991). **Anchoring successfully mitigates equipment toppling and falling hazards.** In this study, anchored equipment consistently performed better than unanchored equipment, and withstood relatively strong ground motion without serious damage. For example, all electric cabinets and racks in the Devers Substation control house were anchored when the Palm Springs, CA earthquake hit in 1986. As a result, they suffered no damage during the 0.97g strong ground motion (EPRI, 1988).

Batteries providing emergency power to protective equipment are especially vulnerable to this type of failure. They are relatively important because they provide backup power to protective equipment and control room information and communication systems. Unanchored batteries may slide and topple, while anchored batteries generally remain undamaged.

Large Power Transformers (LPTs) and other heavy equipment suffer a lot from inertial seismic loading. Depending on the intensity of ground motion, the damage from rocking may range from slight to catastrophic. The slightest form of damage in this study was tripping of equipment protection devices because of vibration. The units are inspected and, if there is no additional damage, reset and re-energized within less than 24 hours after the earthquake.

The response of heavy equipment to stronger rocking depends on the type of foundation supports. LPTs, Emergency Diesel Generators (EDGs) and turbines may break off from their foundations and tilt, topple or move horizontally. Tilting or toppling may also drain transformer oil. The earthquake load is distributed in proportion to the relative stiffness of the resisting members. Therefore, anchoring and base-isolation are successful hazard mitigation options: in this study, anchored or base-isolated heavy equipment withstood PGAs of up to 0.2g without significant damage. However, anchoring is not a panacea, and our study included cases with severe damage at a PGAs of 0.35g. Heavy equipment, such as LPTs and turbine units, is often critical for the power grid. Unless spares are available, damage to this type of equipment may be the major determinant of recovery time.

Mounting heavy equipment on rails was a controversial hazard mitigation technique in this study. Rail-mounted transformers have less chance of toppling and can absorb energy by sliding. Although sliding provides ductility, excessive sliding has other problems. In this study, there was only minor damage to rail-mounted transformers that slid up to 50 cm or fell off the rails. However, excessive movement caused damage to elements attached to the transformers, such as bus bars, lighting arrestors and electrical connections.

Rigid connections are particularly vulnerable to seismic forces (Krausmann et al., 2011). Heavy equipment attached to transformers, such as radiators and oil tanks may be detached or drained. On the other hand, elements connected with flexible couplings suffer less damage. For instance, two large radiators attached to a large power transformer at the Kariwa Substation suffered no damage during the Niigataken-Chuetsu-Oki, Japan earthquake of 2007. The radiators were supported independently of the transformer, but on the same foundation slab. The transformer was connected to the radiators with flexible couplings. Because of soil liquefaction, the foundation slab tilted, but there was no damage to neither the transformer nor the radiators (Tang and Schiff, 2007).

Simple repairs, such as refilling oil tanks, takes two or three days. However, more complex works may require up to two weeks if conducted onsite, or considerably more time if the equipment needs to be transported to a factory or repair facility.

Switchyards are the most vulnerable part of electric power substations and facilities. They are often critical power grid nodes and provide essential connectivity between power generation, transmission and distribution systems. Switchyard equipment includes circuit breakers, transformers and disconnect switches, all of which use ceramic columns for insulation. These slender and brittle components suffered the most severe earthquake damage among all other equipment categories in the cases reviewed in this study. Ceramic columns typically break off at the lower third of their height, near the connection to more ductile elements. **Widespread damage to the switchyard is a common occurrence.** Ceramic components of heavier equipment, such as bushings and surge arrestors, are also fractured in a similar manner. These failures usually result from seismic excitation or tension forces applied to equipment terminations due to limited cable slack, hanging equipment (e.g. wave traps) or rocking of adjacent equipment. **Supporting ceramic columns was found to be a relatively effective hazard mitigation technique in this study.** Laterally supported ceramic elements suffered consistently less damage. Despite the widespread damage inflicted to switchyards by earthquakes, ceramic components are relatively inexpensive compared to buildings and heavy equipment, and electric utility operators usually maintain supplies of spares. In addition, replacement parts can be purchased relatively easily and quickly. Therefore, switchyard repairs depend on manpower more than on expensive equipment (i.e. they are more labor-intensive) and the impact of this type of damage on recovery time is a function of the criticality of the affected substation and the manpower required for repair. For instance, in the aftermath of the Luchan, China earthquake on April 20, 2013, a crew of 110 repaired a severely damaged substation switchyard in 3 days (Eidinger, Tang and Davis, 2014).

Next to generation facilities and substations, *transmission towers* are also highly vulnerable to earthquake forces. Transmission tower damage was recorded in nearly all earthquakes in this study. Transmission towers are lightweight and slender structures, which have little inertia but provide for little damping. The bearing structure is typically a three-dimensional truss with cold-formed steel section members. The most frequent earthquake failure modes are tower collapse or permanent drift, and deformations of tower members and/or legs. Inertial force and ground failure are the most typical causes of damage. The impact of the loss of a single transmission tower or a single line depends to a large extent on the configuration of the network, as discussed in section 5.1. **The replacement of a single transmission tower may take about 10 days, provided that the site is accessible by road.** However, several workarounds have been used to temporarily support critical transmission towers. Examples include using mobile construction cranes or prefabricated towers, which may also be airlifted to the site and then assembled. Leaning towers may also be supported with guy-lines.

Earthquake damage to the *subtransmission and distribution subsystems* is similar to that of the transmission network. Electricity distribution systems are particularly vulnerable to seismic forces and suffer extensive damage in major earthquakes, affecting many customers over wide areas. However, this type of damage is not a major determinant of the entire grid recovery time for three reasons. First, MV (distribution) and LV (distribution) circuits are arranged in grids. Therefore, in case of a loss of a small number of lines, power can be rerouted by switching to a backup configuration. In case of more widespread damage, electricity supply may be restored by repairing a small number of critical nodes. Second, spare equipment and materials are far less expensive than those of transmission systems. Distribution Systems Operators (DSOs) maintain reserve stocks to handle rather extensive repairs, while additional items are available on order relatively quickly. Third, individual repairs take less time than repairs to components of the transmission assets.

In addition to direct shaking damage to electricity subsector facilities and system components from inertial forces, severe damage results from ground failure[18]. **In this study, ground failure was the single most important determinant of the level of earthquake damage to the power grid.** Ground deformation, including settlement, soil liquefaction[19] and lateral spread[20], may destroy an entire switchyard, and cause severe damage to buildings, large transformers and other heavy equipment. Soil liquefaction also affects buried cables. Foundation failure is a very common cause of transmission tower

(18) The term "ground failure" is used in this report as a general reference to consequences of strong ground motion which affect the stability of the ground, such as landslides, liquefaction or lateral spreads.

(19) Soil liquefaction is a phenomenon whereby the soil temporarily loses strength and acts as a liquid. It usually occurs in cohesionless soils with poor drainage, such as sand and gravel. Soil liquefaction often results from earthquake shaking, which increases the pore water pressure of the soil and consequently decreases its effective stress. The phenomenon is observed as "sand boils" and/or land instability.

(20) Lateral spread or lateral flow is a landslide occurring on low-angle slopes.

damage or loss. Poor foundation support contributes significantly to this type of damage. Landslides and rockfalls may also damage or destroy buildings and equipment. **Ground failure adds considerably to the post-earthquake recovery time**, not only because of the extent of the damage, but also because of the added work required for repairs. Several years may be required to assess damage and complete repairs, while severely damaged facilities may have to be abandoned. However, temporary workarounds may help to restore power to customers until more permanent solutions are found.

Fire may also be a secondary earthquake hazard for power grid facilities. In this study, there was only one occurrence, in which a GSU transformer caught fire due to soil settlement. Although a rare phenomenon, fire can cause severe or catastrophic damage to buildings and equipment, and affect entire facilities. The level of damage is a function of the underlying cause and the availability of passive and active fire protection.

The analysis of response strategies also helped to assess the repair time of transmission towers and large power transformers, two of the most critical components of the electric power network. Table 2 presents rough estimates of the time required to conduct various types of repairs, conjectured from information about the response to the earthquakes reviewed in this study, supplemented with information from the technical documentation.

Table 2. Estimated repair time

Component	**Repair strategy**	**Repair time**
Transmission Tower	Replacement	10 days
	Erect temporary tower	1-2 days
Large Power Transformer	Inspect, reset and re-energize	14-20 hours
	Refill oil, onsite	2 days
	Minor repair, onsite	1-2 weeks
	Change windings, onsite	3 months
	Replace (no existing spare)	1 year or more
	Replace with spare	5 days

4.1.2 Damage to individual facilities

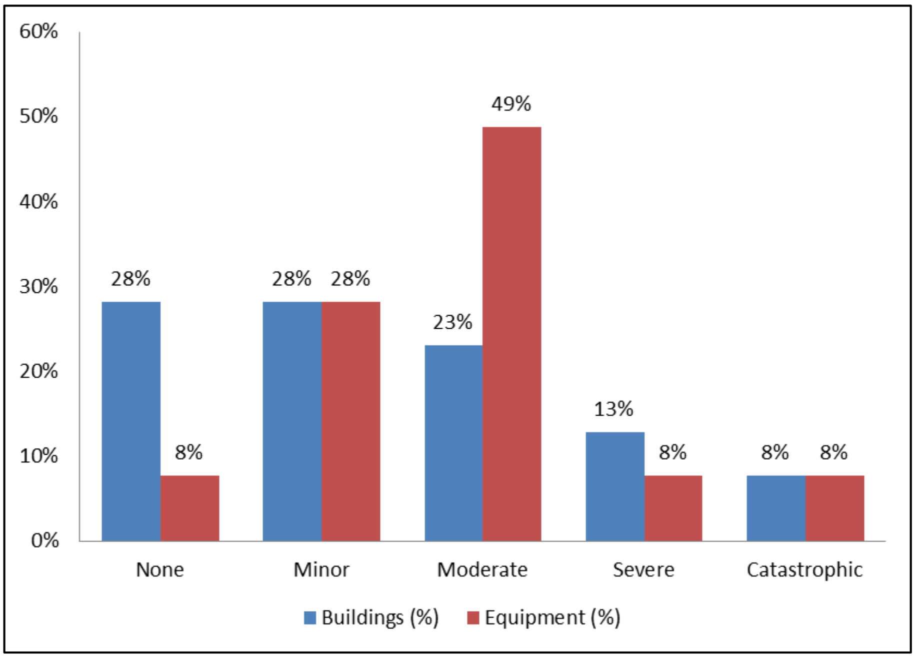
Information regarding the level of damage to individual facilities was available for 11 of the 16 earthquakes reviewed in this study. Reports about the damage to 39 facilities, including substations and power plants, were analyzed to develop a typology of the impact of strong ground motion. Two damage scales were defined, one for buildings and structures, and one for equipment (Table 3).

Figure 3 presents the relative frequency of observation of each level of facility damage in this study. The facilities in this sample were exposed to peak ground accelerations ranging from 0.15g to 0.97g. The distribution of building damage is skewed to the left, which shows that buildings are more likely to suffer minor, moderate or no damage. On the other hand, the distribution of equipment damage is less skewed, which indicates that equipment is more vulnerable to strong ground motion.

Table 3. Earthquake damage and failure modes

Damage state	Buildings/Structures	Equipment
Slight/Minor	— Damage to building contents — Nonstructural damage — Localized damage to load-bearing members	Tripping due to vibration Toppling of batteries, control panels
Moderate	Stress of load-bearing members Failure of a limited number of load-bearing members, without loss of structural integrity	Breaking of ceramic elements Horizontal displacement or tilting of heavy equipment, without damage Draining of transformer oil
Severe	Failure of load-bearing structure members, with compromise of structural integrity	Horizontal displacement or tilting of heavy equipment, with damage
Catastrophic	Partial or complete collapse Foundation/ground failure	Foundation/ground failure Fire

Figure 3. Distribution of damage severity per damage level (based on a sample of 39 facilities)



Moderate and severe equipment damage typically requires lengthy repairs, during which the damaged items are out of service. Even minor building damage may render a building unusable for some time, and the repair of buildings with moderate or severe earthquake damage takes weeks. However, in case of catastrophic damage, which is relatively uncommon for both buildings and equipment, the only option is to replace crippled equipment or rebuild collapsed structures. In both cases, recovery time increases disproportionately compared to even the most complex repairs. In other words, **recovery**

time in earthquakes seems to be attributable to the widespread moderate and severe damage, rather than catastrophic damage to individual buildings and equipment.

