European Commission

JRC TECHNICAL REPORTS

Climate change and critical infrastructure – storms

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2019

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JRC Science Hub
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JRC113721

EUR 29411 EN

PDF ISBN 978-92-79-96403-9 ISSN 1831-9424 doi:10.2760/986436

Luxembourg: Publications Office of the European Union, 2019

How to cite this report: Karagiannis, G.M., Cardarilli, M., Turksezer, Z.I., Spinoni, J., Mentaschi, L., Feyen, L. and Krausmann, E., *Climate change and critical infrastructure – storms*, EUR 29411 EN, Publications Office of the European Union, Luxembourg, 2019, doi:10.2760/986436.

Climate change and critical infrastructure – storms
This study attempts to elucidate the vulnerability of critical energy infrastructure to storms. First, it gauges how certain characteristics of storms affect the resilience of the power grid. Then, it presents a methodology for assessing the change in the level of risk to critical infrastructure due to the impact of climate change on the frequency and severity of storms.

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Executive summary

Infrastructure systems are the backbone of modern economies, and critical infrastructure resilience is essential to sustainable development. 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 attempts to elucidate the vulnerability of critical energy infrastructure to storms and outlines how certain characteristics of this hazard affect the resilience of the power grid based on forensic analysis. Wind loading and debris impact are the main causes of storm damage. Tall, slender structures, such as transmission towers, distribution poles and wind turbines are most affected. Transmission and distribution assets can also be damaged by the impact of flying debris. Moreover, freezing rain forms glaze ice which accumulates on power lines and increases their catenary load. The added weight can cause the line to break or distribution poles and transmission towers to collapse. Substations were also found to be affected by storms, particularly by inundation and airborne debris. However, damage from flying debris was less compared to that sustained by transmission and distribution lines. Storms in coastal areas may affect transmission and distribution networks by increasing the amount of saltwater deposits on electrical equipment. Given adequate preparedness, early warning can help expedite recovery by allowing TSOs and DSOs to activate disaster response plans, including surge mechanisms and mutual aid agreements, before the storm hits.

We also present a methodology to investigate the impact of climate change on the risk posed by storms to the power grid. Our approach combines a future projection of the recurrence interval of selected storm scenarios and the assessment of the estimated economic losses incurred by critical infrastructure and those resulting from the disruption of daily economic activity. A case study was conducted to demonstrate the methodology in a large urban area in Western Europe. We derived the projected peak wind gust of the 10-, 50- and 100-year storm scenarios for five time periods. For each recurrence interval, the cost to repair the damage to overhead lines and the economic losses from the interruption of the daily economic activity amount each to about half of the total losses. The proportion of the repair cost increases by approximately 10% for the 50-year and the 100-year storms compared to the 10-year scenario. This increase causes the total expected losses from the 50-year and the 100-year storms to rise as well.

The duration of the power outage has a major impact on the estimated losses for all scenarios across all time periods. In this case study, the increase of the duration of the power outage from 3 days to 10 days increases the total expected losses 3.5 times. With longer-term power outages, the economic losses caused by interruption of the daily economic activity progressively become the main determinant of the total impact.

The scope of this study is limited to demonstrating the feasibility of the methodology and inductively drawing preliminary conclusions regarding the impact of storms on critical infrastructure given climate change conditions. It is not intended to supplement, replace or challenge existing risk assessment and management plans prepared by Member States.

The following recommendations emerged from the findings of this study:

- Consider increasing transmission tower design requirements for resistance to wind loading in standards and regulations.
- Consider the risk from climate change in investment analyses.
- Consider events with recurrence intervals longer than 100 years in hazard mitigation and emergency planning.
- Standardize mutual aid resources.
- Plan for surge capabilities and external contractors.

1 Introduction

Infrastructure systems are the backbone of modern economies, and critical infrastructure resilience is essential to the societal well-being and sustainable development. The risk environment facing critical infrastructure in Europe is complex and in constant change. The *Overview of Natural and Man-made Disaster Risks the European Union may face* ([1]) outlines numerous natural, technological and human-caused hazards and threats. Meteorological hazards, such as floods, storms and wildfires ([2]), are among those most frequently identified by Member States in their National Risk Assessments. In a recent study, Forzieri et al. (2016) predict a likely increase in the frequency of extreme weather events across Europe. The exposure of coastal and floodplain areas to extreme weather is expected to increase. Neumann et al. (2015) estimate that between 82.9 and 85.7 million people will be living in low-elevation coastal zones ([3]) and the 100-year floodplain in Europe by 2030.

Because of the high population density and important economic activity, infrastructures are also concentrated in coastal and floodplain areas. Therefore, the exposure of critical infrastructures to meteorological hazards is likely to increase disproportionately with climate change. Forzieri et al. (2018) estimate that damage to critical infrastructure due to climate change in Europe could increase to ten times present values by the turn of the century, but southern and southeastern European countries will be most affected. The impact of storm surge, riverine and flash flooding, and windstorms on critical infrastructure is expected to increase across Europe. The losses are likely to be highest for the chemical, manufacturing, transportation and energy sectors.

Several authors (Forzieri et al., 2018; Neumann et al., 2015; Mechler et al., 2014) highlight the need for further research in the quantification of vulnerability of critical infrastructures to meteorological hazards. This study focuses on the energy sector, mainly because of its ubiquity in everyday life and the dependence of all other critical infrastructures on a reliable supply of electric power (Karagiannis et al., 2017a). A previous study (Karagiannis et al., 2017b) presented a methodology to investigate the impact of climate change on the risk posed by floods to critical infrastructure and suggested the approach be expanded to other natural hazards as well.

This study attempts to elucidate the vulnerability of critical energy infrastructure to storms, with emphasis placed on the power grid. First, we discuss the impact of storms on the power grid and outline how certain characteristics of this type of hazard affect the resilience of the power grid using forensic analysis. Second, we present a methodology to investigate the impact of climate change on the risk posed by storms to the power grid infrastructure. Our approach combines a future projection of the recurrence interval of selected storm scenarios and the assessment of the estimated losses incurred to critical infrastructure and those resulting from the disruption of daily economic activity. A case study was conducted to demonstrate the methodology in a large urban area in Western Europe. The scope of this study aims at demonstrating the feasibility of the methodology and inductively drawing preliminary conclusions regarding the impact of storms on critical infrastructure given climate change conditions. It is not intended to supplement, replace or challenge existing risk assessment and management plans prepared by Member States.

This is a two-part study. Chapter 2 is the first part, which is intended to improve the understanding of power grid's resilience to storms. It is based on the analysis of past storm occurrences and their impact on the power grid. Its purpose is to inform policy-

([1]) Commission Staff Working Document: Overview of Natural and Man-made Disaster Risks the European Union may face, Brussels, 23.5.2017, SWD(2017) 176 final, http://ec.europa.eu/echo/sites/echo-site/files/swd_2017_176_overview_of_risks_2.pdf (accessed October 29, 2018)

([2]) NFPA 1600 Standard on Disaster/Emergency Management and Business Continuity/Continuity of Operations Programs, 2016, https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=1600 (accessed October 30, 2018)

([3]) Defined as *the contiguous and hydrologically connected zone of land along the coast and below 10 m of elevation* (Neumann et al., 2015).

making and strategic and disaster risk management planning in the European Union and Member States. Additionally, however, this analysis serves as a foundation of the risk assessment methodology that follows. Specifically, Chapter 3 is the second part of this study and outlines a methodology for the estimation of the change in the risk level of failure or disruption of the power grid resulting from the impact of climate change on the frequency and severity of storms. Risk is quantified in economic terms to support cost-benefit analyses.

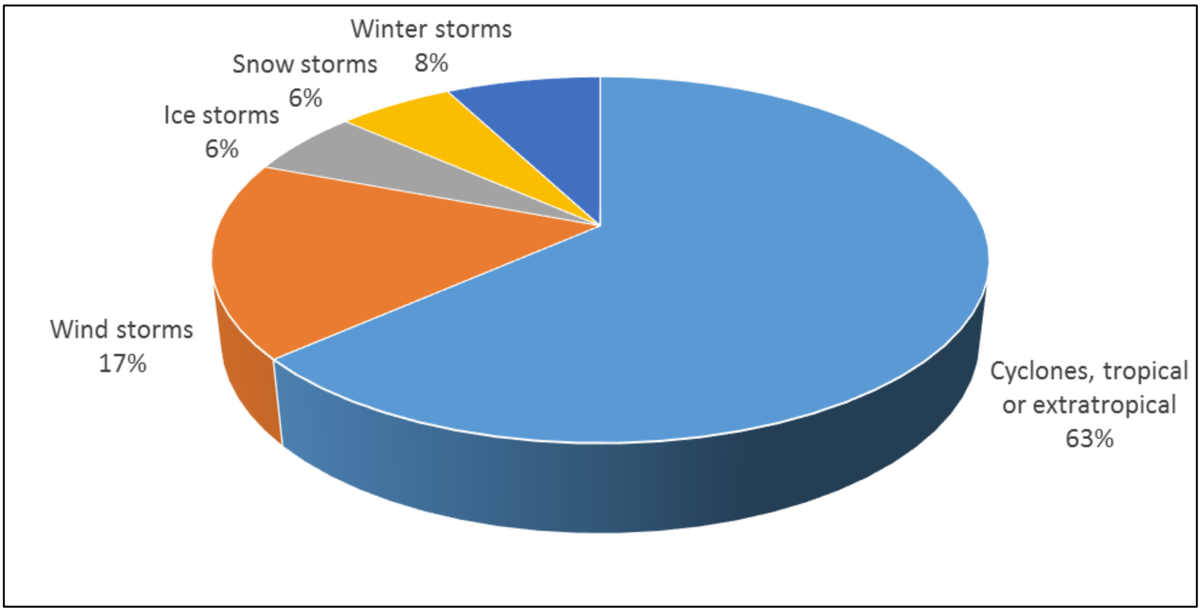
2 Power grid resilience to storms – incident analysis

Widespread power outages are a common occurrence during storms. This chapter examines storm damage to the power grid with a focus on restoration and resilience. It endeavors to elucidate how the impact of storms affects the recovery of the power grid. It is intended to inform policy-making and disaster risk management planning in the European Union Member States.

2.1 Research design and data collection

The research design for this part of the study was predominantly purposeful. It focused on disruptions of the power grid caused by storms and explored the relationship between recovery time and hazard characteristics. This part was data-driven, using an inductive approach. The findings in this chapter are based on the **analysis of lessons identified from 52 storms**, including tropical and extratropical cyclones, as well as ice, snow and wind storms (Figure 1) affecting 14 countries in 4 continents (the full list of the events is included in the Annex). Whenever a storm affected more than one countries, a separate record was made for each affected country, producing a total of 58 cases ([4]). Cyclones made up approximately 2/3 of our sample, followed by wind storms.

Figure 1. Breakdown of storms reviewed in this study, by type



Source: JRC

Storms were included in the analysis if they caused damage to power grid components. **This study was based exclusively on publicly available information.** Sources included the scientific literature, technical reports, disaster response operations situation reports and press articles. The quality, detail and granularity of data describing the storm intensity, damage, power outages and impact on the population were a particular challenge. Most of the information in the dataset was categorical, but numerical data was considered whenever feasible and available. The level of detail varied across sources. The information was sufficient to establish the type of damage and the failure mechanism. The affected population was typically reported as the proportion of customers or households where the hazard impacts were observed.

Nevertheless, several limitations undermined data collection and analysis. The intensity of the wind storms and cyclones was either reported in terms of the mean wind speed or

([4]) The terms "records" and "cases" are used here interchangeably.

peak wind gust for wind storms, but reporting was inconsistent in terms of the metric used. Precipitation height was reported as a proxy of snow and ice storm intensity. In addition, the exposure of power grid components to varying storm intensity levels (i.e. wind speed or precipitation height) was difficult to establish. Spatial distributions of wind speed and/or precipitation were generally neither comprehensive nor readily available.