4.2 Space weather

Until recently, space weather was almost unknown to the disaster risk management community (MacAlester & Murtagh, 2014). The term 'space weather' encompasses a variety of phenomena which shape the space environment between the Earth and the Sun. It is a function of solar activity and its interaction with the Earth's geomagnetic field. Most of the disruptions caused by space weather result from their interaction with technological systems. The power grid is particularly vulnerable to Coronal Mass Ejections (CMEs), explosions of magnetic field and plasma from the Sun's corona. As they reach the Earth, they cause the terrestrial magnetic field to fluctuate over time, resulting in so-called geomagnetic storms and inducing currents in closed loops formed by transmission lines connected to the ground through grounding connections (Piccinelli & Krausmann, 2017). These Geomagnetically Induced Currents (GICs) affect the power grid and have the potential to severely compromise electricity transmission.

The transmission part of the power grid is the most vulnerable to space weather events. Generators may also be affected, but to a lesser extent. Electricity distribution networks have higher line resistances and lower voltages, and are relatively immune to GICs. They are typically affected by space weather when they lose power supply from the transmission or subtransmission lines.

Power outages resulted from 5 of the 15 space weather events reviewed in this study. Each time, power supply was restored in less than 24 hours. However, multiple outages occurred during each space weather event. Interruptions of power supply did occur on a regular time basis and had different durations. The following sections discuss the impact of equipment damage and system-wide effects on the power grid recovery time.

4.2.1 Equipment damage

GICs have a lower frequency than the electric power grid, and are referred to as quasi-DC currents. High-voltage transformers are vulnerable to GICs because they are not designed to handle direct current. The existence of GICs in the transmission network drives LPTs into half-cycle saturation[21], which increases reactive power[22] consumption and injects harmonics[23] into the system. This response can cause a wide range of problems to LPTs, including overheating, damage to the windings, and even fire. **The level and extent of transformer damage is a major determinant of recovery time in space weather events.** Harmonics may also affect power generators[24], albeit to a lesser extent.

Minor problems, such as overheating, can be addressed relatively easily, by backing down transformers to allow them to cool down. If the level of GIC in the system is low and action is taken early enough, damage may be minimal and there may be no interruption at all. However, if the level of GIC is higher, or action is not taken promptly, the damage may be catastrophic. Overheating may destroy the windings and even set the transformer on fire. As in the case of earthquake damage (section 4.1.1), repair time depends on the type of damage and repair capabilities. For instance, a transformer with high levels of dissolved gasses, which is an indicator of prior GIC-induced stress, may have to be taken out of

([21]) Half-cycle saturation occurs when a DC or quasi-DC excitation is superimposed to the normal AC cycle of the transformer. The magnetic flux is increased during the positive half-cycle of the transformer, resulting in overheating of the windings, high winding losses and potential damage to the insulation of the windings.
([22]) Reactive power is power which is absorbed and returned to the system in periodic fluctuations due to the phase angle difference between voltage and current in AC circuits. An AC circuit consumes more reactive power during a DC or quasi-DC excitation because of the increase in half-cycle flux density.
([23]) Harmonics are AC currents with a different frequency than the frequency of the electricity supply (called fundamental frequency). Harmonics result from the superposition of series of sinusoidal waveforms, and their frequency is an integer multiple of the fundamental frequency.
([24]) Harmonics flowing into a generator produce an oscillating magnetic field which causes heating of the rotor. The generator needs to be taken offline to prevent damage.

service until the underlying problem is resolved. Winding change onsite takes approximately 3 months, assuming no other damage, but may take twice as long if the unit has to be dismounted and transported to a factory or repair service. **On the other hand, if a transformer is destroyed by very high levels of GIC, then the time to replace may be upwards of one year.**

In addition to direct damage, GICs may cause protective relays to trip, therefore taking offline transformers, transmission lines, capacitors and circuit breakers. As discussed in section 4.1.1, tripping of isolated devices is easy to repair, provided there is no additional damage. In the events analyzed in this study, when there was no further damage, power supply was restored in less than two hours after the disturbance. However, **resetting tripped devices may have to wait until the geomagnetic storm and the GICs in the system have subsided, in which case the recovery time will be prolonged** by the duration of the event. Geomagnetic storms are often associated with a series of high-GIC events over a period of several days. Several devices may trip during each event. The duration of the outage which may or may not result from each event, and the affected area are a function of the number and type of the tripped devices, and the network topology. In other words, **geomagnetic storms may be associated with a series of power outages, each with a different duration and affecting another area.**

Besides their wide reach, **GICs may cause delayed effects**. For instance, in the aftermath of the Halloween solar storms of October and November 2003, there was repeated damage in the South African power grid after the event. Two transformers presented high levels of dissolved gasses in June 2004, seven months after the solar storm, and another tripped on a gas detector relay[25] in November 2004, one year after the event. In all three cases, the damage was traced back to the 2003 solar storm (Gaunt & Coetzee, 2007). Delayed damage effectively reduces the service life of the equipment and adds on the economic burden of the restoration effort.

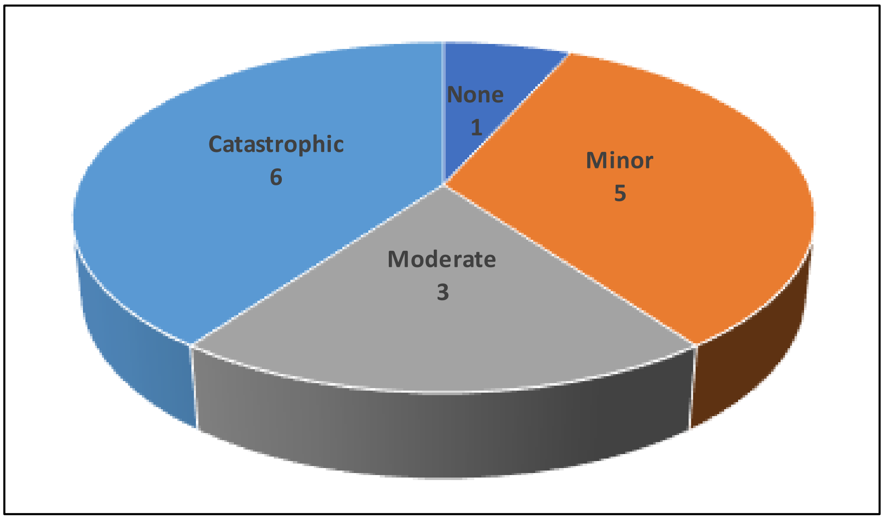
Table 4 outlines the damage scale developed for the impact of GICs on equipment. Figure 4 illustrates the relative frequency of observation of each level of equipment damage. Minor and catastrophic damage are predominant. The figure also shows that **during geomagnetic storm conditions some form of abnormal operating conditions or equipment damage is likely, even if only minor.** The single event which did not result in damage was a short-lived radiation event, not associated with strong geomagnetic activity. Tripping of protective relays and fire were the most common failure modes. In addition, in at least two cases, damage was discovered several days after the event. Because of the high potential for catastrophic damage and the possibility of delayed failure, GICs present a particularly insidious threat to electric equipment.

Table 4. Electrical equipment GIC damage and failure modes

Damage or service disruption	Description
Slight/Minor	Tripping
Moderate	Equipment malfunction Overheating, without winding damage (transformers)
Severe	Overheating, with winding damage (transformers)
Catastrophic	Fire

([25]) Gas detector relays, or Buchholz relays, are safety devices designed to electrical equipment from failures of dielectric material. When mounted on oil-filled transformers, they are sensitive to the accumulation of gasses produced from the decomposition of the oil, which may occur as a result of GIC-induced stress. In these cases, these relays are designed to disconnect the transformer before the damage becomes severe.

Figure 4. Distribution of damage severity per damage level (based on a sample of 14 events)

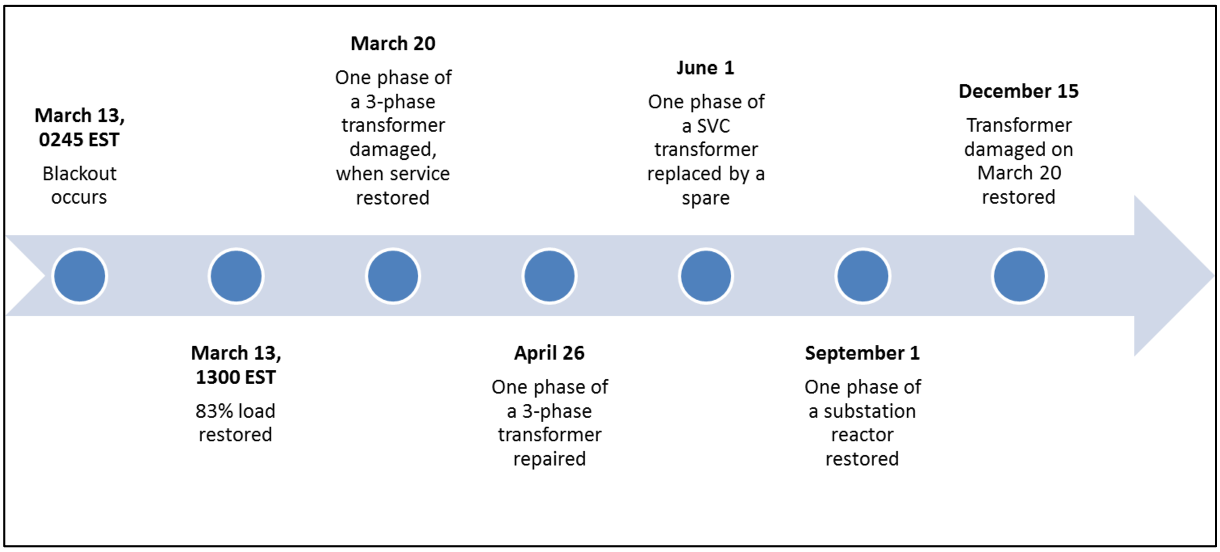


4.2.2 System-wide impact

The biggest threat to the power grid from space weather events stems from the potential for system-wide impact. The greatest threat from a space weather event to the electric power system is voltage collapse, which may result from the combination of extreme reactive power consumption and the loss of reactive power support devices. The 1989 Quebec blackout is referred to as the canonical example of an extended blackout caused by a solar storm. Although the intensity of the geomagnetic storm was significantly smaller than the 1859 Carrington event, the worst geomagnetic storm on record, the response timeline provides insight into the power grid recovery time in case of voltage collapse. Following the Quebec blackout, it took 9 hours to restore 83% of the pre-incident power supply. While repairs were being made, power was rerouted through interconnections to help restore electricity to customers. Damaged equipment was progressively repaired and put back into service, but the process took at least nine months (Figure 5). The Hydro-Quebec system is not part of the Eastern Interconnection, which extends from Central Canada to Florida, and from the Atlantic coast to the east foot of the Rocky Mountains. Because Hydro-Quebec is operated as a standalone, asynchronous system, the disruption did not propagate into the Eastern Interconnection. Had the disturbance been caused by a Carrington-level event and allowed to spread to the Eastern Interconnection, the power outage would likely be longer and affect a much wider area, and the recovery time would likely be considerably longer, as well. In fact, there is concern that an extreme geomagnetic storm could take out significant parts of the US power grid, causing ripple effects in all sectors, with an estimated societal and economic cost of 1-2 trillion $US in the first year, and 4-10 years to full recovery (US National Research Council, 2008). Unfortunately, the data and methodology used for this assessment were not disclosed.

In addition to voltage collapse, one of the most important threats arising from GICs is the potential for simultaneous damage to multiple high-voltage transformers. Natural disasters are notorious for crossing national and jurisdictional borders, but a single extreme space weather event may affect countries in different continents at the same time. Of the 14 space weather events reviewed in this study, 4 affected more than one country. For instance, the Halloween storms of October-November 2003 affected electricity networks in the US, Sweden, South Africa and the UK. The Carrington solar storm of 1859, used as the canonical extreme space weather event, affected telegraph services in Canada, the US, Norway, Sweden, France, the UK, Belgium and Australia. This type of effect can be a major determinant of recovery time because of the long lead time required to build and replace a large power transformer. LPTs are designed for a specific location of the system, and every device is unique in this sense. Because of their specificity and high cost, it is difficult for power grid operators to maintain large stocks of spares.

Figure 5. Power grid recovery timeline following the 1989 Quebec blackout



Source: Bolduc, 2002

As discussed in section 4.2.1, moderate repairs, such as changing the windings, may take 3 months to finish onsite, or twice as long if the transformer needs to be transported to a distant repair facility. However, **GICs from geomagnetic storms may damage multiple LPTs located in different facilities in several countries within minutes.** In addition, global repair capabilities are finite; therefore it may not be possible to conduct repairs concurrently. In addition, the design, manufacture and testing of a new LPT takes between 12 and 18 months. There are a handful of qualified manufacturers, most located in Eurasia. Therefore, a strong geomagnetic storm affecting multiple transformers could rapidly overwhelm global production capabilities and significantly prolong the recovery of the electricity grid in several countries.

4.2.3 Early warning and emergency response

Notwithstanding the potential for system-wide damage, power companies and TSOs can take protective measures if provided with early warning. Current forecasting capabilities do not allow to predict the timing and intensity of each event with much lead time. Geomagnetic storms exhibit some seasonality, and they generally occur during the maximum of the 11-year solar magnetic activity cycle. However, space weather events have occurred during the solar minimum as well. Despite the lack of medium-term prediction capabilities, early warning of an impending geomagnetic storm is possible. A watch is issued as soon as an Earth-directed CME is detected, providing advance warning 1-3 days before it hits the Earth. However, fast-moving CMEs can reach the Earth is as little as 17 hours. In either case, the warning would include the CMEs estimated time of arrival to Earth, but not the orientation of its magnetic field. The latter is a critical piece of information, because CMEs with strong southward-oriented magnetic fields are the most destructive. The orientation of an incoming CME is only known once it is detected by the ACE spacecraft, which provides a 15- to 45-minute warning before the storm reaches Earth (Krausmann et al., 2016). An alert is issued when magnetometers on the earth's surface pick up the storm.

The early warning provided by this suite of watch, warning and alert messages gives electric power companies and TSOs some time to react, but comes with two drawbacks. First, it bears the same uncertainty of terrestrial weather early warning. Currently, the orientation of an incoming CME can only be determined 15 to 45 minutes before it hits the Earth. In addition, the calculations to determine which device may be affected given a specific CME take time, which is not available. However, risk assessments conducted before a space weather event takes place can reveal which equipment items are most vulnerable to GICs, so that protective measures can be targeted to the most critical part of the network. Second, electric power companies and TSOs require lead times of ideally 2 to 4 days to take protective measures, including returning to service of all circuits, connecting all LPTs to distribute the GIC, increasing voltage support and calling back extra staff. **Early warning, if heeded, can mitigate the threat of GICs and reduce the potential of damage.** Before and during the 2003 Halloween geomagnetic storm, power companies in the United States received the standard watches, warnings and alerts, and responded by reducing system load, disconnecting system components and postponing system maintenance (MacAlester & Murtagh, 2014). Damage to the US power grid was limited compared to Sweden and South Africa (NOAA, 2004; OECD, 2011; Gaunt & Coetzee, 2007). However, it is difficult to determine the impact of protective measures, because the damage from space weather events is a function of several parameters, including the local intensity of the geomagnetic storm, ground conductivity and network topology.

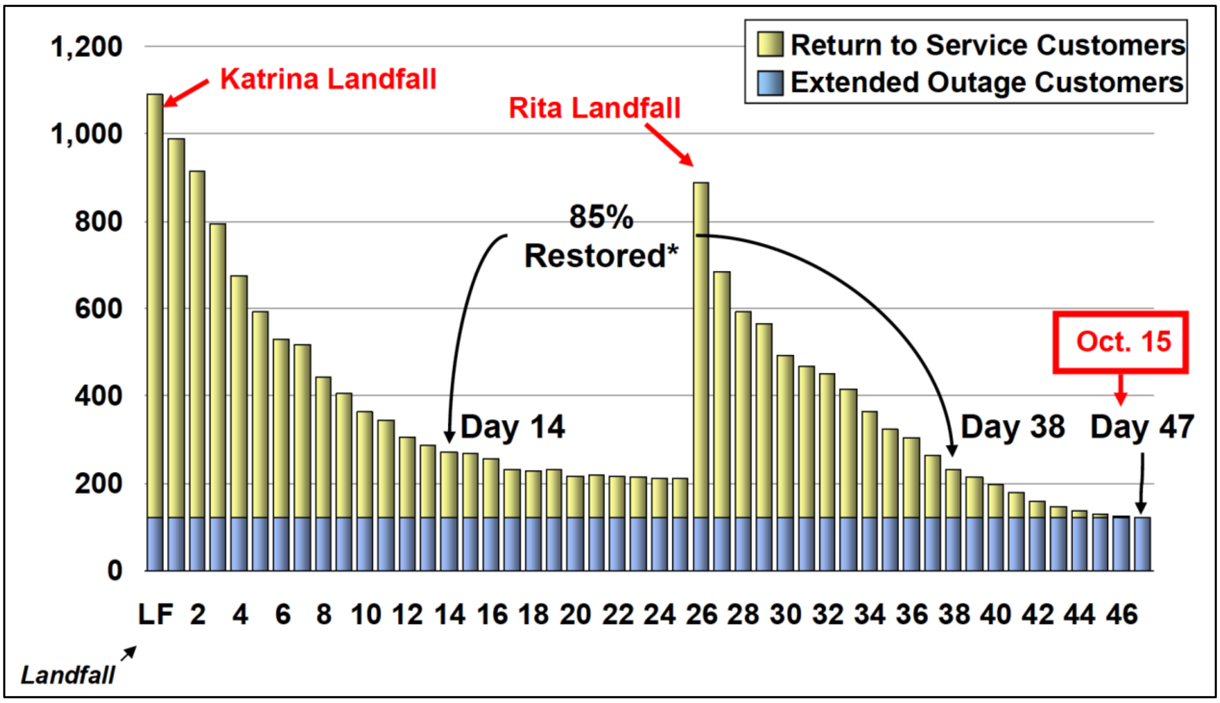
4.3 Floods

Floods are commonly associated with power outages. **Electricity was interrupted in 100% of the flood events reviewed in this study.** As in the aftermath of earthquakes, power is restored progressively. In our sample, the **blackout lasted from less than 24 hours to more than one month**. Except in extreme cases, it took one week or less to restore power to all customers who could receive it. **The longest blackouts were caused during floods associated with hurricanes.** However, in these cases it was unclear what fraction of the damage was caused by floodwaters versus that generated by high winds. For instance, Figure 6 illustrates the total number of power outages restored in the days following the landfall of Hurricanes Katrina and Rita for Entergy, an integrated power provider servicing 2.7 million customers in Arkansas, Louisiana, Mississippi, and Texas. The term "Return to Service Customers" is used here for customers who can take power. The following sections describe the impact of equipment damage and early warning on post-flood electricity recovery.

4.3.1 Equipment damage

Because water is a very good conductor of electricity, **some electrical equipment items can suffer catastrophic failures in the presence of even minute quantities of moisture and dirt.** For example, when Hurricane Sandy made landfall in New York, a submerged transformer located in a substation near the bank of the East River exploded, leaving much of Lower Manhattan in the dark. The explosion was visible from across the river (Huffington Post, 2012; Walsh, 2012). Large amounts of water and mud may be trapped in several types of substation equipment items following submersion. Inundated circuit breakers, transformer parts, control house equipment, and metallic switchgear need to be disassembled and cleaned before they can be put back into service. **The level of damage and the required repairs increase with the time the equipment in submerged for.** Some equipment items may even be unsalvageable. Given the delicate nature of the repairs, the task workload increases rapidly as more items are submerged. The restoration efforts following the Missouri floods in 1993 illustrate the order of magnitude of the time needed to make repairs (Abi-Samra & Henry, 2011). Restoring a single control house took hundreds of work hours, because of the countless devices and wiring terminations which had to be cleaned. Circuit breakers were repaired if the cost of the intervention was less than half of a new piece of equipment. Positive-pressure systems, such as some hydraulic components, were more robust.

Figure 6. Restoration of power in the aftermath of Hurricanes Katrina and Rita (in thousands)



Source: Entergy Corporation, 2005

Buried equipment is more expensive and more vulnerable. Burying electrical equipment, such as distribution substations and power lines, is often considered in urban areas, as a measure to reduce building density, improve security, and protect against weather-related hazards, such as storms and floods. However, this solution has been proven to be expensive and time-consuming. For instance, the State of North Carolina in the United States considered replacing all existing overhead distribution lines with underground cables after a major ice storm in December 2002. However, it was estimated that the project would cost US$ 41 million, nearly six times the net books value of the distribution assets of all State DSOs, and would require 25 years to complete (North Carolina Public Staff Utilities Commission, 2003). In addition, buried equipment is more difficult to access for maintenance and repairs and, more importantly, are more vulnerable to floods and other weather-related hazards. For example, underground assets have been washed away during hurricanes and are reportedly prone to frequent flooding (Abi-Samra, 2013).

Because of their ubiquity and high concentration of sensitive equipment, substations are at increased risk from floods. It is generally accepted that **the restoration of a flooded substation takes much longer than the repair of a downed power line damaged by ice or wind** (Ab-Samra, 2010). As more equipment items are inundated, the time needed to conduct repairs with a limited workforce becomes a major determinant of the power grid recovery time. Table 5 outlines the damage and service disruption scale developed for the impact of floods on substation equipment.

Flood mitigation strategies were effective in reducing the damage to critical substation equipment, and therefore cutting down recovery time, in this study. **Examples of successful strategies include locating the substation above flood levels, levee protection and elevating sensitive equipment.** For example, the Tennyson Substation in Queensland, Australia, was built well above inundation levels and suffered no interruption during the 2010 flood. In another substation, flood waters reached about 1m in the switchyard and 40 cm in the control house, but did not pose a threat to equipment. In that case, power was only interrupted for 3 hours for the TSO to reroute the electricity supply safely through the substation (Powerlink Queensland, 2011).

Table 5. Substation equipment flood damage and failure modes

Damage or service disruption	Description
Slight/Minor	Shut off preemptively Tripping
Moderate	Inundated, repairs economically feasible
Severe	Inundated, beyond economically feasible repair
Catastrophic	Explosion Washed away by floodwaters

Floodwater-caused structural damage to technological systems typically results from a combination of buoyancy, hydrostatic and hydrodynamic loads, as well as debris impact (Krausmann et al., 2011). In this study, however, there was no indication of structural damage to substation equipment contributing to recovery time. The mechanical properties of these items may offer one potential explanation. Substation equipment has a relatively high weight-to-volume ratio, which helps to resist buoyancy forces, and a relatively slim profile, which affords less exposure to hydrostatic and hydrodynamic forces.

Although structural damage was not a concern for substation equipment, **floodwaters were a threat to transmission towers in this study**. Landslides and soil erosion caused by the flood or rainfall may severely undermine the foundations of transmission towers. For example, during the 2011 floods in Australia, one transmission tower collapsed because of a landslide. Although there was no interruption of high-voltage supply, a replacement, H-frame concrete tower had to be erected, and the endeavor took 2 weeks. During the same floods, 30 m of river bank was eroded back to the base of another tower, forcing the TSO to take the two circuits mounted on this tower offline until a replacement tower could be built on safe soil (Powerlink Queensland, 2011).