Inconsistencies in the description of the impact, location and duration of power outages caused by storms were another challenge. The impact of a power outage was described in several different units of measurement, including people, customers, households, houses, homes, businesses and properties suffering an outage. The impact was described with numbers in 55 out of 58 records (including relative descriptions in 14 cases), with categorical descriptions in 2 cases, and was unknown in 1 case. Furthermore, several different thresholds were used to report recovery time. Information on the duration of the outage was available in only 34 cases. Each source used different definitions and indicators of recovery. Most sources reported the time needed after the onset of the outage to restore power to varying numbers or percentages of affected units (e.g. customers, households etc.).

Information on the type of damage and the types and numbers of affected assets were reported in 38 out of 58 cases, of which only 30 included numbers of damaged equipment and assets per category. However, it was often unclear whether damage was caused by storm-related flooding, wind loading, debris impact, or a combination of the above. In addition, the localization of damage or outages was also unclear, and was described as a general area, not associated with any clear geographical or administrative boundaries, or for the entire event. Similar challenges were noted in a previous study (Karagiannis et al., 2017a), but the quality of reported information on storms seems to be lower than for earthquakes or floods. Clearly, **the granularity of reported information needs to be improved if statistical correlations between wind speed and the duration of a power outage are to be made at a larger scale.**

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.

2.2 Damage types and storm impact on power grid resilience

Power outages occurred during all but one of the storms reviewed in this study. The one exception was a wind storm which occurred in September 1996 in France (Abi-Samra, 2010). The high winds collapsed 22 transmission towers and 18 wood poles. Despite the collapse of a regional transmission system, equipment located outside the 2-km-wide storm track was undamaged and no customers were affected. **One reason for the limited impact was the narrow storm corridor.**

Storms of all kinds can bring heavy rains, strong winds, hail and lightning, and may also spawn tornadoes (Bullock, Haddow & Coppola, 2012). **The main causes of storm-related damage to electricity network assets are inundation, wind**

loading and debris impact. Inundation resulting from heavy rains associated with storms and storm surge can be detrimental to the power grid. Because water is a good conductor of electricity, electrical equipment is highly sensitive to even minute quantities of moisture and dirt. Some components, such as transformers and electrified substation equipment, may even suffer catastrophic and even explosive failures if wet. The effect of flood-related damage has been addressed in Karagiannis et al. (2017b); therefore, this report focuses on wind damage, which has also been demonstrated to create significant damage to the electricity infrastructure system (Reed et al., 2010). Nevertheless, inundation damage is taken into consideration in the analysis when relevant.

As expected, the areas on or adjacent to the storm's track were affected the most. All other things being equal, the number of people affected by these disruptions increased with the peak wind speed and the population density in the affected area. However, the data available to us was insufficient to derive a statistical correlation between the peak wind speed, the population density in the affected area and the number of people affected by the outage.

Despite the fragmented nature of available data, this analysis helped elucidate important aspects of the power grid's resilience to storms. Table 1 below outlines the main findings. **Transmission and distribution towers and lines appear to be the most vulnerable components of the networks.** Utility poles ([5]) suffer bending failures and can be damaged by the impact of flying debris, which may also sever overhead lines. Inundation is more severe of a threat for substations. Early warning is possible and, together with disaster preparedness, goes a long way in expediting recovery.

Recovery time ranges between hours and months, depending on the extent of the damage and the effectiveness of disaster response. Recovery here is construed as the restoration of power supply to all customers who are able to receive it. Given the inconsistencies in reporting discussed in the previous section and the inherent uncertainty governing temporary repairs and recovery operations, recovery time is reported here as a range instead of a precise value. It is driven by the sheer number of damaged items and the time it takes to repair or replace them. The following sections discuss these aspects in further detail.

Table 1. Overview of damage types and storm impacts on the resilience of the power grid

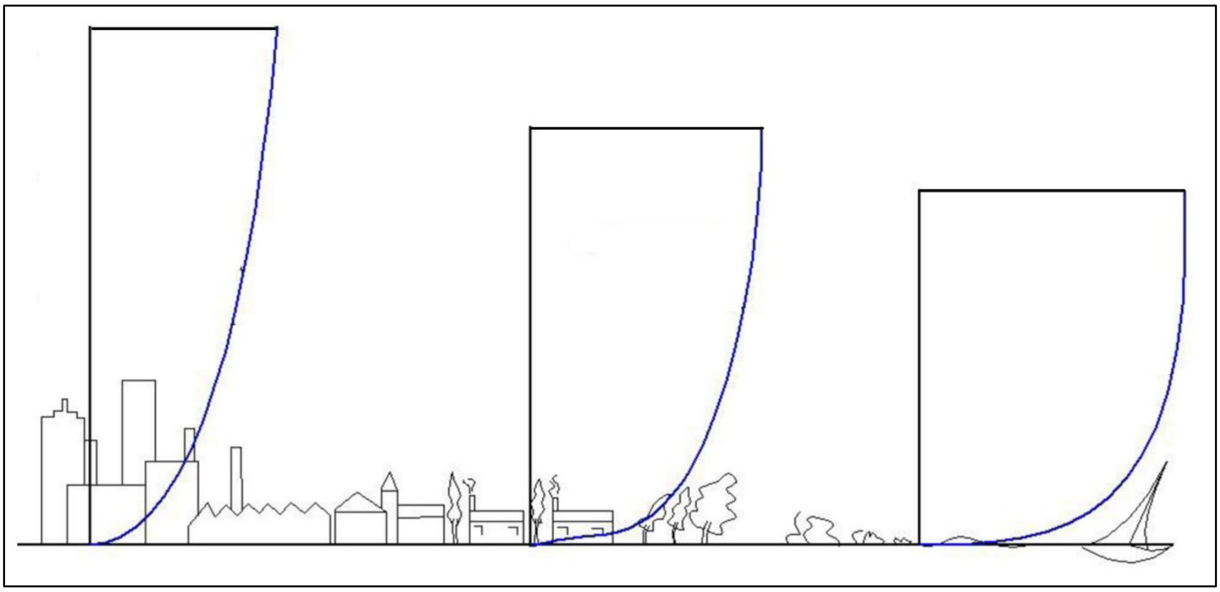
Damage types	Bending failure due to wind pressure Impact of flying debris Inundation (substations mostly)
Contributing factors	Early warning possible Disaster preparedness
Most vulnerable components	Utility poles and overhead lines Substations (including transformers)
Recovery time driven by	Number of items in need of repair or replacement Access to conduct repairs
Recovery time range	A few hours to six months; most commonly, up to one month. Recovery time was longer for hurricanes than for other storms.

([5]) The term "utility poles" is used in this report to refer collectively to transmission and distribution cable-bearing structures.

2.3 Equipment damage and hazard mitigation

Wind loads increase with wind speed ([6]), which fluctuates with time and increases with height. Close to the ground, the wind is slowed down by friction, while at higher elevations, the wind is faster. In structural and environmental engineering, the variation of the mean wind speed variation within the atmospheric boundary layer is described using power law profiles (Chen & Richard Liew, 2003). Several building codes consider that wind speed achieves a practical maximum speed a few hundred meters above ground level (Edgar & Sordo, 2017). The friction increases with terrain roughness, which depends on the size and number of the surface features on the ground over which the wind blows (Figure 2). Therefore, the wind forces exerted on a structure also increase with height.

Figure 2. Wind profiles on different terrain types



Source: Adapted from Bendjebbas et al. (2016)

Wind forces act inward on the windward side of a structure and outward on the other sides (Figure 3). The response of a structure exposed to wind, i.e. the effect of the wind on it, depends on the structure's size, shape and dynamic properties. Higher wind pressures are exerted on tall, slender structures presenting a wide profile against incoming winds, resulting in higher bending moments and base shear internal forces.

Impact by debris was the second major cause of damage identified in this study. Falling trees or large branches were the most frequently cited examples of this type of effect.

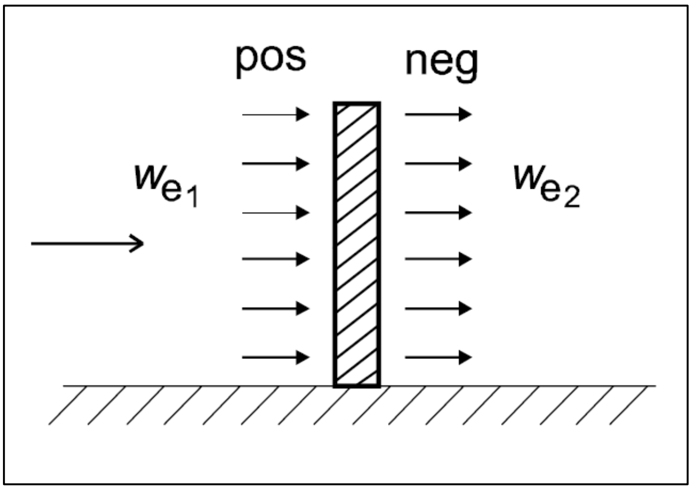
Because of their high exposure, transmission and distribution towers and lines are affected the most. Transmission towers are tall, three-dimensional steel trusses, designed to carry and support transmission cables. Several standards apply to the design of towers to resist wind loads (Table 2). Because transmission towers transport electricity over large distances, they are typically located in the open. They can also be exposed to high wind forces due to their height and the absence of surrounding features that could mitigate the impact of the wind forces. In addition, these structures may be subjected to higher wind pressures when the cross-arms (the members protruding to the side which support transmission cables) are facing the wind at a right angle.

Transmission tower failures were recorded in nearly all incidents reviewed in this study. Wind loading produced two distinct mechanisms of damage. The first was

([6]) Specifically, the wind pressure is proportional to the square of the wind speed.

bending failure of the tower under the wind's distributed horizontal load. This mechanism typically causes the affected towers to twist downward. Although the photographic evidence available to us was in no way exhaustive, the point of inflection appears to be located in the middle third of the structure's height, above the juncture of the legs. In most cases, the horizontal conductor support cross-arms appear to remain unaffected, but the tower twists until its top comes to rest on the ground. The second mechanism was **failure of the tower foundation**, causing the structure to tilt. This failure mode is typical in hurricanes, when wind pressures are combined with heavy rain which reduces the cohesion and resistance of the soil under the tower, causing the foundations to fail.