4.3.2 Early warning and emergency response

Early warning was a major determinant of power grid resilience, as it gave TSOs and DSOs in the affected area time to activate their emergency response and business continuity arrangements. **Preemptively interrupting power supply, and pre-staging repair crews, equipment and supplies proved highly successful in this study.**

One of the most effective strategies implemented by power companies when a flood is imminent is preemptively shutting down power to vulnerable substations located in the flood zone. This prevents catastrophic damage incurred when water comes in contact with live equipment. The unavoidable disadvantage is that outages may extend to areas otherwise unaffected by the flood. For example, a neighborhood may suffer a power disruption if it is serviced by a substation at risk of being inundated. Even if that area ends up in the flood zone, it is likely that the outage may start long before the flood. In at least 4 cases in this study, the outages were at least partially due to preemptive interruptions. Despite the inconvenience, this strategy ultimately reduces recovery time, because the most severe damage is avoided.

Early warning also provides TSOs and DSOs time to activate their emergency response systems. An effective strategy is to activate surge mechanisms before the onset of the flood and staging repair capabilities at the edge of the flood zone. When a damage from a flood is expected to overwhelm the capabilities of a single TSO/DSO, the affected operator requests assistance from neighboring TSOs/DSOs. Help typically includes repair crews, equipment and supplies. For instance, the effective response of power companies is largely credited for the fast restoration of power in the aftermath of Hurricanes Katrina and Rita. Widespread power outages, caused by the combined impact of flood and wind, had left more than 2 million customers without power in at least seven States. Power companies in the affected areas activated their emergency plans prior to landfall, and brought in repair crews from 23 States and Canada. Entergy, an integrated energy provider, mobilized more than 30,000 workers to restore power, including its own staff, workers recruited before the storm, and crews provided by neighboring power companies (Entergy, 2005).

Although the rapid surge of repair capabilities was instrumental in expediting recovery after Katrina and Rita, it also sent logistics needs through the roof. In the emergency management field, not or poorly addressing response-generated demands has often been cited as a cause of disaster response failures (Karagiannis, 2005; Karagiannis & Synolakis, 2017). The response of the electricity sector to Katrina and Rita was an exception to that trend. For example, all of the customers of Mississippi Power lost electricity during Hurricane Katrina. This integrated provider promptly activated its disaster response plan and pre-positioned repair crews at the edge of the hurricane zone. During the peak of the response, the company provided shelter to approximately 11,000 personnel, served up to 32,500 meals per day, commissioned 65 buses, and operated 18 shelter and 12 logistics sites. By rapidly deploying surge capabilities and addressing response-generated demands, Mississippi Power was able to restore power to every customer who could receive it in as little as 12 days (Ball, 2006).

Although disaster preparedness was an important determinant of restoration throughout this study, it played a critical role in flood response. The discussion of the response to Hurricanes Katrina and Rita highlights that pre-disaster planning is needed for the provision of early warning, the deployment of surge capabilities, and addressing disaster-generated demands. In addition, **preparedness integrates the response efforts of system operators (TSOs and DSOs) with those of the wider emergency management community**. The resulting agility and unity of effort is a well-known contributor to operational effectiveness. Two examples help to illustrate this. First, several oil refineries lost power when Katrina battered the Southeastern United States. Because these facilities were considered vital to the national economy, restoration of power became a priority, and the recovery effort had to be coordinated between the power utility, the refineries and the US Department of Homeland Security (Entergy, 2005). Second, coordination between the emergency management community and the electricity sector helped expedite the power grid recovery after the 2011 Queensland, Australia floods. Because Powerlink, Queensland’s TSO, sat in the State Disaster Coordination Committee, it had access not only to daily briefings with the Queensland Bureau of Meteorology, but also to aerial resources made available by the Australian Defense Force and flood boats from the State Emergency Service and the Water Police (Powerlink Queensland, 2011).

Irrespective of the effectiveness of emergency plans, **many types of repairs cannot start until the waters recede.** The duration of the inundation was a major determinant of the power grid recovery time consistently in this study. Repairing substation equipment is meaningless if the substation is inundated. Attempts to repair downed transmission lines in inundated areas means putting workers at risk of electrocution and entanglement. In addition, any operations in moving waters are considered high-risk endeavors, and are generally justified only for rescue and evacuation purposes by trained personnel.

4.4 Comparison of damage types

Each of the three natural hazards reviewed in this study causes different types of damage, as they stress power grids in different ways. Earthquake damage is caused by strong ground motion, which exerts inertial loads on buildings and may result in ground failure. Space weather generates GICs which may damage AC equipment not designed to handle DCs. Floods damage occurs as floodwaters seep in inundated equipment and soils. Because each hazard generates a different type of stress, it results in different types of damage and affects another set of power grid components (Table 6).

For instance, both earthquakes and floods have the potential for causing foundation damage, albeit through different mechanisms. Earthquake strong ground motion results in ground failure, which may threaten the foundations of buildings and transmission towers. Floods cause landslides by increasing pore water pressure within the soil, therefore reducing shear strength. Floodwaters may also cause excessive erosion and undermine foundations. In this study, there was no indication of flood-induced damage to substation building, but there were cases of foundation damage to transmission towers.

Moreover, both earthquakes and floods cause widespread damage to electrical equipment and power grid components. The damaged items need to be either repaired or replaced, and the time to conduct repairs or install new equipment drives the recovery of the power grid. In the case of earthquakes and floods, it was the number of items which drove recovery time in this study. In addition, **access to the damaged sites was a major determinant of recovery time in the aftermath of both earthquakes and floods**. In some cases, access to substations or transmission towers was blocked by landslides (triggered by strong ground motion or rainfall). Other factors which were found to affect recovery time in this study were the extent of the damage, the complexity of required repairs, the availability of spares (either with the affected utility, through mutual aid agreements, or from the manufacturer), and transportation arrangements.

Earthquakes and floods cause widespread destruction of electrical equipment, and recovery time is driven by the duration of repairs and access to damaged equipment and facilities. **In contrast to earthquakes and floods, which affect individual components of the power grid, space weather events may affect the entire grid at the same time.** Damage to far less equipment by GICs can cause disproportionately greater damage to the power grid. First, GICs have a higher potential for catastrophic damage compared to earthquakes and floods. In this study, GICs were associated with a higher comparative frequency of catastrophic damage compared to earthquakes and floods. Second, the effects of space weather events are insidious and attack the power grid from within. GICs may cause the entire grid to collapse when multiple nodes go offline. Although there has been only one instance of network-wide collapse (the 1989 Quebec storm), it clearly demonstrates the potential for system-wide impact of GICs. Additionally, this study did not find instances of system-wide collapse cause by earthquakes or floods.

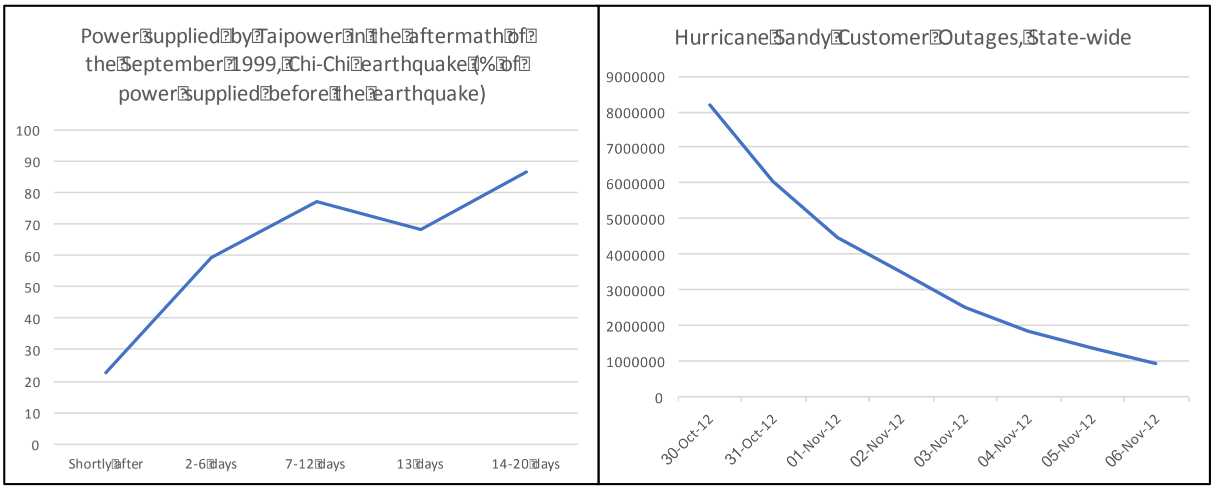
Irrespective of the cause, **system-wide damage can be exacerbated if the disturbance is allowed to propagate through multiple transmission lines**. Interconnections generally improve resilience against damage to individual components (cf. Section 5.1). Damage to critical nodes, such as substations, may be mitigated by rerouting power through other circuits, while the loss of generating facilities may be moderated if the remaining assets are able to cover the demand. Because earthquakes and floods affect only individual components, such as substations, generating assets and transmission lines, network theory suggests that interconnections increase the power grid's resilience. However, interconnections may also increase the grid's vulnerability, if they allow a disturbance to propagate and affect multiple components. Because quasi-DCs have the potential to cause system-wide damage, high network betweenness centrality may increase the vulnerability of an electric power network to GICs resulting from space weather storms.

Although the recovery timeframe may vary among different hazards, as illustrated in Table 6, recovery is always progressive. Figure 6 illustrates power grid recovery, quantified in terms of the number of power outage restorations in the aftermath of Hurricanes Katrina and Rita. Figure 7 illustrates the recovery of the power grid versus time in the aftermath of the September 1999, Chi-Chi, Taiwan earthquake and Hurricane Sandy. In all 4 cases, the recovery timeline is consistent with the concept of engineering resilience advanced by recent publications and guidance documents (Ganin et al., 2016). Although the shape of the plots is very similar, the time scale and recovery time are different in every case.

Table 6. Overview of damage types and natural hazard impacts on the power grid

	Earthquake	Space weather	Flood
Damage types	Structural damage due to inertial loading Foundation/ground failure	Damage to transmission and generation equipment from GICs Potential for system-wide impact	Damage to transmission tower foundations due to erosion and/or landslides Moisture and dirt
Contributing factors	Soil liquefaction No warning time	Early warning possible	Early warning possible
Most vulnerable equipment	Heavy equipment (e.g. generators, LPTs) Ceramic parts (e.g. bushings, bus bars) or equipment (e.g. transformers)	Equipment vulnerable to direct current (e.g. transformers) Equipment protected from DC excitation (tripping)	Transmission towers Substation equipment
Recovery time is driven by	Number of items in need of repair or replacement Access to conduct repairs	System-wide impact Delayed effects	Floodwaters recession (access) Number of items in need of repair or replacement
Recovery time range	A few hours to months; most commonly, 1 to 4 days	Power to areas serviced by equipment which has only tripped offline restored within less than 24 hours after the end of the storm Repairs of damaged equipment may take several months	Less than 24 hours to 3 weeks Longer recovery times (up to 5 weeks) with hurricane and/or storm damage

Figure 7. Left: Power supplied by Taipower in the aftermath of the September 1999, Chi-Chi, Taiwan earthquake, as a percentage of the power supplied before the earthquake). Right: Number of power outages reported after Hurricane Sandy landfall.



Source: Schiff & Tang, 2000; Manzfield & Linzey, 2013.

In addition, the recovery process may itself be disrupted and suffer setbacks. The power outage restorations in the aftermath of Hurricane Katrina, for example, were interrupted by the landfall of Hurricane Rita, which caused nearly 80% as many outages as Hurricane Katrina, and set back the recovery process by 23 days. In the case of solar storms, delayed effects of GICs, such as the transformer damage discussed in section 4.2, may also delay the recovery process.

5 Other factors affecting recovery time

The previous chapter discussed the impact of the damage caused by natural hazards on power grid recovery time based on physical damage. However, recovery time is also a function of the resilience of the critical electricity infrastructure subsector. This chapter describes the effect of natural hazards on the emergency response and recovery capabilities of electric utility operators and disaster-affected communities. Section 5.1 focuses on the resilience of electric power utilities. Section 5.2 describes how the disruption of other critical infrastructure may affect community resilience in terms of the power grid recovery time. Last, section 5.3 discusses how the impact of cascading disruptions of critical infrastructure, stemming from power outages, may feedback in the power grid recovery time.

5.1 Resilience of electric power utilities

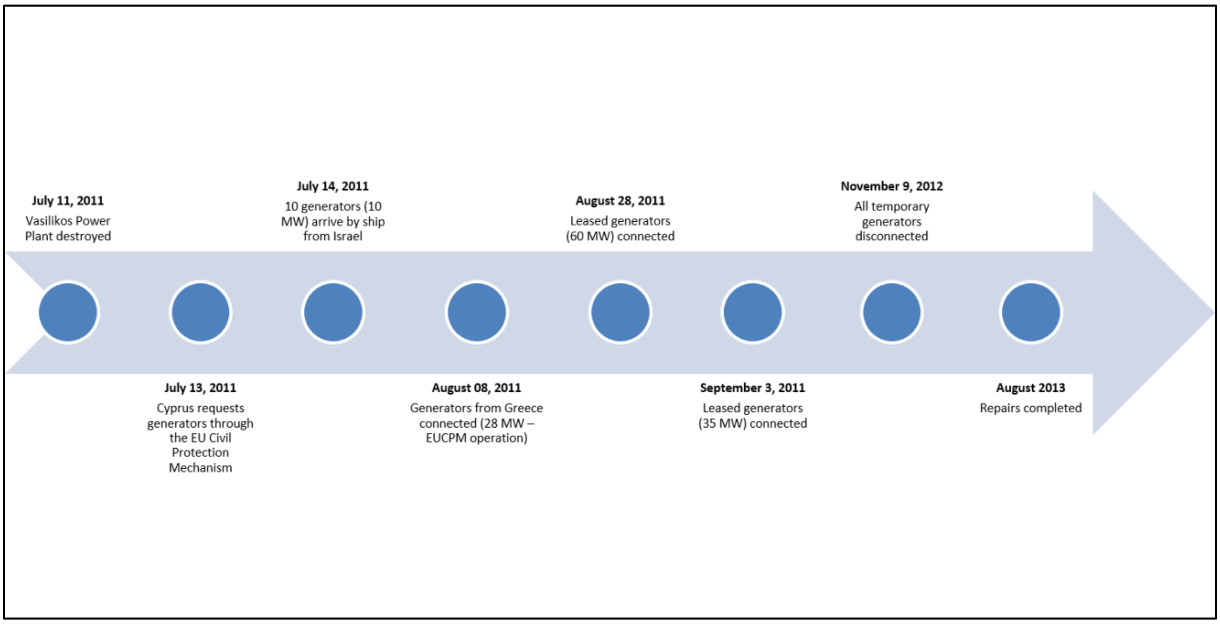
Chapter 4 illustrated the impact of the level of damage on recovery time. Although different natural hazards affect electric utilities in a different way, as the intensity of the hazard increases, the level of damage increases as well. As damage accumulates, more complex, time-consuming and costly repairs need to be conducted to restore power supply to customers and repair critical equipment and facilities. Therefore, recovery time is prolonged. However, for a given damage level, recovery time depends on the capability of the affected electric utility companies and TSOs to respond promptly and effectively. Emergency response capabilities encompass trained staff, adequate resources, and an appropriate organization.

Emergency diesel generators are typically used to quickly restore electricity supply to customers until repairs are conducted. In this study, this course of action has been effective in the aftermath of earthquakes or floods, when distribution cables have been severed or generation capacity is reduced. Emergency diesel generators can be procured by commercial suppliers or through mutual aid agreements, but their specifications need to be appropriate for the part of the grid they are connected to. Emergency planning can speed the response by identifying capability requirements and suppliers before disaster strikes. However, response-generated demands are notoriously underestimated by emergency operations plans (McEntire, 2007) and during incident planning (Karagiannis & Synolakis, 2017). Once an appropriate generator is located, **logistics becomes the single most important determinant of electricity supply restoration time in the affected area.** Medium-sized generators may be airlifted, but require large transport aircraft which may only be available to the military of a few countries. In addition to their limited availability, these aircraft come with constraints on runway bearing capacity and length. Larger generators may only be transported by ship. Furthermore, road transportation of heavy equipment, such as high-capacity generators and large power transformers, is likely to be challenging. Special trailers may have to be used and traffic may have to be redirected for a large truck to pass. The load bearing capacity of the road may have to be assessed before heavy equipment can be safely moved. It is not uncommon for several weeks to pass before heavy equipment arrives and can be put into service in the disaster-affected area.

The transportation of heavy equipment, such as emergency diesel generators, is further complicated by the operational friction that results from the overwhelming and often conflicting demands posed by disasters. In the aftermath of a natural disaster, the need to transport high-capacity generators is measured against the need to deploy search and rescue teams, emergency medical care resources and food to assist the affected population. In terms of disaster response logistics, a high-capacity generator rapidly takes up half the capacity of a large commercial transport aircraft. The choice is exceptionally difficult to make, especially in the early phases of disaster response, when emergency care and search and rescue are of paramount importance.

The destruction of the Vasilikos Power Plant in Cyprus in July 2011 points to the logistics challenges of using emergency diesel generators. Although the power plant was not destroyed by a natural hazard, but by an explosion of confiscated ammunition stored in the nearby Evangelos Florakis Naval Base, the effort to restore power supply shares many of the characteristics of natural disaster responses. The timeline of the operation (Figure 8) provides insight into the importance of logistics and preparedness of what has been identified as *one of the largest operations – both in terms of value and size – ever conducted through the EU Civil Protection Mechanism by a single country* (DG ECHO, 2012). The Vasilikos Power Plant contributed 50% of Cyprus' production capacity, and its destruction resulted in power outages all over the island. Cyprus requested international assistance, including through the EU Civil Protection Mechanism. It took more than 90 days for generators of a total capacity of 165 MW to ship to Cyprus from various locations and get connected to the grid. Among others, generators of a total capacity of 70 MW were shipped from Greece, and this operation was co-funded by the Civil Protection Financial Instrument of the European Commission. Repairs to the power plant were completed 25 months after the explosion and cost more than €43 million (EAC, 2013). In the meantime, the Cypriot government advised customers to limit power usage, and resorted to buying power from external sources. In addition to being a realistic demonstration of the dynamics of long-term power outage, this operation also highlights the role of the European solidarity and the Union Civil Protection Mechanism in critical infrastructure resilience.

Figure 8. Power grid recovery timeline following the 2011 explosion at the Evangelos Florakis Naval Base, Cyprus



Source: Adapted from DG ECHO (2012), Kathimerini (2011), Naftemporiki (2011), EAC (2011, 2012, 2013)

In addition to production capabilities, the availability of spares used to replace damaged equipment or parts can reduce recovery time. For instance, when the Kocaeli, Turkey earthquake of August 17, 1999 happened, the transmission system was undergoing a major expansion. Therefore, new equipment and materials were readily available, and helped speed up the recovery process. The availability of spares depends almost entirely on cost versus benefit. Electric power utilities, TSOs and DSOs often maintain stocks of small size and relatively inexpensive equipment for maintenance and emergencies. The availability of these spares helps expedite the repair of distribution lines, and transmission and distribution substations. However, spare LPTs are difficult to maintain, because of their high cost and specificity. In some cases, parts may be salvaged by out-of-service equipment to conduct repairs, but this may not always be possible.

In addition to preplanning, political support can also go a long way in enhancing the restoration and repair capabilities of electric utilities. For example, after the Lushan, China earthquake of April 20, 2013, the Chinese Prime Minister issued an executive order prioritizing the need for functioning lifelines. As a result, the repair of transmission substations damaged by the earthquake was expedited. The Lushan 110 kV substation was among the most severely damaged, including the loss of 40% of the equipment in the 110 kV switchyard. A crew of 110 technicians repaired the switchyard in a record time of 3 days and restored a 110 kV transformer 28 days after the earthquake (Eidinger, Tang & Davis, 2014).

In addition to restoration capabilities, **network interconnections also increase resilience, not by speeding repairs, but by providing alternative power supply routes.** These often make it possible to reroute power from other sources quite quickly and minimize the duration of power outages while repairs are being conducted. For instance, after the Kocaeli, Turkey earthquake of August 17, 1999, power received from Bulgaria, Georgia and Iran was used to restart power plants outside the affected area (EPRI, 2001). In the aftermath of the 1989 Quebec blackout, caused by GICs from a geomagnetic storm, power rerouted from New Brunswick, Ontario, New York and New England was used to temporarily restore power supply to customers while repairs were underway (OECD, 2011). By the same token, independent power producers also increase the resilience of electric utilities by providing alternatives for temporary restoration of power supply to either domestic users or critical customers, such as hospitals and industry). For example, 5 days after the Chi-Chi, Taiwan earthquake of September 21, 1999, power from an independent producer was used to restore electricity supply to the high-tech facilities at the Hsinchu Science Park, the disruption of which was already affecting the global computer industry (Schiff & Tang, 2000). Nonetheless, interconnections may also contribute to damage from GICs, as discussed in section 4.4.

Last, **network configuration may also increase the resilience of electric utilities**. Grid configurations allow the network to be modified in case of failure of one or more nodes and arcs, by opening and closing switches. Switches may be controlled automatically, manually, or remotely from a control room using SCADA systems. Subtransmission and distribution circuits are usually arranged in non-radial grid configurations. Therefore, even catastrophic damage to individual facilities or components may result in shorter outages because utility operators are able to divert power through other parts of the network. For example, when the small distribution substation at Sumner Redcliffs was destroyed by a rockfall triggered by the February 22, 2011, earthquake in Christchurch, New Zealand, the disruption was minimal, because the DSO was able to bypass the substation using the existing network (Tang, 2016). On the other hand, **radial networks have less redundancy**. For instance, four transmission lines were used by Taipower (Taiwan Power Company) to carry power from the south and central parts of the island to the north, where demand exceeds generation supply. The loss of a single transmission tower, which carried two of these circuits during the Chi-Chi, Taiwan earthquake of September 21, 1999, severely compromised Taipower's capability to carry power to the north of the island, and contributed to a long-term blackout (Schiff & Tang, 2000).

5.2 Disruption of other critical infrastructure

The previous section presented the impact of repair and restoration capabilities, and network topology on the resilience of electric utility companies. This section is a discussion of "second-order" effects of natural hazards on the power grid recovery time. In other words, it explores how the disruption of other critical infrastructure, caused by natural hazards, may affect the repair and restoration of the electricity supply. Of all critical infrastructure, **the disruption of transportation and telecommunications posed the most significant threat to the recovery of power systems in this study**. Table 7 outlines the damage from earthquakes, space weather and floods.

Table 7. Impact of earthquakes, space weather events and floods on critical infrastructure sectors other than the power grid

	Earthquake	Space weather	Flood
Transportation	Structural damage to ports, airports, bridges, roads and railroad tracks. Debris may block road and rail transportation. Tsunamis may damage port infrastructure.	GNSS unavailability and/or positioning errors (navigation). Radiation risk to avionics. Minor disruption to road and railway transportation.	Flooding of roads and railway tracks. Obstruction of roads due to debris left by floods. Traffic congestion associated with evacuation may delay preventive shut down.
Communications	Structural damage to cell towers and two-way radio repeaters. Cell phone network congestion.	HF radio communications blackout. Satellite communications affected. Cellular network base stations and two-way radio repeaters could experience increased static at dawn and dusk.	Inundation of telecommunications systems facilities and assets.

The following sections describe how the power grid recovery time is affected by the disruption of transportation and communications caused by earthquakes, space weather and floods.

5.2.1 Earthquakes

Earthquakes wreak havoc on air, sea and land transportation infrastructure. Ground failure and structural damage are the most common causes of disruption. Airport runways may be severely damaged from ground failure, while operations may be severely compromised due to structural damage to the control tower, terminals and other buildings. Aircraft refueling may be impossible if fuel tanks and pipelines, which are often located inside airports, suffer damage from inertial forces or soil liquefaction. Liquefaction of loose, saturated and sandy soils and fills is the primary cause of damage to ports. It results in excessive deformation of dikes, retaining structures and pavements, failure of pile supports and damage to port buildings (Schiff & Buckle, 1995).