Figure 3. Wind pressure on structure surfaces (w_{e1} and w_{e2} denote respectively the positive pressure exerted on the windward side and the negative pressure exerted on the leeward side of the structure)



Source: Eurocode 1, Part 1-4 (European Committee for Standardization, 2010)

Table 2. Standards applying to the design of transmission towers under wind action

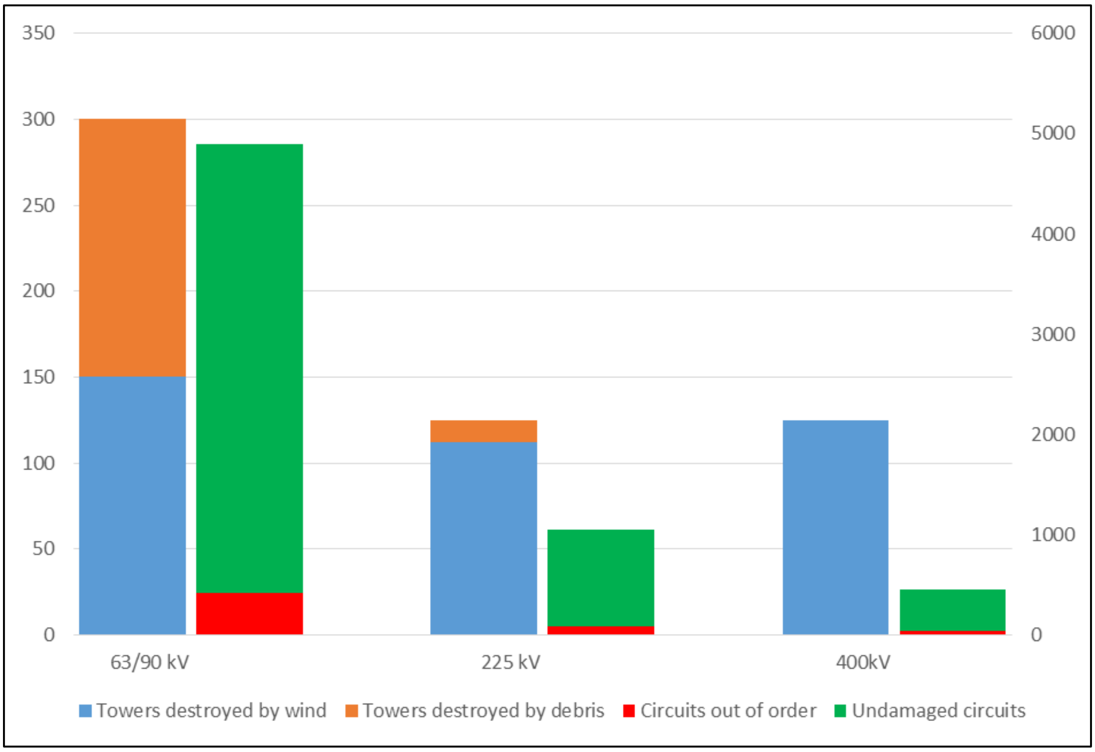
Organization	Standard/Regulation	Year
American Society of Civil Engineers	Guidelines for electrical transmission line structural loading, ASCE Manuals and Reports on Engineering Practice No. 74	1991
International Electrotechnical Commission	(IEC Standard 60826) Design criteria of overhead transmission lines.	2003
Mexican Federal Electricity Commission	Civil works manual. Chapter of wind design	2008
American Society of Civil Engineers	(ASCE/SEI 7–10) Minimum design loads for buildings and other structures.	2010
European Committee for Standardization	(EN 1991-1-4:2005+A1:2010) Eurocode 1: Actions on structures – Part 1-4: General actions – Wind actions	2010
Standards Australia, Standards New Zealand	(AS/NZS 1170.2) Structural design actions. Part 2: Wind actions	2011

In addition to direct damage from wind loads, severe damage to transmission towers and lines resulted from flying debris. Smaller debris, such as tree branches, may dangle and/or shear aerial cables at several points along a line. Larger debris, such as trees, can knock down transmission towers and distribution poles, and damage heavy equipment upon impact. The numbers of transmission tower failures because of wind loading vs. those attributed to debris impact were only available for a fraction of the events reviewed in this study. However, wind loading appears to be the most frequent failure mechanism. For instance, when cyclones Lothar and Martin hit Europe, most of the damage sustained by the French transmission grid resulted from wind loads rather than from debris impact, as illustrated in Figure 4. It also appears that 63 and 90 kV towers were much more vulnerable to debris damage than 225 and 400 kV towers. In this case, falling trees were the main cause of debris damage (OSCE, 2016).

Furthermore, Figure 4 shows that in absolute terms the number of damaged 63 and 90 kV towers is more than twice the number of damaged 225 and 400 kV towers. Nevertheless, this information alone does not support any conclusions about the vulnerability of any type of tower over another to storm damage. Although it can be argued that there are more 63 and 90 kV towers than 225 and 400 kV towers in any one area, the reported information does not include the number of towers exposed to equivalent wind speeds but undamaged.

The number of exposed (i.e. the sum of out-of-order and undamaged) 63 and 90 kV circuits is more than four times higher than the number of exposed 225 kV circuits and about 9 times higher than the number of exposed 400 kV circuits. However, approximately 8% of exposed circuits of each voltage category went offline.

Figure 4. Damage to the French transmission grid resulting from cyclones Lothar and Martin: towers destroyed by wind and debris (left axis), and circuits out of order (right axis)



Source: OSCE, 2016

Wind turbines also suffered damage from wind loading. These structures are made of a tall and relatively slender column supporting a heavy load at the top. Therefore, despite their aerodynamic shape which somewhat reduces wind pressures, a relatively small displacement of the large mass at the top generates a disproportionately greater bending moment at the base. The result is a failure mechanism similar to that of transmission towers.

Wooden and concrete distribution poles were also affected. Distribution pole failures were more frequent than losses of transmission towers and occurred during every storm in this study. The mechanisms of damage were similar to those of transmission towers. When subjected to direct wind loading, wooden poles may snap (Figure 5) and concrete poles may fail in bending. Although the numbers of failures of distribution poles and transmission towers were only available for a fraction of the incidents reviewed in this study, the distribution system suffered disproportionately in terms of absolute numbers. For instance, Hurricane Katrina damaged 3,000 miles (4,828 km) of transmission lines and 28,500 miles (45,866 km) of Entergy's infrastructure in the United States (Entergy Corporation, 2005). Although the fraction of this damage attributed to flooding, wind forces or debris impact was unclear, transmission and distribution substations typically take a higher toll during floods (Karagiannis et al., 2017a). The higher impact of storms to distribution poles and lines is arguably attributed to their higher number in the affected area, as there are more distribution lines than transmission lines, and the former tend to be more concentrated in urban areas.

Figure 5. Snapped utility poles in St. Thomas, U.S. Virgin Islands, after Hurricane Irma

Source: FEMA, 2017 ([7])

In addition to the effects of wind loads and debris impact, a particular kind of transmission and distribution line damage occurs during ice or snow storms. **Freezing rain forms glaze ice which accumulates on power lines and increases their catenary load.** The added weight can cause the line to break or distribution poles and

([7]) Federal Emergency Management Agency, https://www.fema.gov/media-library/assets/images/141939 (accessed December 5, 2018) transmission towers to collapse. Furthermore, glaze ice may accumulate on trees, causing large branches to fall tearing down power lines. For instance, these types of effects were quite pronounced during the winter storm which hit the Northeastern United States (New Hampshire, New York, Vermont, Massachusetts, Connecticut, Pennsylvania and Maine) in December 2008, leaving 1,365,500 customers without power. In the State of New York alone, National Grid replaced 350 utility poles and 235 km of cables (Nelson et al., 2009).

Substations were also affected by storms in this study, albeit to a lesser extent compared to transmission and distribution lines. Inundation and airborne debris were the leading mechanism of damage. Because electrical equipment is often sensitive to even minute amounts of moisture and dirt, flooding can take substations offline for days or weeks (Karagiannis et al., 2017a). Flying debris may also affect substation equipment, such as transformer retaining structures. Records of substation damage were found in 15 (out of 52) storms reviewed in this study. Of those, 12 were related to hurricanes and 3 to other types of storms. Hurricane records were unclear as to whether damage was due to flooding, wind loading or airborne debris. Other than inundation, **substations went offline when they were disconnected from the grid because power lines were severed due to tower failures or debris**.

Storms in coastal areas may affect transmission and distribution networks by increasing the amount of saltwater deposits on electrical equipment. As discussed in Karagiannis et al. (2017a), this may cause catastrophic failure of some electrified devices. Non electrified equipment may also be affected, because the saltwater deposits must be thoroughly cleaned before the equipment gets back online.

Several mitigation strategies have been used to increase the grid's resilience to storms. One example is the use of alternative tower designs which limit the structure's response to wind loads. For instance, according to a report by the Puerto Rico Energy Resiliency Working Group (2017), monopole towers fared better than the lattice structures when Hurricane Maria hit Puerto Rico in 2017. Although not specified in the report, it is safe to presume that the reason is that their narrower profile reduces wind pressures. Another structural mitigation method is strengthening the foundations of transmission towers to reduce their vulnerability to toppling. This measure may also help to mitigate against flood and earthquake hazards (Karagiannis et al., 2017a).

However, **structural mitigation measures may have unwanted side-effects.** For example, one flood mitigation strategy involves elevating vulnerable equipment, such as switchgear and relays, above the expected water level (Karagiannis et al., 2017a). However, this strategy may expose substation equipment to debris impact. For instance, airborne debris was the primary cause of heavy damage caused by Hurricane Rita to elevated substation equipment in Texas (Reed et al., 2010).

2.4 Early warning, emergency response and recovery

Early warning can play a significant role in electricity grid resilience during storms. Modern weather forecasting systems can provide notification of a forming storm system or worsening weather conditions with a lead time of a few days, depending on local and regional conditions. Uncertainty is inherent in all hydrometeorological predictions, but is seldom communicated with weather forecasts. The lack of information on the uncertainty of weather predictions can undermine decision-making in disasters (National Research Council, 2006).

Although there is little that can be done to protect power grid assets from high winds in the hours or days before a storm hits, early warning is a significant component of electricity resilience in two ways. First, **effective early warnings can help TSOs and DSOs mitigate the effects of the inundation caused by the intense rainfall which often comes with storms, by preemptively shutting down substations which may be flooded.** This measure prevents catastrophic damage which would otherwise be caused when electrified equipment came in contact with water and reduces the asset recovery time to that needed for cleanup and repair (Karagiannis et al., 2017a). **Second, early warning gives TSOs and DSOs time to activate their emergency operations plans.**

The impact of storms on critical power infrastructure follows a pattern of widespread moderate to catastrophic damage to the most vulnerable components along the storm's path. **Power grid recovery in the aftermath of storms is therefore driven by the need to repair or replace large numbers of utility towers and poles, and replace large lengths of electric cables.** The success of emergency response for TSOs and DSOs is judged by how fast power is brought back online to the maximum number of users possible. The need to rapidly conduct a vast number of repairs often exceeds the capacities of any single TSO/DSO and generates a demand for rapid repair capability, which is highly dependent on disaster preparedness.

Rapidly increasing electricity infrastructure repair capabilities in the aftermath of a major storm requires mobilizing manpower, equipment and spare parts. TSOs/DSOs often enter into mutual aid agreements with neighboring jurisdictions to acquire repair crews and equipment in the event of an emergency. Additional equipment and spare parts are usually acquired through mutual aid agreements, from corporate suppliers, or both. Response-generated demands include shelter, food and water for both mutual aid and home-based repair crews, transportation for people and equipment, fuel and consumables. For example, the rapid restoration of power to every customer of Mississippi Power who could receive it in the aftermath of Hurricane Katrina is largely attributed to the company's efficient disaster logistics (Ball, 2006).

Lessons identified after the response to a severe winter storm that hit Slovenia in 2014 emphasize the **need for disaster preparedness in a European context**. Over the course of five days, from January 30 to February 3, 2014, between 40 and 200 mm of precipitation fell on most of the country. In the western and southwestern part of the country, rainfall reached 300 mm (Markosek, 2015). Freezing rain caused extensive damage to the country's transmission and distribution infrastructure. Electro Ljubljana rapidly reinforced their capabilities through mutual aid agreements with foreign distribution companies. The response effort was carried out by 1,500 people from civil protection, fire/rescue, the military, voluntary organizations, construction companies and electricity companies. The use of temporary transmission towers was particularly effective, as it helped to rapidly reconnect transmission substations to the grid (OSCE, 2014).

However, several problems hampered the response and slowed down recovery efforts. Most were due to the lack of interoperability with non-traditional responders and mutual aid resources. First, record keeping during the operation was a challenge, because different companies used different systems. Second, local surge arrangements lacked efficiency. Several workers were engaged without written agreements, either because printing was impossible due to the power outage, or because of the perceived urgency to make the resources available in the field. Contractors selected through a tender were sometimes unfamiliar with the area. Many volunteers were former employees of the company, by then retired. Despite their technical competencies, they could not be insured and were thus assigned less difficult tasks. Third, language barriers hampered communications with mutual aid crews. In addition, local staff were tied liaising with mutual aid crews which were unfamiliar with the area and local practices, which reduced the number of available local resources. Last, transportation was difficult because of road closures, and cellular service was interrupted as soon as base stations ran out of backup power. Until power was at least partially restored, the operation had to rely only on satellite communications (OSCE, 2014).

Access is also a major determinant of the power grid recovery in the aftermath of storms. Transmission towers are often located in remote areas serviced by dirt roads which are easily blocked by landslides and debris such as fallen trees. For instance, most towers damaged by Hurricane Rita were located in marshes and were thus difficult to access (Reed et al., 2010). Relocating transmission towers alongside main roads is likely to increase the grid's resilience. Although it is unknown whether this strategy will reduce the failure rate of towers, it is argued that it will make it easier for repair crews to access damage locations and thus speed up recovery. Distribution lines are usually located alongside urban and suburban roads, which may also be blocked by debris. However, urban and suburban roads are more accessible than dirt roads in mountainous regions and are also usually easier to clear by heavy equipment.

One successful response strategy involves phasing the operation to protect repair crews, responders and equipment, by keeping them out of the hazard zone. This means staging local and mutual aid resources at the edge of a hurricane zone or sheltering them inside strong buildings while the storm passes. Resources are then typically deployed after the storm has passed. For example, Mississippi Power used this strategy to streamline its response to Hurricane Katrina (Ball, 2006). This course of action is also popular in search and rescue operations in the aftermath of hurricanes.

Another successful strategy involved the use of temporary transmission towers. Called Emergency Restoration Systems (ERS) or simply Restoration Towers in some countries, these versatile structures are relatively easy to transport and can be erected with minimal equipment. Although a transmission tower may take 10 days to build, a trained crew can erect an ERS tower within a day or two (Karagiannis, et al., 2017a) and allow a TSO to quickly restore a line until a permanent structure is built. Such ERS towers were used by Electro Ljubljana in the aftermath of the 2014 ice storm and contributed a lot to the quick recovery.

3 Effects of climate change on the level of risk from an economic perspective

A pan-European multi-hazard analysis by Forzieri et al. (2016) indicates that the frequency and severity of windstorms is likely to increase in coastal areas in Western, Eastern and Northern Europe. Because of the high population density and intense economic activity of coastal areas, the level of risk is likely to increase substantially. This chapter demonstrates a methodology for the estimation of the change in the level of risk (quantified in economic terms) of failure or disruption of the power grid resulting from the impact of climate change on the frequency and severity of storms. The assessment of the level of risk is based on the estimation of potential losses from wind loads on the transmission grid. A selected area in Europe is used as a case study.

3.1 Methodology

Disaster risk results from the probability of occurrence of a storm and the severity of the impact of the event. The probability may be expressed either qualitatively or quantitatively, depending on the level of knowledge about each hazard. The severity is expressed in terms of the expected morbidity and mortality, damage to property, disruption of infrastructure, and social consequences (Agius et al., 2017). The scenario-based approach is a popular disaster risk analysis methodology and is highly appropriate for the analysis of hazards when statistical information is available.

Here, the change in the level of risk is estimated by the change in the probability and the impact severity of storms. Specifically, we analyze the change in the level of risk incurred by the increase or decrease of the probability of occurrence of several storm scenarios brought about by climate change. For each scenario, the level of risk is derived as the expected value of the economic losses resulting from the storm under review (Hickman & Zahn, 1966). The following sections discuss how we determine the change of the probability of occurrence of each scenario and estimate the losses.

3.1.1 Probability of occurrence

The probability of occurrence of a storm is quantified by its recurrence interval, defined in this case as the average number of years between storms of the same intensity ([8]). Using the approach discussed in Forzieri et al. (2016; 2018), we derived the projected peak wind for a range of recurrence intervals over several future time slots. We use the ensemble mean values from 15 simulations combining different Global Circulation Models (GCMs) with different Regional Climate Models (RCMs) at a resolution of 0.11 degrees, as in the EURO-CORDEX ([9]) framework (Table 3). The return levels were computed using a peak-over-threshold (98.5%) generalized Pareto distribution with daily maximum wind speed as the input variable.

3.1.2 Loss estimation

Each scenario is analyzed to determine the consequences of the storm on the affected communities. The potential losses are a function of the intensity of the hazard and the exposure of people and economic activities to that hazard. Loss estimations conducted in support of disaster risk assessments and hazard mitigation plans consider the expected losses to people, buildings, infrastructure and other community assets (Coppola, 2015). Here, loss estimation includes the economic losses from the damage incurred to electric utilities and the impact to the local economy from the power outage. The total losses due to each scenario are calculated as the sum of the costs to repair the damage incurred to

([8]) The actual number of years between storms of any given intensity varies a lot. A common misconception about the 100-year storm is that it is likely to happen only once in 100 years. In reality, a 100-year storm is the storm which has a 1% annual exceedance probability, that is, a 1% chance of occurring every year. In other words, it is possible for the 100-year storm to occur two or more times per year.

([9]) Coordinated Downscaling Experiment - European Domain, https://www.euro-cordex.net/ (accessed December 4, 2018) electric utilities and the impact to the local economy resulting from the storm and the outage. The process is illustrated in Figure 6 and detailed in the following sections.

Table 3. List of EURO-CORDEX simulations used in this study

Simulation	Global Circulation Model	Regional Climate Model
1	ICHEC-EC-EARTH	DMI-HIRHAM5
2		KNMI-RACMO22E
3		CLMcom-CCLM4-8-17
4		SMHI-RCA4
5	CNRM-CERFACS-CNRM-CM5	CLMcom-CCLM4-8-17
6		SMHI-RCA4
7	MPI-M-MPI-ESM-LR	CLMcom-CCLM4-8-17
8		MPICSC-REMO2009
9		SMHI-RCA4
10	MOHC-HadGEM2-ES	KNMI-RACMO22E
11		CLMcom-CCLM4-8-17
12		SMHI-RCA4
13	NCC-NorESM1-M	DMI-HIRHAM5
14	IPSL-IPSL-CM5A-LR	IPSL-INERIS-WRF331F
15		SMHI-RCA4

Source: EURO-CORDEX ([10])

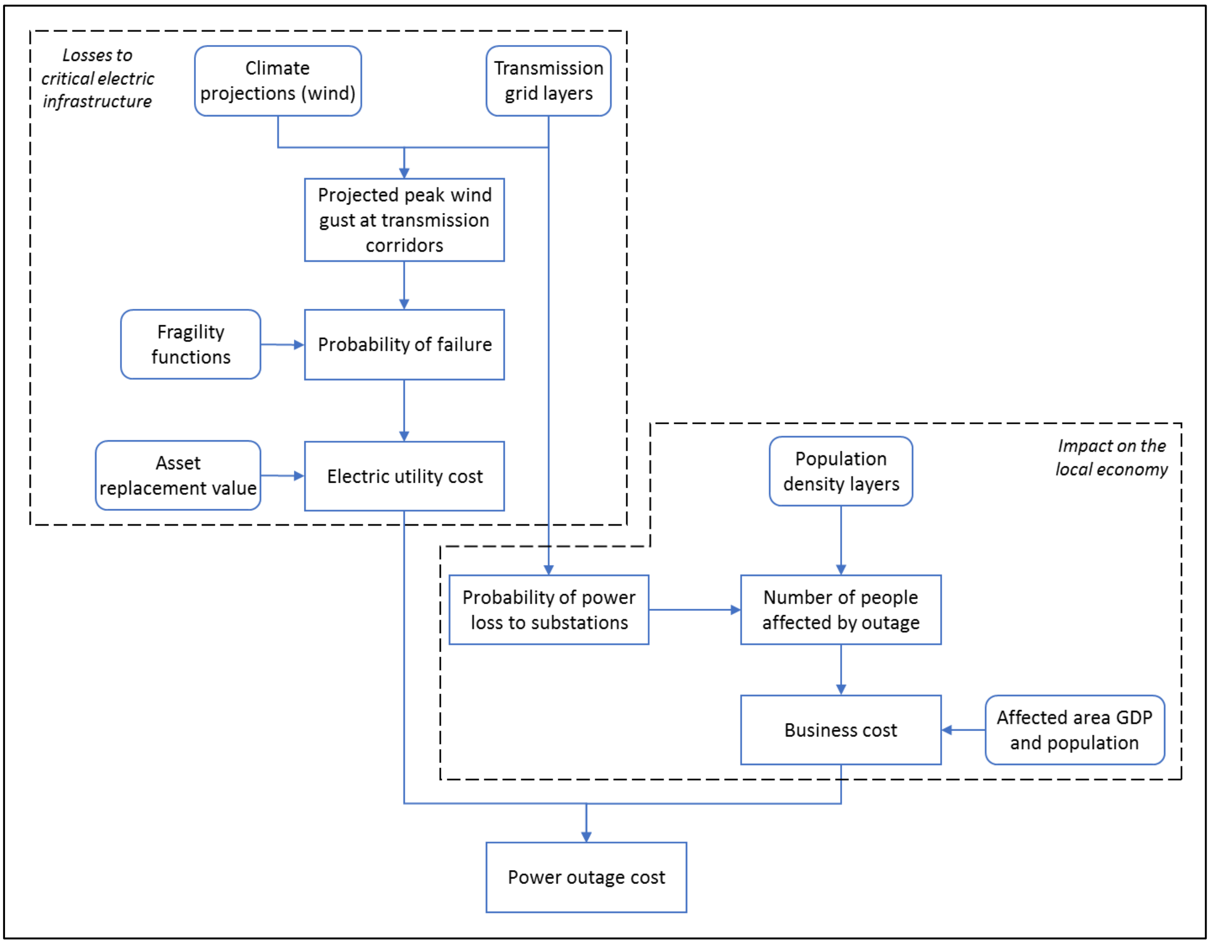
The underlying assumption is that the power outage associated with the storm does not cause additional casualties, injuries, or loss of property. This is likely to be an underestimation, because a prolonged power outage is expected to undermine disaster response capabilities, disrupt healthcare facilities, render heating and air-conditioning systems inoperable, generate traffic jams and contribute to traffic accidents (Petermann et al., 2011; Karagiannis et al., 2017a). However, existing methodologies cannot grasp the secondary effects of power outages, as these depend to a large extent on additional parameters, such as local climate and weather, and disaster response capabilities.

3.1.2.1 Losses to critical energy infrastructure

The direct losses to critical energy infrastructure are estimated as the cost of repairing the damaged power grid assets. **The repair costs are calculated from the replacement value of the assets and the potential for asset failure.** The latter is estimated from the exposure of assets to the projected peak wind speed using appropriate fragility functions (Veeramany et al., 2015).

([10]) Coordinated Regional Climate Downscaling Experiment, http://www.cordex.org/ (accessed December 4, 2018).

Figure 6. Loss estimation approach



First, we determine the exposure of power grid components to the storm. We combined geospatial data layers of electricity network assets with storm scenarios (developed as discussed in section 3.1.1) to derive the peak wind speed that power grid components are exposed to. The storm scenarios yielded the projected peak wind speed values on the vertices of a square grid with a .11 degree (approximately 12 km) edge. The projected peak wind speed was assumed to expand over the influence zone of each vertex, derived using Voronoi/Thiessen polygons (Sen, 2016; Longley et al., 2015).

Subsequently, fragility functions are used to derive the cost of repairs of damaged components from the peak wind speed data. Fragility functions express the conditional probability a damage state will be reached or exceeded as a function of the intensity of the hazard (Porter, 2015). Several fragility functions have been developed for towers and transmission lines (Dunn et al., 2018; Fu et al., 2017; Espinoza et al., 2016), which have been shown by the analysis of previous storms discussed in Chapter 2 to suffer more damage from windstorms than any other type of power grid asset. In their general form, storm fragility functions relate the probability of damage to the peak wind speed:

$$F_d(x) = P[D \geq d | X = x] \quad (1)$$

where:

— D = 0, 1... : damage state of a particular asset

— d: a particular damage state

— X: value of the hazard, i.e. the peak wind speed

— x: a particular value of X

The wind speed at the height of transmission lines is estimated from simulation values using the logarithmic law discussed in Troen & Lundtang Petersen (1989):

$$u_2 = u_1 \frac{\ln \frac{z_2}{z_0}}{\ln \frac{z_1}{z_0}} \tag{2}$$

where:

— z_2: height at which the wind speed is sought (m)

— z_1: reference height at which the wind speed is known (m)

— u_2: wind speed at height z_2 (m/s)

— u_1: wind speed at reference height z_1 (m/s)

— z_0: surface roughness, taken from Table 4 (m)

Table 4. Roughness length values used in this study and corresponding landscape types

Roughness length (m)	Landscape type
0.0002	Water surface.
0.03	Open agricultural area without fences or hedgerows and very scattered buildings. Only softly rounded hills.
0.4	Villages, small towns, agricultural land with many or tall sheltering hedgerows, forests and very rough and uneven terrain.
0.8	Larger cities with tall buildings.