Damage to ports and airports can hinder the transportation of critical equipment or parts, and can cause significant delays to the recovery process. In addition, the disruption of sea and/or air transportation can **delay the delivery of key resources, such as fuel for emergency diesel generators**, thus further exacerbating power outages. Islands are particularly vulnerable to port and airport transportation disruptions. For instance, when the Vasilikos Poser Plant in Cyprus was destroyed in 2011, the country’s ports and airports were not affected. All emergency diesel generators used to temporarily restore power supply to the affected area were brought in by boat. Therefore, the restoration and recovery process would have certainly taken significantly longer if sea and/or air transportation had been compromised.

In addition to ports and airports, road and railroad transportation networks are also susceptible to earthquake damage. Road and railroad bridges are the most vulnerable part of these networks. The most common failure mechanism is damage to the substructure and foundations. The **unavailability of bridges may delay restoration and repairs, as personnel and equipment need to find alternative routes to reach the affected areas**. Road pavements are principally affected by ground failure, such as liquefaction. Damaged pavements may become unpassable by trucks and trailers, which usually carry much needed heavy equipment, such as generators and replacement transformers. The need to find alternative routes will prolong the recovery process. Another common reason of road closure is landslides, especially in mountainous regions. Transmission towers are often in mountainous areas, and may only be accessible by narrow, winding, unpaved roads. Roads need to be cleared of debris before repair crews can access the site to assess the damage. After the Chi-Chi, Taiwan earthquake of September 21, 1999, the replacement of the collapsed transmission tower which had been supporting two of the four lines carrying much needed power to the north of the island was delayed for 3 days until the access roads were cleared. Only after access was re-established could replacement parts be brought to the site.

Furthermore, traffic congestion is not uncommon in the immediate aftermath of major earthquakes. Traffic jams are caused in urban areas, as people attempt to self-evacuate for fear of aftershocks. Unfavorable traffic conditions are likely to delay the movement of repair and maintenance crews, and hinder the recovery process in the early hours of the response. Nevertheless, traffic congestion usually subsides within a few hours of the earthquake.

Other than because of the disruption of the transportation infrastructure, the **recovery of the power grid after an earthquake may be hindered by the failure of telecommunications systems**. Electric utility companies **rely on two-way radios and/or cellular telephones to coordinate repair and maintenance crews** in daily and emergency operations. Both telecommunications systems were damaged by earthquakes reviewed in this study. In several cases, seismic forces caused structural damage to two-way radio repeaters and mobile network cell towers. Without a working repeater, two-way radios can only support line-of-sight communications, which are practically useless in urban areas. When a cell site is damaged, mobile phone service in the cell is lost until another antenna takes over or the damaged antenna is fixed. In addition, cell phone networks were often congested in the immediate aftermath of earthquakes, as people sought to communicate with family members and loved ones in the affected area. Cell phone congestion usually subsided within a few hours or days after the earthquake. However, without working communications, electric utility companies had a hard time coordinating repair and maintenance crews, which arguably slowed down the recovery process.

5.2.2 Space weather events

Space weather events may affect transportation systems, but in a different way than earthquakes. First, solar flares[26] may disrupt Global Navigation Satellite Systems (GNSS), such as the Global Positioning System (GPS) and Galileo. These systems may experience outages of navigation signals on the sunlit side of the Earth, causing loss of satellite positioning capabilities. In addition, there may be increased errors in positioning, which tend to be concentrated to the sunlit side of the Earth, but may extend into the dark side as well in extreme cases. Avionics can be affected and HF radio communications compromised. Solar radiation storms[27] may seriously damage satellites, cause a complete HF blackout through the polar regions, and expose passengers of airliners flying over high latitudes to radiation risk. The reduced availability and reliability of satellite navigation and HF radio blackout affect air and maritime navigation, causing routes near the poles to be diverted (Krausmann et al., 2015). This may result in a moderate delay of the delivery of equipment and supplies to the affected areas and prolong the recovery process.

The disruption of GNSS may also cause cascading failures in the future[28]. Present-day electric power networks use, among others, synchronized measurements from devices called Phasor Measurement Units[29] (PMUs) to monitor the state of the system (Phadke, 1993; Shepard, Humphreys & Fansler, 2012). This technique may become a key component of future smart grids. However, synchronized phasor measurements rely on accurate timing. To this end, PMUs are usually synchronized to the common time source of a GPS clock, while atomic clocks provide redundancy. It has been demonstrated that the disruption of the GPS signal can distort the measurements made by PMUs and project an erroneous picture to system controllers. If these measurements will be used as the main input for system control in the future, then the offset signal would trip the components of the grid which would erroneously appear as out of phase. Because GPS timing is gaining popularity as a timing source for synchronized phasor measurements it argued that, if it came to be used as the exclusive timing source, then power grids would become highly vulnerable to space-weather-induced disruption of the GPS signal (Krausmann et al., 2013).

([26]) Solar flares are large eruptions of electromagnetic radiation from the Sun. They travel at the speed of light, and last from minutes to hours. The increased level of radiation disturbs the lower levels of the ionosphere on the sunlit side of the Earth. As a result, High Frequency (HF) radio waves, which are normally refracted in the upper layers of the ionosphere, can become degraded or completely absorbed. This causes a HF radio blackout. GNSS receivers can also be impacted.

([27]) Solar radiation storms include particles (mostly fast-moving protons). They are caused by solar magnetic eruptions and are often associated to coronal mass ejections and solar flares. Accelerated protons can reach the Earth in just 30 minutes. They penetrate the magnetosphere and travel on the magnetic field lines until they penetrate the Earth’s atmosphere near the poles. These energetic protons present a radiation hazard, and can cause damage to electronics and biological DNA. They can also create a HF radio blackout by ionizing the lower level of the ionosphere.

([28]) Synchronization is the process of ensuring that the frequency of the current flowing through a network is the same across the entire grid. Synchronization is of paramount importance to the operation of AC networks. An AC generator can only provide power to an electrical grid if both are running on the same frequency. If two parts of the grid are disconnected, they can only exchange power after they have been re-synchronized in case of an AC interconnection between them. Currently in Europe there are 5 different synchronous areas, all of which operate at 50Hz.

([29]) A phasor or phase vector is a basic construct in AC circuit analysis. In mathematical terms, it is a complex number representing a sinusoidal function with constant amplitude, angular frequency and initial phase. It allows to analyze AC circuits by transforming all electric current waveforms in vectors, which are easier to manipulate in calculations.

Road and rail transportation may also be disrupted during space weather events. Power transformers mounted on electric trains can be damaged by quasi-DC currents in the same way as transmission line transformers. Signaling may also be affected. For instance, during a geomagnetic storm that hit the Earth on July 13-14, 1982, railway traffic lights in Sweden turned erroneously to red (Wik et al., 2009). However, the disruption of road and railway signals due to space weather will only cause a minor concern to power grid recovery efforts.

In addition to transportation, the disruption of telecommunications systems may slow down the recovery process. Solar flares and solar radiation storms can cause an HF radio blackout, but electric utilities do not use them for neither everyday nor emergency communications. On the other hand, there may be a minor disturbance to two-way radio and cellular systems. Specifically, cellular network base stations and radio repeaters (including two-way radio and TETRA, used by most electric utilities) could experience increased noise at dawn and dusk for the parts of the network facing the sun. Nonetheless, it is unlikely that space weather events will cause a blackout of these systems, and the disruption is expected to be minor.

5.2.3 Floods

Floods affect transportation and telecommunications systems alike. **Access to inundated facilities was a major determinant of the power grid recovery time in this study.** As discussed in section 4.3, substation repairs can only be conducted once the water has receded and the substation is on dry land. In addition, floodwaters may block access to electrical utility assets and facilities, and further delay the repair and restoration. Inundated roads and railway tracks, and impassable bridges are among the most typical consequences of floods. **In the aftermath of a major flood, access to substations, transmission towers and other facilities may be possible only by boat**, which makes bringing in heavy or sensitive equipment impossible. Furthermore, the hydrology of inundated areas is unknown, and is notorious for presenting many hazards even to flood rescue operations (Ray, 2013). Therefore, boat operations supporting power grid repairs may have to be gauged against the risk to boat operators and repair crews from water travel alone. In this case, power grid repairs may have to be delayed until flood waters have receded and the damaged facilities or assets become accessible by road.

Floods, like earthquakes, may also be associated with traffic congestion. The difference is in the timing of the excess traffic with respect to the occurrence of the hazard. Traffic jams usually occur in the immediate aftermath of an earthquake and subside shortly after, as discussed in section 5.2.1. On the other hand, traffic jams are a typical phenomenon before the onset of a flood, especially in areas which are evacuated. For instance, traffic congestion during Hurricane Isaac in 2012 delayed the delivery of emergency portable generators and the restoration of the power grid (Miles et. al, 2016).

In addition to transportation, floods may also affect telecommunications. First, telecommunications systems facilities and assets may be inundated. Telecommunications electronics are potentially even more sensitive to the intrusion of moisture and dirt than electric utility equipment. For example, during the monsoon-driven floods of South Indian of November and December 2015, telecommunications companies in Chennai, the capital of the Indian state of Tamil Nadu, reported that network services were disrupted because backup generators of critical sites were inundated and failed to operate (Narasimhan & Babu, 2016). In addition, strong winds associated with storms and hurricanes may knock down cell site towers while the rainfall is causing the water level to rise.

5.3 Cascading effects

The previous section outlined the impact of earthquakes, floods and space weather on critical infrastructure other than the electricity subsector, and how these disruptions undermine the power grid recovery. This section explores another aspect of the interdependencies among critical infrastructure. **Electric power is the utility on which most other critical infrastructure sectors rely for daily operations.** Therefore, a prolonged power outage is likely to adversely affect many critical infrastructure sectors which lack redundant systems, such as backup generators. However, **some of these sectors may be supporting emergency repairs and the power grid restoration effort.** This produces a vicious circle, in which the disruption of the power grid caused by a natural hazard adversely affects other critical infrastructure sectors, the disruption of which undermines the recovery of the power grid. What follows is a discussion of how power outages cascade into other critical infrastructure sectors, and how the disruption of the latter prolongs the recovery of the power grid. Specifically, two sectors have been identified in this study are telecommunications and emergency services.

5.3.1 Telecommunications

As noted in section 5.2.1, electric utilities use two-way radios and cellular telephones for daily and emergency telecommunication with repair crews. Two-way radios need repeaters to operate beyond line-of-sight and cellular networks rely on transceivers mounted on cell towers. Both facilities need electricity to work, and are connected to the electricity grid. To mitigate against power outages, both types of facilities are equipped with backup batteries or generators. However, batteries can only keep the network running for a limited amount of time. When the batteries run out, communications with the areas serviced by that cell tower is lost, and two-way radios are only effective within line-of-sight distances. The duration of the battery supply differs from one country to another. For example, cell sites in Japan have 30 hours of reserve battery power, and some ran out in after the Niigataken-Chuetsu-Oki earthquake of July 16, 2017. On the other hand, 1,500 cellular base stations went out of service due to power failure 3 hours after the Chi-Chi, Taiwan earthquake of September 21, 1999. Cell sites in the United States also have 3 hours of battery power (Schiff & Tang, 2000; Tang & Schiff, 2007).

In addition, generators require a steady supply of fuel to keep working. For instance, many cell sites in the Lushan Province, China ran on power generators up to 20 days after the Lushan earthquake of April 20, 2013. About 80 generators had to be brought in (some using military air transportation) to maintain or restore telecommunications coverage in the affected area in the aftermath of the Christchurch, New Zealand earthquake of February 22, 2011 (Eidinger et al., 2014; Tang, 2016). However, fuel for backup generators may not be available in the aftermath of a natural disaster, or limited resources may be prioritized to other activities.