Source: Troen & Lundtang Petersen, 1989.

The failure of a line is considered to be independent from tower failure, so different fragility functions are used. In addition, the outage of a transmission tower is considered to be independent of the condition of adjacent towers. The total damage is derived from the projected peak wind speed and replacement value of each affected facility or asset:

$$Total\ Repair\ Cost\ (TRC) = \sum_{j=1}^{m} \sum_{i=1}^{n} \sum_{d=0}^{D} f_{dj}(x_{ij}) \cdot RV_{ij} \tag{3}$$

where:

— i = 1, 2, …, n : facilities or assets belonging to each category

— j = 1, 2, …, m : categories of facilities or assets

— RV_{ij}: replacement value of each facility or asset i (of each category j)

— x_{ij}: peak wind speed at each facility i (of each category j)

— $f_{dj}(x_{ij})$: fragility function of facility or asset category.

3.1.2.2 Impact on the local economy

The effect of the power outage on the local economy is approximated by the economic activity that is interrupted, on a per capita basis. When all circuits supplying power to a transmission substation fail because of wind shear and/or wind-borne debris, customers connected to that substation will lose power, unless the TSO can reroute power from another location. Most transmission systems use three-wire, three-phase circuits, which are arranged in corridors consisting on series of transmission towers. In transmission grids designed for robustness and resilience, there may be more than one circuits in each corridor and each substation may be supplied by more than one corridor. In this study, a substation was assumed to lose power when all lines supplying it power were severed. A transmission line was assumed to be severed when there was at least one failure of a tower or a wire between two substations. Therefore, the probability of a substation losing power is determined based on the probability of failure of its power supply:

$$F_{out} = \prod_{C=1}^{m} F_C = \prod_{C=1}^{m} \left[1 - \prod_{T=1}^{n} (1 - F_T) \right] \tag{4}$$

where:

— F_{out}: probability of outage of a given substation

— F_C: probability of failure of corridor C

— n: number of line segments in corridor C

— m: number of corridors supplying the substation

— F_T: probability of failure of a line segment T (a line may include one or more circuits, and each circuit is made of three wires)

The area affected by the loss of power to a transmission substation is approximated by its influence zone, which is derived using Voronoi/Thiessen polygons (Sen, 2016; Longley et al., 2015). The combination of the affected area with a population density map yields the number of people affected by the outage.

The business losses from the outage are approximated by the daily economic activity that is interrupted (Zimmerman et al., 2005). The outage stops all business in the affected area until power is back online. Costs are estimated on a per capita basis. The business losses from power loss at a single substation are estimated by the following equation:

$$Business\ Cost\ (BC) = \frac{GDP \cdot t_{out} \cdot P_{out} \cdot F_{out}}{365 \cdot P_{tot}} \tag{5}$$

where:

— GDP: the Gross Domestic Product of the jurisdiction under review

— t_{out}: the estimated duration of the outage (in days).

— P_{tot}: the jurisdiction’s entire population.

— P_{out}: the population affected by the outage.

Then, the total business cost is the sum of the future business losses from the loss of power at each individual substation:

$$Total\ Business\ Cost\ (TBC) = \sum_{k} BC_i \tag{6}$$

This formulation is based on three underlying assumptions. The first is that the power outage lasts longer than the storm, therefore the first term in the numerator of the Business Cost (BC) formulation is dominated by the duration of the outage and not of the storm. This is a realistic hypothesis, because the repair of damaged electric utility assets only starts after the storm has passed. The second assumption is that the duration of the outage is the same throughout the affected area. This could be an overestimation, because power is restored progressively as repairs are made (Karagiannis et al., 2017a).

The third assumption is that the local economic activity is homogeneously distributed throughout the storm affected area. This could be an underestimation or overestimation of the business cost, depending on the locus of economic activities. For instance, if business is more concentrated near the coast, then the estimated business cost will be lower than the actual one. On the other hand, if local businesses are located away from the coast, then the estimated cost would constitute an overestimation.

3.1.3 Change in risk level

The combined impact is calculated as the sum of the total repair cost and the impact to the local economy resulting from the outage. Then, the level of risk is derived as the present value of the expected future losses incurred from each scenario (Hickman & Zahn, 1966):

$$Risk\ = E\left[\sum_{t=1}^{N}\frac{TRC_t}{(1+i)^N}+\sum_{t=1}^{N}\frac{TBC_t}{(1+i)^N}\right] \quad (7)$$

where:

— TRC_t: the total repair cost in year t, which is calculated using equation (3)

— TBC_t: the expected business losses in year t, which are calculated using equation (5)

— i: the social discount factor

— N: the number of years in the future

We analyze the change in the level of risk (expressed in terms of the expected economic losses) caused by the change (increase or decrease) of the probability of occurrence of several storm scenarios because of climate change.

In valuation analysis, the concept of time value of money reflects the notion that money available today is worth more than in the future. Therefore, a discount factor is used to convert future cash flows in their equivalent present values. In this case, cash flows are the expected total repair cost and business losses over an extended period of time in the future. From the point of view of a private entity, such as a TSO or DSO, the discount rate is the interest it has to pay. On the other hand, governments use what is called the social discount rate, which reflects the relationship between the interest rate faced by consumers and producers (Stiglitz & Rosenbauer, 2015). The choice of the social discount rate is a contested political issue and differs widely among countries. For instance, the European Commission advocates a social discount rate of 3-5% for major projects funded under the Cohesion Policy 2014-2020 programming period (DG REGIO, 2015). However, Member States use different social discount rates for different projects (Evans, 2006), or may have not regulated a social discount rate at all.

Another set of difficulties arise with the change in the characteristics of the study area over an extended period of time. First, the GDP of any country is expected to change in response to the country's economic environment, resources and other factors. All other things being equal, an increase in the GDP would bring about a proportionate increase of the business cost estimated from Equations 5 and 6, but also arguably increase the affected country's resilience. Shocks such as economic crises are notorious for being able to dramatically shrink the economy of the affected country to a fraction of its pre-crisis capability. However, economic outlooks are notoriously uncertain for periods of time longer than one or two years (Silver, 2012), let alone a few decades, as is the case in this study.

Second, population density is dynamic and depends on the population and land use. The United Nations World Population Prospects (2017) project that Europe's population will steadily decline by approximately 12% until 2100. Nevertheless, this trend is not homogeneous across the continent and the population of some EU Member States is expected to increase. In addition, landscape and land use cannot be expected to remain constant over several decades, yet are impossible to predict with any reasonable accuracy for the needs of our study. Different combinations of changes in population and land use would have wide ranging results in the business cost estimated from Equations 5 and 6. All other things beings equal, a homogeneous increase in the population density of the affected country would have no effect on the business cost, because the increases in the population of the affected country and the area suffering a power outage would cancel each other out. However, if the change was heterogeneous across the country, for instance, if the population increased more in urban areas and less in rural areas, then the business cost would change accordingly.

Last, critical infrastructure itself is aging. If no maintenance is undertaken, the condition of infrastructure assets and equipment may have been seriously degraded within the timeframe of this study. A degradation of the serviceability would only naturally increase the vulnerability to natural hazards. On the other hand, ongoing maintenance can slow down the aging process and new projects could add to the power grid's resilience through distributed generation, increased centrality and hazard mitigation measures. However, whether any such actions, or a combination thereof, will be undertaken or not, and by when, is impossible to foresee with any accuracy.

3.2 Demonstration of the methodology

A case study, based on a coastal metropolitan area in Europe, was used to demonstrate how the methodology outlined in section 3.1 would be implemented. The following sections outline the implementation. Section 3.2.1 presents the case study site. In the interest of avoiding the unintentional disclosure of any potential vulnerabilities, every effort has been made to maintain the anonymity of the case study site, even at the cost of the accuracy of the results. Section 3.2.2 discusses the change in the projected peak wind speed for several return periods given two climate change scenarios. Section 3.2.3 describes the impact severity of the storm scenarios, which was approximated by the damage to transmission grid assets and the interruption of the daily economic activity in the area because of the storm and the power outage. The change in the level of risk is outlined in Section 3.2.4.

3.2.1 Case study site

Galorndon is an anonymized sub-regional administrative division with a Chief Elected Official – Council type of government. It has a population of approximately 1,500,000 and a surface area of about 10,000 km^2. Galorndon is located on Europe's Atlantic Coast, with two navigable rivers converging near its major urban center, Galorndon Core. The topography of Galorndon is relatively flat, with forests in the south and agricultural or rural areas throughout its territory. The mean temperature ranges from 6.6^{o}C in January to 21.4^{o}C in August. The average annual rainfall is 944 mm, with a peak in November (110 mm). Electricity in the country Galorndon is managed in accordance with European and national law. The choice of the site was driven by the availability of the data needed for the loss estimation discussed in section 3.1.2, notably geospatial information on the transmission grid and the characteristics of components such as lines and substations.

3.2.2 Hazard analysis

Using the approach discussed in Forzieri et al. (2016; 2018), we derived the projected peak wind speed of the 10-, 50- and 100-year storm scenarios for five time periods, i.e. from 1981 to 2010, from 2011 to 2040, from 2021 to 2050, from 2031 to 2060, and from 2041 to 2070. In conjunction with the IPCC Fifth Assessment Report, we used two Representative Concentration Pathways (RCP) emission scenarios. The RCP8.5 scenario represents very high greenhouse gas emission, which continues to rise even after 2100, whereas the RCP4.5 scenario calls for the stabilization of radiative climate forcing at the end of the century (Moss et al., 2008).

Under both RCPs, the intensity of today's storms for a given return period would change in the future. The estimated peak wind velocities are generally greater for RCP8.5 than for RCP4.5. However, the variance of the projected velocities is generally more limited under the RCP8.5. Because of the relevance of this study to civil protection and critical infrastructure protection policies, we demonstrate the risk analysis using the RCP8.5, which *is representative of the 90th percentile of the baseline CO_2 emissions range* (Moss et al., 2008), as a reasonable worst-case scenario. Nevertheless, the methodology can be used for any RCP.

The annual probability of occurrence of each event is calculated from the return period assuming a Poisson process. For each scenario, we used a logarithmic law (Equation 2) to estimate the wind speed based on local factors, such as the above ground level (AGL) height of the affected transmission towers and land use. Table 5 below shows one example.

Table 5. Estimation of the wind speed [m/s] for a transmission tower with a height of 18m AGL, located in a residential area with a surface roughness of 0.4m

Scenario	**50-year storm**					**100-year storm**				
Time slot	1981-2010	2011-2040	2021-2050	2031-2060	2041-2070	1981-2010	2011-2040	2021-2050	2031-2060	2041-2070
Area wind speed	28.72	28.88	28.74	28.69	28.72	29.61	29.73	29.58	29.53	29.6
Local wind speed	29.72	29.81	29.73	29.63	29.54	32.51	32.70	32.54	32.48	32.51

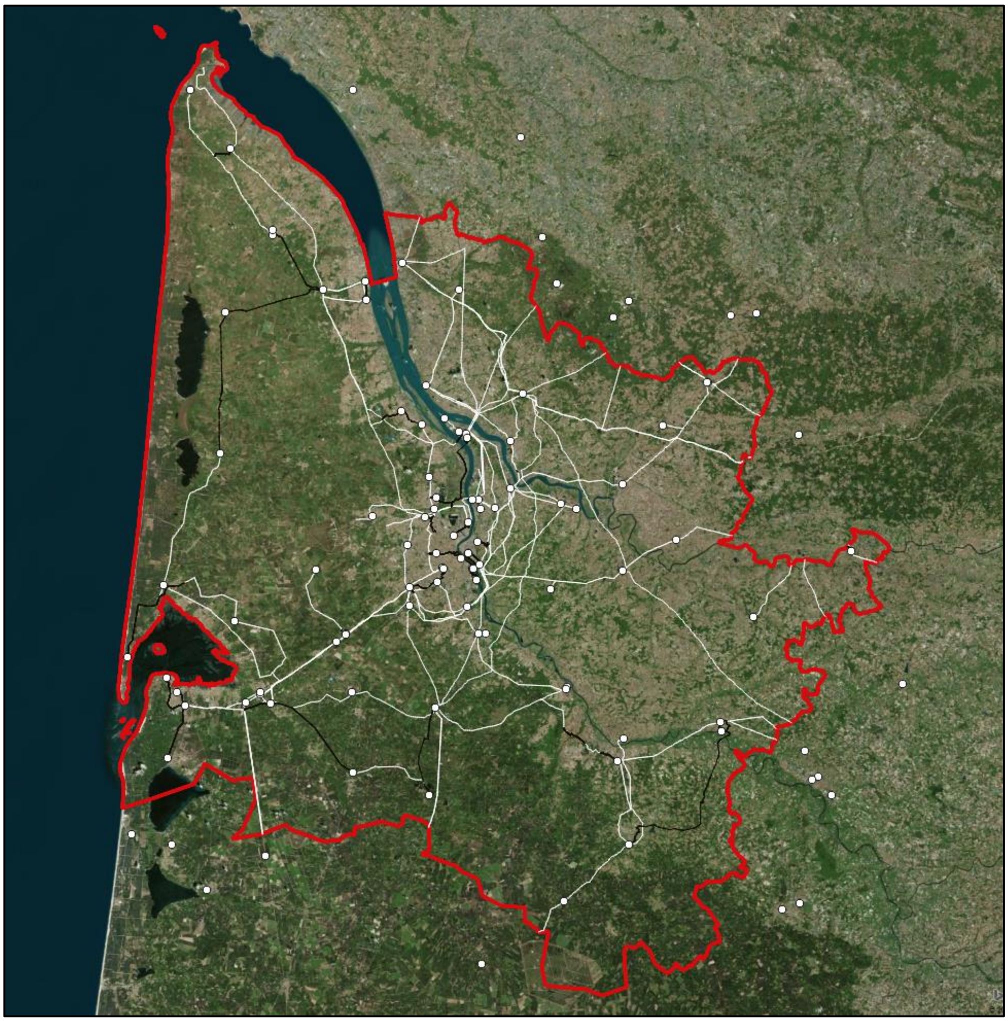
3.2.3 Loss estimation

3.2.3.1 Data and assumptions

The transmission grid layers were obtained from the open data platform of the country's TSO. In this study, we used the layers of substations and transmission lines. There are 41 transmission substations (maximum voltages of 400 kV down to 63 kV) and over 227 km of transmission lines (400 kV, 225 kV, 90 kV and 63 kV). Figure 7 below illustrates the transmission network in and around Galorndon. The jurisdiction's layers were taken from the country's open data portal and the transmission grids layers from the open data portal of the country's TSO. There are 41 substations and over 227 km of lines. We assumed no significant upgrade in or degradation of the transmission grid infrastructure until 2070.

As discussed in Chapter 2, tall, slender structures, such as transmission towers, distribution poles and wind turbines are most affected by storms. Transmission and distribution assets can also be damaged by the impact of flying debris. Substations were also found to be affected by storms, particularly by inundation and airborne debris, albeit to a lesser extent compared to transmission and distribution lines. Nevertheless, fragility functions have been developed for transmission towers and lines only (among others, Dunn et al., 2018; Panteli & Mancarella, 2015; Prahl et al., 2015; Prahl et al., 2016; Winkler et al., 2010). Winkler et al., (2010) use building fragility functions to estimate the potential losses to transmission substations. Here, we used the analytical fragility functions for transmission towers and overhead lines developed by Panteli & Mancarella (2017). This family of fragility functions, which includes separate functions for overhead lines and towers, was considered a better fit for the needs of this particular study than a single fragility or damage function for both types of assets across a corridor. Panteli et al. (2017) highlight the relative lack of empirical fragility functions and the high costs associated with the development of experimental fragility curves for transmission towers and overhead lines. The replacement value of transmission lines was considered as € 900,000 per km (ICF Consulting, 2002).

Figure 7. Map of the transmission grid on and around Galorndon (white: substations and overhead lines; black: underground lines)



Source: JRC. Background: Bing®.

In this particular case, the projected peak wind speeds were quite low, consequently the probability of damage to individual transmission towers was consistently null according to the base case fragility function proposed by Panteli et al. (2017). Therefore, the analysis shows no damage to transmission towers. This outcome however is in contrast to the incident analysis in Chapter 2, which indicates that transmission towers are affected in nearly every storm in that dataset.

In addition, as discussed in section 3.1.2.2, a substation was assumed to lose power when all lines supplying it with power were severed. When a substation loses power, all customers connected to that substation will lose power, unless the TSO can reroute power from another location. The area affected by the loss of power to a transmission substation is approximated by its influence zone, which is derived using Voronoi/Thiessen polygons. Therefore, the probability of any location experiencing a blackout is equal to the probability of loss of power to the substation. However, transmission networks are built so that each higher-voltage substation supplies power to one or more lower-voltage substations and so on. For example, each 400 kV substation will be supplying power to several 225 kV substations, each 225 kV substation will be supplying power to several 90 or 63 kV substations etc., until power reaches the sub-transmission and distribution network. In other words, each customer will be connected to at least one substation from each voltage category. Therefore, if we considered the area affected by the loss of power to more than one category of substations, we would be counting each location more than once and would be estimating the expected business losses based on a largely overestimated population. To avoid multiple counting, only 225 kV substations were included in the analysis. This voltage category was selected as a good compromise between granularity of coverage and the need to minimize the impact of the grid's centrality on the analysis.

Population density was determined based on national census data for the area under consideration. Several assumptions were made in the interest of anonymity, including homogeneous population density throughout the case study area and no significant population changes since the last population census. With a view to maintaining the anonymity of the case study area, we used the same GDP throughout the study period, assuming no significant change in the national economy of the case study site until 2070. The social discount factor was not included in the calculations for the same reason.

3.2.3.2 Results

One of the first outcomes of this approach is the probability of loss of power to individual substations. As an example, Figure 8 illustrates the probability of loss of power to each 225 kV substation in the study area in the 100-year storm for each time slot due to line severing. The substations have been designated as A to N. Substation K is by far most likely to lose power throughout all 5 time slots, because it is connected to less corridors which are exposed to higher wind speeds. By contrast, the probability of loss of supply to substations A, D L is negligible, and very limited for substations C, G and J. The lower level of risk is due to a combination of two factors. First, these substations are connected to more corridors, which makes their power supply more resilient. Second, they are exposed to milder winds, which reduces the likelihood of damage to any line or circuit.

Of particular interest is the lack of significant change of the probability of loss of power supply to the substations across the five time periods. This is attributable to the limited variation of the intensity of the 100-year storm for short- and medium-term projections. The reason of this relative homoscedasticity is that we use the ensemble mean from 15 simulations, some of which may project an increase in return levels, while others may project a decrease.

The expected economic losses resulting from direct damage to the transmission grid and the interruption of daily economic activity are illustrated in Figure 9. Here, it was assumed that 400 kV and 225 kV corridors included twin circuits, whereas 90 kV and 63 kV corridors each included a single circuit. This configuration is used here as an example of a typical case in that area. However, the number of circuits for each individual corridor can be easily modified according to any grid architecture. In addition, in this case, the power outage was assumed to last for three days on average throughout the area.

For each recurrence interval, the cost to repair the damage to overhead lines and the economic losses from the interruption of the daily economic activity amount each for about half of the total losses. Nevertheless, **the repair cost fraction increases (by approximately 10% of the total cost) for the 50-year and the 100-year storms compared to the 10-year scenario.** Because the projected peak wind speed values were relatively low, the risk due to damage to transmission towers was negligible in this case. Furthermore, the expected economic losses from each scenario follow a discernible pattern across all time slots. Specifically, there is an initial increase in the total economic losses during the period 2011-2040, which is followed by a progressive decrease until 2070. The change is more pronounced for the 10-year scenario, but remains statistically insignificant overall.

Figure 8. Probability of loss of power to 225 kV substations under the 100-year storm