The insufficiency of reserve power was a recurring problem in this study. There were numerous reports of cell sites running out of battery power during prolonged power outages, or backup generators failing to start or lacking fuel. The resulting **loss of two-way communications between a power utility and its repair crews has been a major determinant of the power grid recovery time.** Several utilities reported that restoration of power to customers was hindered and/or delayed because of the lack of communications between head offices and repair crews.

5.3.2 Emergency services

The disruption of telecommunications probably affects emergency services more severely than any other critical infrastructure sector. With the transition from the traditional to the professional paradigm (McEntire, 2006), the number of responding organizations in any given disaster has risen sharply and horizontal relationships between these organizations are emphasized. As a consequence, emergency management has become even more telecommunications-intensive. Present-day emergency services worldwide use two-way radios and cellular telephones intensively during the disaster response phase. When both run out of power, fire/rescue, ambulance, police and other agencies fall back to their redundant systems. For example, emergency services in Taiwan routinely use cell phones for day-to-day tactical communications. When cellular service went down in the aftermath of the Chi-Chi earthquake of September 21, 1999, they had to resort to using satellite telephones for tactical communications (Schiff & Tang, 2000). In another example, during the 2015 Lancaster, UK, flood the resulting power outage took out most modern communications systems in the affected area, leaving residents with nothing but local radio stations for receiving disaster-related information. After their studio was inundated, the main radio station in the area could only obtain updates through a landline from a reporter dispatched to an unaffected location, and broadcast out of an improvised alternative office using a backup generator (Ferranti et al, 2017).

The lack of telecommunications may also affect early warning. Perhaps the most flagrant example is the Tonga tsunami of May 4, 2006, when a tsunami warning issued from the Pacific Tsunami Warning Center (PTWC) was not received because of a short island-wide power blackout (NBC News, 2006). Although PTWC eventually cancelled the warning, the consequences of a larger tsunami would have been potentially devastating due to the lack of warning. In addition to the potential for widespread human losses, if the earthquake had generated a larger tsunami, the early warning could have bought the island's power utilities time to take protective action to mitigate the damage from the tsunami surge, such as preemptively shutting down facilities and assets in the inundation zone.

6 Discussion and recommendations

Electricity is the one critical infrastructure sector upon which all others depend. A reliable supply of electric power is a major underpinning of the economy of the European Union and its Member States. This study has outlined the impact to the power grid from earthquakes, space weather and floods, and how the recovery time may differ based on the type of damage sustained by each hazard.

We found that different hazards affect the power grid in a different way. Earthquakes cause inertial damage to heavy equipment and brittle items, such as ceramics, and ground failure and soil liquefaction can be devastating to electric infrastructure assets. Equipment anchoring was the most effective mitigation strategy we identified, and site selection can arguably reduce the exposure to ground failure. Recovery time is driven by the balance of repairs and capabilities. Poor access to damaged facilities, due to landslides or traffic congestion, can also delay repairs. In this study, recovery time ranged from a few hours to months, but more frequently from 1 to 4 days.

Erosion and landslides triggered by floods undermine the foundations of transmission towers. Serious, and often explosive, damage may occur when electrified equipment comes in contact with water, while moisture and dirt intrusion require time-consuming repairs of inundated equipment. In contrast to earthquakes, early warning is possible, and enables electric utilities to shut off power to facilities in flood zones, therefore minimizing damage. The most effective mitigation strategies included elevation, levees and locating critical facilities outside the flood zone. Recovery time was driven by the same parameters as in the case of earthquakes, namely the sheer number of needed repairs, and access as repairs cannot start until floodwaters have receded. In this study, power was back online from 24 hours up to 3 weeks after the flood. However, longer recovery times (up to 5 weeks) were associated with floods spawned by hurricanes and storms.

Space weather affects transmission and generation equipment through GICs. In contrast to earthquakes and floods, GICs have the potential to affect the entire transmission network. Although some early warning is possible, warning lead times are typically very short and existing forecasting capabilities need to be improved to provide transmission system operators all the information they need for preparing for a severe event. Delayed effects and the potential for system-wide impact were the main drivers of recovery time in this study. When damage is limited to tripping of protective devices, restoration time is less than 24 hours. However, repairs of damaged equipment may take up to several months.

The following is a discussion of the findings of this study with a view to producing a set of recommendations for policy development, hazard mitigation and emergency management.

6.1 Policy recommendations

From a policy perspective, the main challenge is harmonization of the multiple policy areas which affect the safety and security of Europe's electricity supply. Jurisdiction over management of the risk to the electric power grid from natural hazards is spread over several administrative levels. At each administrative level, electricity supply involves a multitude of public and private stakeholders, and authority over risk management is spread horizontally over many actors. Policy-level recommendations focus on improving harmonization with a view to streamlining power grid resilience efforts.

At the European Union level, the protection of electricity from natural hazards is addressed in energy, civil protection and critical infrastructure policies. Energy-related regulations focus on maintaining generation/demand balance. Risk assessments are geared towards ensuring security of supply, and address natural hazards only implicitly. Civil protection regulations require Member-States to produce comprehensive national risk assessments, and several Member-States have included the disruption of the electricity subsector in their national risk assessments. However, current disaster risk assessment guidance documentation focuses on human and economic losses, and does not specify how critical infrastructure may be included in national risk assessments. Critical infrastructure protection policies require System Operators to develop and maintain Operator Security Plans addressing the risk of disruption from major threat scenarios. These policies focus on critical infrastructure from a resilience perspective, and highlight the interdependencies among various critical infrastructure sectors. However, there is no explicit requirement for addressing natural hazards, and the current trend is to prioritize man-made threats.

Each of these existing policies tends to focus on one aspect of the power grid resilience. Without a complete picture of the natural hazards facing the electricity grid, energy-related regulations may be protecting the power grid against the wrong hazards. Without a proper understanding of the capabilities and resilience of the power grid, civil protection plans may be calling for the wrong mitigation and response measures.

In addition, each of these policies establishes another set of regulatory requirements and places an additional burden on Member State authorities and System Operators. For example, a TSO may need to develop an Operator Security Plan, because it is a critical infrastructure, cooperate with the Member-State’s National Civil Protection Authority to develop the National Risk Assessment, and (once the proposed Regulation on risk-preparedness in the electricity sector is approved) work with a Regional Operation Center to develop a crisis risk assessment. Besides the added burden, there is a risk of confusion stemming from each of these strategic documents addressing another hazard. For example, the NRA may be based on the 100-year flood, the crisis risk assessment on the 50-year flood, while the OSP may not include floods at all. Each document may suggest different flood protection measures for the utility’s facilities, and add to the economic burden of maintaining a reliable electricity supply. In addition, the emergency plans produced based on each strategic document, may be built on a different set of assumptions and dictate a different set of measures. Early disaster research has pointed out the risk for confusion stemming from the use of multiple plans to manage a single incident (Auf Der Heide, 1989).

The resilience and electricity supply can benefit from better harmonization among energy, civil protection and critical infrastructure policies. Harmonization does not involve the development of a new policy area, rather the alignment of the requirements established by each policy, as outlined in the following two recommendations:

Recommendation 1: *Whenever possible, risk assessments should use a consistent set of scenarios.*

Using a consistent set of scenarios in the risk assessments required by each policy is expected to support the development of collaborative thinking about strategic needs across all risk management phases. It would also help public and private organizations involved in the energy subsector across all administrative levels to share a common understanding of all hazards and threats the power grid faces and the resulting risks. At least one Member State has used a consistent set of scenarios to conduct both the National Risk Assessment, under the Union Civil Protection Mechanism Council Decision, and the identification of critical infrastructure, under the European Critical Infrastructure Directive. The initiative was praised as a good practice by the Peer Review exercise that ensued (Falck, 2016).

At the European level, the seasonal outlooks produced by ENTSO-E on a bi-annual basis should consider at least the natural and technological hazards outlined in the Overview of Natural and Man-made Disaster Risks (EC, 2017) in the direction of being evolved into a full vulnerability analysis, at least for the risks with cross-border impact. The proposed Regulation on risk-preparedness in the electricity sector could be amended to include a similar requirement. At the Member State level, critical infrastructure protection agencies could consider requiring identified National Critical Infrastructure Operators to include in their OSPs at least the scenarios identified in the National Risk Assessment.

Recommendation 2: *Risk management efforts should be integrated to maximize efficiency.*

Using the same set of scenarios across all risk assessments can provide a common base for integrating risk management efforts and making the best of each policy area. For example, a Member State's National Risk Assessment may identify an earthquake scenario. Based on this scenario, the National Civil Protection Authority of this Member-State may develop a hazard mitigation strategy, eventually supported by an action plan. A TSO may use that earthquake scenario to develop its Operator Security Plan. The OSP will likely describe the impact of that scenario on the security of electricity supply in further detail compared to the NRA. It will also suggest a strategy and action plan for the TSO to reduce the risk of disruption of its system. The measures stipulated in the OSP should be integrated with the national risk mitigation strategy, to maximize the benefit/cost ratio of the interventions and reduce the risk stemming from prolonged power outages to a minimum.

6.2 Hazard mitigation recommendations

In addition to recommendations related to policy, the findings of this study have demonstrated that power grid resilience can benefit from targeted action aimed at mitigating the hazard facing the power grid.

Recommendation 3: *Transition from hardening system assets and facilities to building resilience into the grid.*

Traditional hazard mitigation strategies have focused on strengthening components of the power grid, such as equipment and buildings, based on the expected level of risk. For example, if a risk assessment indicates that a substation is exposed to a flood hazard, utilities may elevate sensitive equipment and/or buildings, or build a levee to protect the substation. However, given the aleatory and epistemic uncertainties of risk assessments, hardening measures may be decided based on poor information. For example, a risk assessment may use, e.g. a 100-year flood scenario as the basis for a hazard mitigation strategy. However, current climate change projections indicate an increased frequency of severe hydro-meteorological events (Field et al., 2014). In addition, grid hardening measures may be prohibitively expensive or impractical (Abi-Samra, 2013). One example is the proposal to bury distribution cables of the State of North Carolina, which was estimated to cost nearly six times the net books value of the distribution assets of all State DSOs (North Carolina Public Staff Utilities Commission, 2003). The cumulative cost for hardening the grid against several hazards would likely be impossible to bear by a single utility.

On the other hand, building resilience into the grid would not focus on preventing damage from a single hazard, but rather to enable the System Operator to continue functioning when critical parts of the system are taken out of service and promptly return to normal operations after a disruption. Resilience requires a change in design to allow the grid to be reconfigured in response to various threats and to enhance the speed of repairs. One approach is to split a large network in microgrids[30] to establish self-sufficient "islands" which will remain operational if electricity supply from the larger grid is disrupted. An assessment of how long the microgrid will be expected to operate independently is necessary. For example, although most of New York was in the dark shortly after Hurricane Sandy made landfall, several locations were unaffected because they had backup generation capabilities and could operate independently of the main power grid (Abi-Samra, 2013). In addition, use of smart grid technologies will allow power grid operators to automate the process of detecting an outage and reconfiguring the grid to reroute power to the affected area through available circuits. Spreading the investment over several fiscal years may be a feasible way to finance the design change. Despite the attractiveness of

([30]) Microgrids are electrical networks which operate either autonomously or inside a larger grid. A microgrid needs at least one distributed energy source, such as a backup generator, or energy-storage capabilities, such as a battery installation. In case of power outage, these backup energy sources provide power to the microgrid and, once the larger grid is back online, they can be disconnected with little or no disruption.

the idea, however, its implementation will require extensive operational and regulatory changes.

Recommendation 4: *Assess the resilience of the entire European power grid to extreme space weather.*

Within the ENTSO-E area, each TSO maintains jurisdiction over their network. Several European countries, such as the UK and Sweden, have compiled vulnerability assessments of their grids against space weather scenarios (Krausmann et al., 2016). However, because most of continental Europe's transmission systems are interconnected, the GIC-excitation from space weather can propagate beyond the initial area of onset and affect countries beyond those typically exposed to high GIC risk. Therefore, a comprehensive analysis of the vulnerability of the European grid against extreme space weather scenarios is necessary to improve the understanding of Europe's risk and help build cost-effective resiliency in the European electricity market.