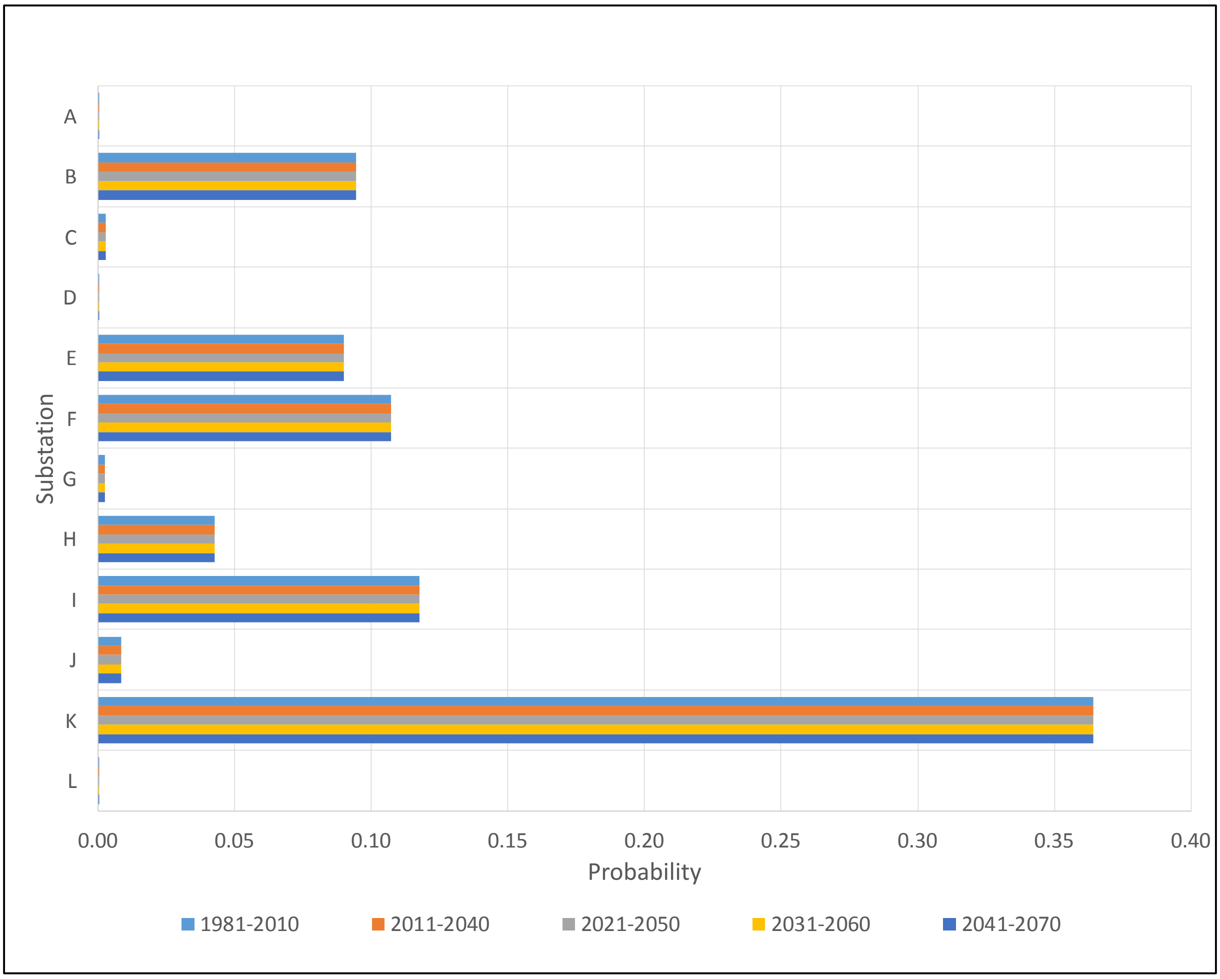
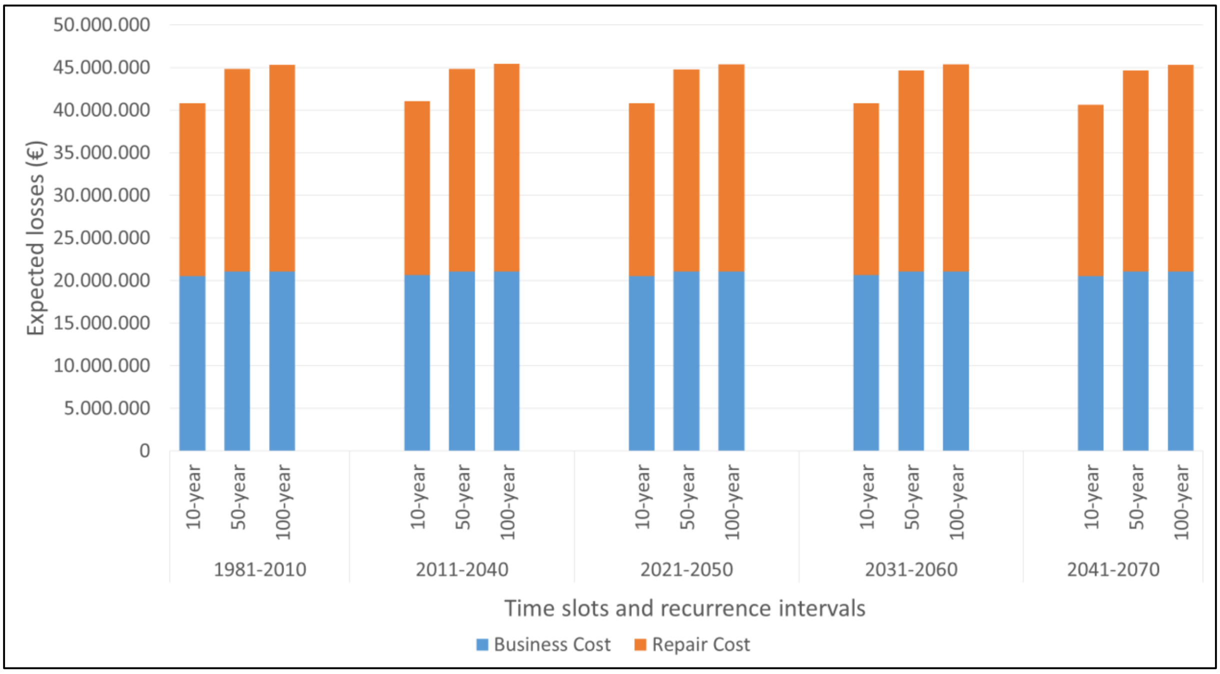


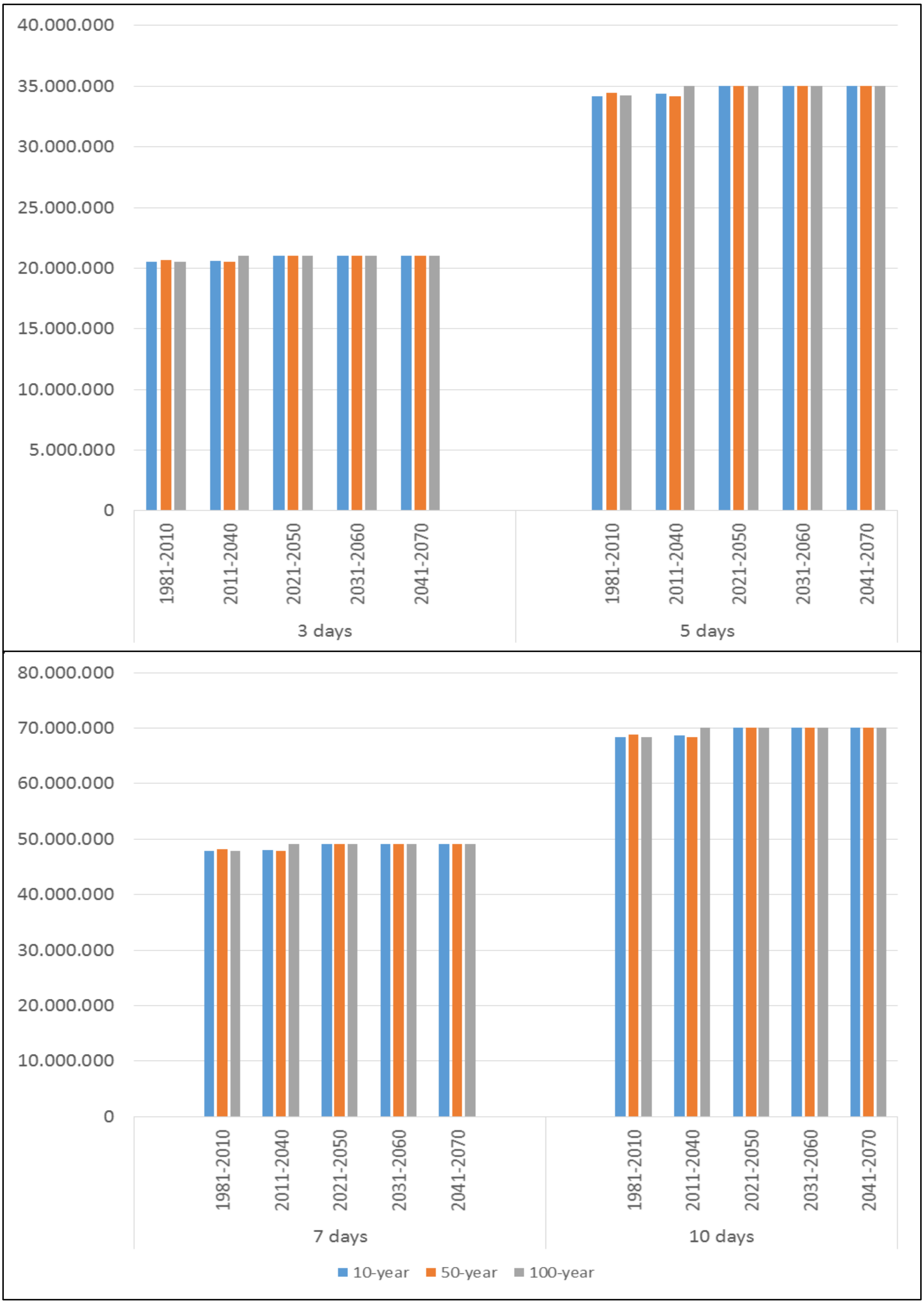
Figure 9. Expected economic losses from the 10-year, 50-year and 100-year storm across five sequential and partially overlapping time periods



Moreover, **the total expected losses increase (by approximately 10% of the total) for the 50-year and the 100-year storms compared to the 10-year scenario.** This change seems to be driven by the repair cost increase. In other words, the damage to the transmission grid becomes more critical for the 50-year and the 100-year scenarios, compared to the 10-year storm. Nevertheless, there is no statistically significant increase of the economic impact from the 50-year to the 100-year storm. Nevertheless, this result is conditional on the assumption of a constant power outage duration across all scenarios. Although, *ceteris paribus*, a higher storm wind speed would arguably result in more severe and widespread damage in the affected area, the incident analysis discussed in Chapter 2 does not provide sufficient information to correlate the return period of the storm with the duration of the power outage.

The duration of the power outage is indeed an uncertain determinant of the expected losses resulting from the disruption of the daily economic activity. On the other hand, the Total Repair Cost was assumed to be independent of the duration of the outage for the range of recovery times outlined in Table 1. So far, the duration of the power outage was assumed to be three days, a minimum emergency planning threshold (McEntire, 2018). As discussed in Chapter 2 and Karagiannis et al. (2017a), the duration of a power outage in any location depends on the duration of the storm (because repairs start when it is safe for crews to operate), the extent of the damage, the repair capabilities of the TSO/DSO and the prioritization of the repairs. Furthermore, power is restored progressively as repairs are made. Figure 10 illustrates the sensitivity of the Total Business Cost of the 100-year scenario to the duration of the outage. As the duration of the power outage increases from 3 to 10 days, the estimated business cost increases as well and progressively becomes the main determinant of the total impact. Whereas at 3 days, the Total Business Cost is about half the Total Cost, at 10 days it is more than double the Total Repair Cost. Investments in emergency repair capabilities can help expedite the power grid's recovery and limit the duration of the outage. A sensitivity analysis such as the one discussed here **can be useful in estimating whether the cost of developing and maintaining these capabilities is justified by the mitigation of the impact resulting from the disruption of the daily economic activity.**

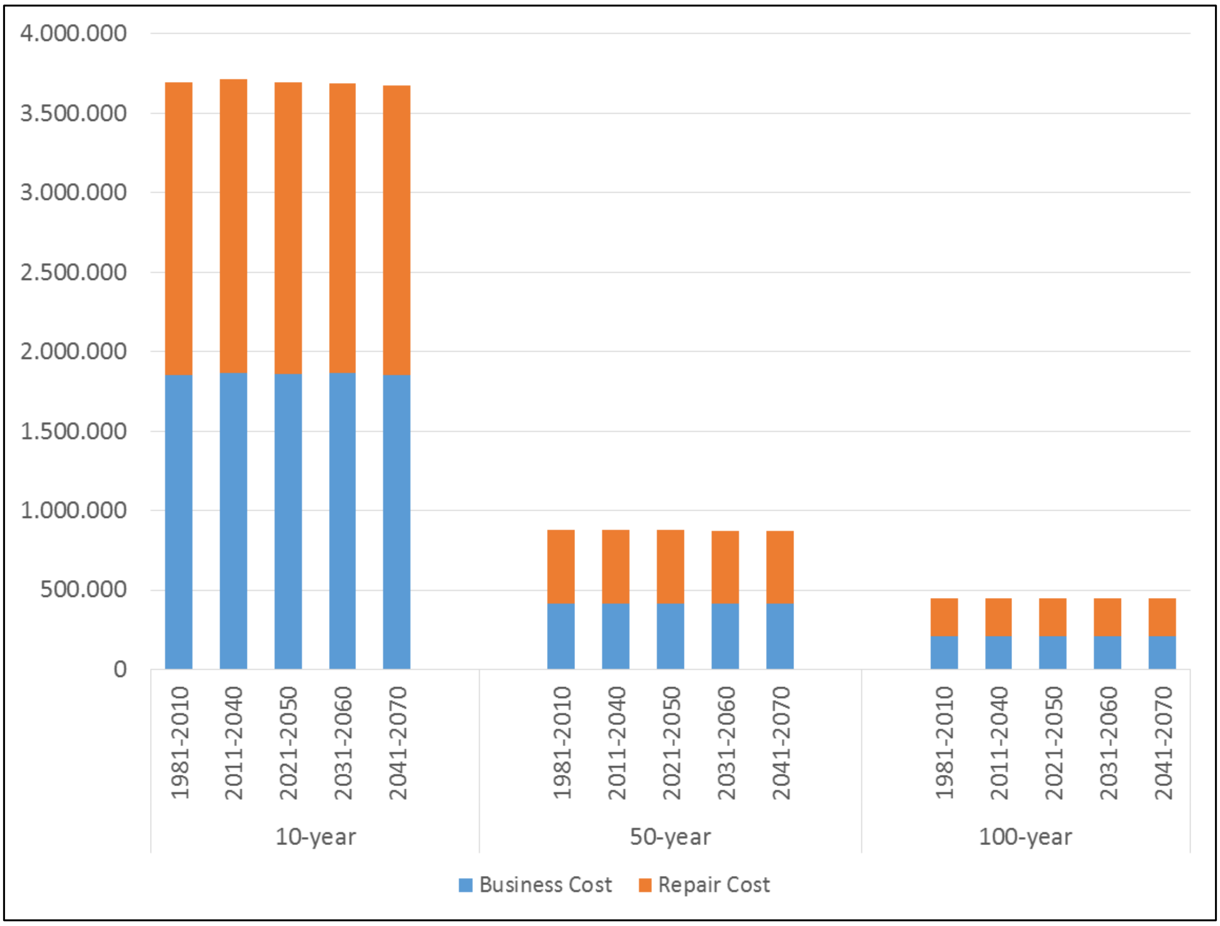
Figure 10. Total business cost for different power outage scenarios (note the y-axis scale change for 7 and 10-day outage)