6.3 Emergency management recommendations

The findings of this study consistently emphasize the value of disaster preparedness for electric utilities. The following recommendations focus on the development of emergency plans, stockpiling repair parts and materials, ensuring interoperability, and prioritizing repairs to critical customers.

Recommendation 5: *TSOs/DSOs should develop, implement and exercise emergency operations plans. These plans should be updated when gaps are identified, e.g. in case of climate change.*

The findings of this study have consistently demonstrated the need for System Operators to develop, implement and exercise comprehensive outage management plans before disaster strikes. Although it was not always clear in this study whether System Operators had prepared emergency operations plans, existing arrangements worked systematically well. These emergency plans should describe emergency repair and recovery actions, assign responsibilities, identify resources, and address coordination and communication (Perry, 2007). They should also establish emergency rosters of, including on-call arrangements for, qualified personnel available to respond to natural disasters or other incidents. In addition, plans should address communications with other responding organizations, information management, logistics and communication to customers. The use of Outage Management Systems (OMSs) helps to prioritize restoration of power, as well as to dispatch, track and manage repair crews (Abi-Samra, 2010). Emergency operations plans developed by System Operators need to be integrated and aligned with emergency response plans developed by local, regional and national civil protection agencies to ensure all disaster- and response-generated demands are covered without duplication of effort. The development of a guidance document for emergency planning by TSOs and DSOs, which is lacking in Europe, would arguably help to harmonize disaster preparedness efforts. Emergency plans should be updated when gaps are identified and to take into account changing boundary conditions, e.g. in case of climate change.

In addition to developing emergency plans, TSO/DSOs should participate in disaster exercises. Exercises aim at training personnel and putting emergency response systems to the test under realistic conditions. They help assess emergency management systems, and identify strengths and areas for improvement. As a rule of thumb, System Operators should conduct an internal drill at least once a year to exercise their internal incident management system (Abi-Samra, 2010). Also, TSOs/DSOs should participate in local, regional, national and international civil protection exercises. DG ECHO should encourage the participation of TSOs/DSOs to simulation exercises co-funded by the UCPM Financial Instrument. Last, TSOs/DSOs would likely benefit from a comprehensive yearly exercise program, starting with one or more training drills using the OMS, followed by an internal functional exercise to test their incident management system, and concluding with the participation to a regional or national civil protection exercise.

Recommendation 6: *Stockpile spare items to expedite the repair or replacement of key assets and equipment.*

The availability of spares and replacement parts and equipment for critical assets and facilities was a critical need throughout this study and often made the difference between a speedy and prolonged recovery. Repairs were faster whenever spare parts were readily available. For instance, switchyard equipment was always faster to repair, because spare parts are less expensive and easier to acquire and store in sufficient quantities. On the other hand, repairing or replacing Large Power Transformers was often cited as a major challenge. Electric utility companies maintain a stock of spare items to handle daily repairs and minor emergencies. Extending these stocks to cover natural disasters and other major emergencies is a form of self-insurance and can expedite repairs and ultimately reduce the duration of outages.

Recommendation 7: *Ensure interoperability among neighboring TSOs, TSOs and DSOs, and between TSOs/DSOs and emergency management organizations.*

Natural disasters and other emergencies may rapidly overwhelm the repair capabilities of a single System Operator. Throughout this study, TSOs/DSOs which were severely affected by natural disasters requested assistance from neighboring companies. For example, in the aftermath of Hurricane Katrina, power companies in the affected areas brought in repair crews and materials from 23 States and Canada. This speedy mobilization was possible because power companies received early warning about the hurricane, had developed and exercised internal emergency plans, and had established mutual aid agreements with neighboring companies beforehand. Two lessons can be identified from the response to Hurricane Katrina.

First, mutual aid agreements have been an invaluable instrument of resource surge in several emergency response mission areas (including rescue and medical care), and can arguably help System Operators to rapidly expand their repair capabilities to respond to the added requirements of major emergencies. TSOs/DSOs should be encouraged to enter mutual aid agreements with other operators in neighboring regions and even Member-States. However, the rapid surge of capabilities often generates an entirely new set of demands. After Hurricane Katrina, Mississippi Power had to operate 18 temporary shelters for 11,000 staff and 12 logistics sites to manage the extra material. In addition, interoperability with external capabilities may be a major concern. For example, when freezing rain battered Slovenia in January 2014, over 250,000 people were left without power, some for more than 10 days. At the peak of the response, more than 1,500 people worked to restore power, including, among others, foreign expert workers. The language was an obstacle to effective operations, and foreign workers needed to be led by local personnel (OSCE, 2016). Although this case is taken from a different natural hazard than those which are the focus of this study, it points out the need for TSOs/DSOs to work with neighboring companies to ensure interoperability with mutual aid resources before disaster strikes.

Second, TSOs/DSOs need to maintain interoperability with the emergency management community in their area of operation. Ideally, System Operators should participate in emergency management committees at least at the national level. By maintaining interoperability with the emergency management organization, TSOs/DSOs can streamline their risk assessments and preparedness efforts (as discussed in section 6.1 above), receive early warning, and rapidly access surge capabilities which would not be available otherwise. For example, because Powerlink Queensland (2011) sat in the State Disaster Coordination Committee, it had access to daily meteorological briefings, aerial resources and boats in the aftermath of the 2011 Queensland, Australia floods. In another example, when the Vasilikos Power Plant was destroyed by an explosion in the adjacent Evangelos Florakis Naval Base in Cyprus, the Cypriot Government requested generators through the then European Union Civil Protection Mechanism. Among others, generators of a total capacity of 71 MW were shipped from Greece. Although the generators were sent by Greece authorities to their Cyprus counterparts, the logistical and administrative part of the operation was handled by the respective Civil Protection National Authorities, and the operation was co-funded by the Civil Protection Financial Instrument of the European Commission.

Recommendation 8: *Prioritize repairs to critical customers.*

Critical customers need to be identified before disaster strikes, so that repairs can be expedited. Critical clients may include oil and gas refineries, water-treatment plants, telecommunication networks, service stations, hospitals, pharmacies and other facilities. This needs to be a concerted effort involving the emergency management community, the TSO/DSO and critical customers.

Critical customers should be identified ideally during the development of emergency operations plans. The latter should include a list of the critical clients, location, an indication of the potential consequences of the outage, the minimum power required to maintain functionality, the TSO/DSO, the capabilities of the customer (e.g. backup generator), as well as their needs. Planning uncertainty will likely make it impossible to order all customers in order of priority before disaster strikes, but the list should at minimum indicate which customers need to receive priority during the response and which during the recovery phase (DGSCGC, 2015). Table 8 is one example of how such as list could be built at the local or regional level.

Table 8. Example of critical customer table, which may be used at the local or regional level.

Customer					Grid			
Designation	**Type**	**Location**	**Outage consequences**	**Minimum power required**	**TSO/DSO**	**Consequence**	**Capabilities**	**Needs**

Source: DGSCGC, 2015

Once disaster strikes, the list included in the emergency plan can be used to establish repair and recovery priorities. This process is likely to be dynamic and priorities will change depending on the response and recovery objectives set by decision-makers and emergency managers, and the resources available to the affected TSOs/DSOs.

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List of abbreviations and definitions

AC	Alternating Current
CACM	Capacity Allocation and Congestion Management
CME	Coronal Mass Ejection
DC	Direct Current
DCS	Distributed Control Systems
DG	Directorate-General
DMIS	Disaster Management Information System
DSO	Distribution System Operator
EC	European Commission
ECG	Electricity Coordination Group
ECHO	Humanitarian Aid and Civil Protection
ECI	European Critical Infrastructure
EDG	Emergency Diesel Generator
EEA	European Environmental Agency
ENTSO-E	European Network of Transmission System Operators for Electricity
EUCPM	European Union Civil Protection Mechanism
GDACS	Global Disaster Alert and Coordination System
GIC	Geomagnetically Induced Current
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GSM	Global System for Mobile Communications
GSU	Generation Step-Up
HF	Hugh Frequency
HVAC	Heating, Ventilation and Air Conditioning
LPT	Large Power Transformer
MS	Member State
NIS	Network and Information Systems
NRA	National Risk Assessment
OMS	Outage Management System
OSP	Operator Security Plan
PMU	Phasor Measurement Unit
PTWC	Pacific Tsunami Warning Center
RES	Renewable Energy Sources
ROC	Regional Operational Centers
RSC	Regional Security Coordinators
SCADA	Supervisory Control and Data Acquisition
SO	System Operation

SVC	Static VAR Compensator
TETRA	Terrestrial Trunked Radio
TSO	Transmission System Operator
UCPM	Union Civil Protection Mechanism (formerly EUCPM)
VAR	Volt-Ampere Reactive

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Annex

This annex includes a list of the natural disasters reviewed in this study. Earthquakes are listed in Table 9, space weather events in Table 10 and floods in Table 11.

Table 9. Earthquakes reviewed in this study

Date	Country	Epicenter	Magnitude (Mw)
July 8, 1986	USA	Palm Springs	5.9 (ML)
October 10, 1986	El Salvador	San Salvador	5.6 (ML)
October 1, 1987	USA	Whittier, CA	5.9 (ML)
December 7, 1988	Armenia	Spitak	6,7
October 19, 1989	USA	Loma Prieta, CA	7,1
August 17, 1999	Turkey	Kocaeli	7,4
September 21, 1999	Taiwan	Chi-Chi	7,3
May 4, 2006	Tonga	100 mi NE of Nuku'alofa	7,9
July 16, 2007	Japan	Niigataken-Chuetsu-Oki	6,7
May 12, 2008	China	Wenchuan	7,9
September 4, 2010	New Zealand	Christchurch	7,1
February 22, 2011	New Zealand	Christchurch	6,3
March 11, 2011	Japan	Tohoku	9
June 13, 2011	New Zealand	Christchurch	6
December 23, 2011	New Zealand	Christchurch	5,9
April 20, 2013	China	Luchan, Sichuan Province	6,6

Table 10. Space weather events reviewed in this study

Start Date	End Date	Affected Countries
13-May-1921	**16-May-1921**	US, Europe
23-Feb-1956	**23-Feb-1956**	(observed in) Royal Greenwich Observatory
11-Feb-1958	**11-Feb-1958**	Sweden
28-Aug-1859	**04-Sep-1859**	Worldwide
13-Nov-1960	**13-Nov-1960**	Sweden
13-Jul-1982	**14-Jul-1982**	Sweden
8-Feb-1986	**9-Feb-1986**	Sweden
13-Mar-1989	**14-Mar-1989**	USA, Canada, Sweden, UK
24-Mar-1991	**24-Mar-1991**	Canada, Sweden
28-Oct-1991	**28-Oct-1991**	Canada
9-Nov-1991	**9-Nov-1991**	Sweden
6-Apr-2000	**7-Apr-2000**	UK
6-Nov-2001	**6-Nov-2001**	New Zealand
19-Oct-2003	**7-Nov-2003**	USA, Sweden, South Africa
8-Nov-2004	**8-Nov-2004**	Sweden

Table 11. Floods reviewed in this study

Date	Country	Location
1988	Bangladesh	
June-August 1993	USA	St. Louis, MO metropolitan area
1998	Bangladesh	Dhaka
September 2000	Japan	Nagoya (Typhoon Saomai)
August 2002	Czech Republic	Prague
August 2004	Bangladesh	Dhaka
August-September 2005	USA	Louisiana and Mississippi (Hurricane Katrina)
August 2007	South Asian floods	Bangladesh
December 2007	USA	Pacific NW
September 2008	USA	Louisiana (Hurricane Gustav)
September 2008	USA	Texas (Hurricane Ike)
December 2010 – January 2011	Australia	Queensland
September 2011	Japan	Tokyo (Typhoon Roke)
August 2012	USA	Louisiana (Hurricane Isaac)
October-November 2012	USA	Mid-Atlantic States & New England (Hurricane Sandy)
May-June 2013	Czech Republic	Various
November-December 2015	India	Chennai (or Madras)
December 2015	UK	Lancaster
July 2017	USA	Illinois (Lake Forest)
August 2017	China	Macau (Typhoon Hato)

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