3.2.4 Risk analysis

The level of risk is estimated based on the expected economic losses from the storm and the power outage it could trigger. Figure 11 presents the level of risk (i.e. the product of the occurrence probability and the estimated economic losses) for each scenario. Here, the business cost estimation is based on a 3-day power outage. The 10-year scenario comes with the highest level of risk and the 100-year scenario is associated with the lowest level of risk. Specifically, the risk of the 50-year storm is twice that of the 100-year storm, and the risk from the 10-year storm is more than three times that of the 50-year scenario. Nevertheless, the level of risk (expressed in terms of economic losses) does not appear to change substantially over time.

Figure 11. Change in the level of storm risk to critical energy infrastructure in the case study area



The risk analysis presents two counter-intuitive outcomes. First, the risk from the 10-year storm appears to be much higher than the 100-year scenario. Yet the intensity of most natural hazards (including meteorological hazards, such as storms) increases as the return period increases. In addition, conventional wisdom suggests that more devastating storms are a rarer occurrence. However, risk is a function of the probability of occurrence and the estimated severity. In this case, the expected losses for the 50-year and the 100-year storms are 10% greater than those for the 10-year storm. **Therefore, the level of risk (expressed as economic losses) is driven by the probability of each scenario. In other words, the 10-year storm has a higher risk because it is expected to occur more frequently.**

As discussed in the previous sections, this outcome is due to several reasons. One is the relatively low values of projected wind speeds in the case study area, possibly because of the coarse spatial resolution. With these projections, the estimated probability of damage to transmission lines was limited and no damage was expected to occur to transmission towers at all. In addition, the increase of the projected wind speed from the 10-year to the 50-year to the 100-year scenario is relatively limited and does not result in a significant increase of the probability of damage to transmission lines, and therefore of the probability of loss of power to substations. Therefore, the increase of the total expected losses from the 10-year to the 50-year and the 100-year storm is about 10%.

Another reason is that the increase of the estimated business losses is limited because of the assumption of a constant duration resulting from the power outage. One could argue that the 100-year storm would be more intense and therefore produce more damage than the 10-year storm. For a constant repair capability level, more damage would arguably prolong the recovery period and thus lead to a longer power outage. However, the relationship between the level of damage and the duration of the power outage may not be linear, and the available data are insufficient to produce a mathematical correlation. Furthermore, the projected peak wind speed values are greater for the 100-year storm than for the 50-year and the 10-year storms, but the difference is relatively limited.

The second outcome of the risk analysis which merits discussion is that the level of risk does not appear to change significantly over time. Although the difference in the level of risk among the 10-year, the 50-year and the 100-year scenarios is dominated by the scenario probabilities, the change over time is driven by the estimated impact, which was shown above to have statistically insignificant changes. In this particular case, this means that **climate change would not result in a substantial change of the level of risk posed from storms to the power grid in Galorndon.** At first glance, this finding could be interpreted as an overall limited change of the risk of economic losses from storms to the power grid under climate change. However, we argue against such a generalization. This finding is probably due to the use of the ensemble mean from 15 simulations, which may project an increase or decrease in return levels. More importantly, Forzieri et al. (2018) underline that it is the Mediterranean, not Europe's Atlantic coast, which is likely to be most exposed to storms in light of climate change. Therefore, the analysis of the risk of an area with higher exposure to wind loads and perhaps a less resilient power grid could arguably yield a much greater change in the level of risk.

The findings of the risk analysis demonstrate a favorable case for Galorndon. Specifically, the highest level of risk of economic losses stems from the 10-year storm. Therefore, prevention and preparedness efforts should focus on this scenario. **The overall low level of probability of failure of individual assets suggests that investing in emergency repair and recovery capabilities should be economically justified** in this case, as the initial investment and maintenance cost will be spread over most, if not all, assets and over a large time frame.

3.3 Discussion

The purpose of this study has been to elucidate the vulnerability of critical infrastructure to storms, especially in light of climate change. We have focused on critical energy infrastructure as a first step. In what follows, we first discuss the implications of this study for disaster risk management, then we outline the limitations of the case study.

As any modeling effort, our results may be suffering from the epistemic uncertainty related to our understanding of climate change and the impact of natural hazards on infrastructure. In this case, the estimated impact of climate change on the level of risk is critically dependent on the potential uncertainties in the data and the climate models used. Due to the coarse spatial resolution and the intrinsic features of climate models, in particular the Global Circulation Models, extreme values may be reduced and simulations may yield lower than expected peak wind speeds for single events. Moreover, the fragility functions for storms are less mature compared to those for other natural hazards, such as earthquakes or floods.

Second, Voronoi/Thiessen polygons effectively approximate the influence zone of each substation, but they come with two disadvantages. First, the influence zone determined by the Thiessen polygon may not correspond to the actual area receiving power from the substation. In other words, the distribution network may be built in such a way that each client does not get power from their nearest substation. Second, the use of Thiessen polygons assumes that each client may receive electricity from only one substation. If that substation is shut down, then this client loses power until the substation is brought back online. However, each client may be connected to two or more substations, and redundancies are often built into the transmission grid (and more often in the distribution grid), which allow TSOs to switch to a different source when a substation is shut down.

Third, as discussed in a previous study (Karagiannis et al., 2017b) the methodology presented in Chapter 3 does not take into account the interdependencies between the power grid and other critical infrastructure systems, and may underestimate the severity of the consequences. The impact of dependencies and interdependencies on the resilience of critical infrastructure systems is notorious (Rinaldi et al., 2001; Pescaroli & Alexander, 2016). In addition, electricity is recognized as the critical infrastructure upon which all others rely.

Last, this approach does not consider the inherent redundancy of the transmission grid. When a line or substation is out of service, the TSO can reroute power through other circuits. In fact, the ENTSO-E Continental Europe Operation Handbook ([11]) requires that the loss of any single element (such as line, generating unit or transformer) shall not cause a cascading failure outside the border of the affected TSO (N-1 principle). Although the assumption of a power outage resulting from the loss of a substation is supported from empirical data to a certain extent, as discussed in Chapter 2 and Karagiannis et al. (2017a), the results may be an overestimation of the probability and consequences of the power outage.

Opportunities for further research include the extension of the approach to other critical infrastructure systems, provided that appropriate fragility functions are available. In addition, the methodology could arguably be improved if it were combined with network analysis to help determine the cascading effects of the loss of one substation to the grid. Another possible improvement would be the consideration of population, land-use and economy dynamics in the estimation of the impact from the interruption of the daily economic activity. Last, the findings of Chapter 2 can be combined with information from previous studies (among others, Karagiannis, et al., 2017a; Petermann et al., 2011) to identify cost-effective and sustainable, structural and organizational protection measures for critical infrastructure against selected natural hazards.

([11]) European Network of Transmission System Operates for Electricity, *Continental Europe Operation Handbook*, https://docstore.entsoe.eu/publications/system-operations-reports/operation-handbook/Pages/default.aspx (accessed November 29, 2018)

4 Recommendations for disaster risk management

The findings of this study reinforce and confirm several recommendations discussed in Karagiannis et al. (2017a), outlined in Table 6. The reader is referred to that previous study for a detailed discussion of these recommendations. The evidence discussed here justifies these Recommendations based on the same rationale as in Karagiannis et al. (2017a). One addition could be made to Recommendation 6 pursuant to this is that Emergency Restoration Systems (ERS) should be part of the emergency response equipment cache of any TSO or DSO whose assets are located in high-risk areas for storm loading.

Table 6. Recommendations from Karagiannis et al. (2017a) supported by the findings of Chapter 2 of this report

Recommendation 3	Transition from hardening system assets and facilities to building resilience into the grid.
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.
Recommendation 6	Stockpile spare items to expedite the repair or replacement of key assets and equipment.
Recommendation 7	Ensure interoperability among neighboring TSOs, TSOs and DSOs, and between TSOs/DSOs and emergency management organizations.

Source: Karagiannis et al., 2017a.

Besides reinforcing several recommendations from a previous study, the findings of this study support four additional recommendations about disaster management for critical energy infrastructure.

Recommendation 1: *Consider increasing transmission tower design requirements for resistance to wind loading in standards and regulations.*

Chapter 2 illustrated that utility poles (i.e. transmission towers and distribution poles) and overhead lines are the most vulnerable component of the power grid to wind storms, suffering failures from horizontal wind loading. In addition, Forzieri et al. (2018) estimated that the peak wind speed is likely to increase throughout Europe in the future and the change is likely to be more pronounced in coastal areas. Chapter 3 showed that, for such an area, the increase in the peak wind speed can also increase the risk from wind storms, resulting from direct damage to the transmission grid and the ensuing power outage. Reinforcing steel lattice tower structures located in coastal and other high-risk areas to resist wind loads should decrease the risk associated with wind storms. Increasing the requirements stipulated in relevant regulations and standards, such as IEC Standard 60826 and Eurocode 1 (Part 1-4), could help harmonize design specifications across Europe. In addition, structural mitigation measures, such as strengthening the foundations of transmission towers to prevent toppling, could also help mitigate against flood and earthquake forces. A benefit-cost analysis should be used to analyze the cost-effectiveness of this approach. The risk assessment methodology introduced in Chapter 3 could be used to support the calculation of the benefit-cost ratio.

Recommendation 2: *Consider the risk from climate change in investment analyses.*

This study and other publications (Forzieri et al., 2018; Karagiannis et al., 2017b) have demonstrated that climate change will change (increase or decrease) the risk posed from meteorological hazards to critical infrastructure in Europe. Risk assessments and cost-benefit analyses are often part of the decision-making process when new infrastructure investments are contemplated. If these studies do not consider climate change, they will likely be based on under- or over-estimated assumptions about the frequency and intensity of meteorological hazards critical infrastructure assets may be exposed to. The methodology presented in Chapter 3 can be used to support such analyses for storms, whereas the approach described in Karagiannis et al. (2017b) can be used for similar analyses for floods.

Recommendation 3: *Consider events with recurrence intervals longer than 100 years in hazard mitigation and emergency planning.*

Although disaster risk assessments will typically analyze several storm scenarios, the 100-year event is considered the standard reference in hazard mitigation and emergency planning for many meteorological hazards. The analysis of the 10-year, 50-year and 100-year storm scenarios in this study showed that the level of risk would not change substantially, largely because the projected peak wind speed values would remain relatively stable. Therefore, a prudent disaster risk management approach would be to consider events with recurrence intervals longer than 100 years when designing hazard mitigation measures. It is also considered a wise emergency management practice to develop emergency operations plans based on the worst-case scenario according to historical data (Perry & Lindell, 2007).

Recommendation 4: *Standardize mutual aid resources*

The lack of direct interoperability with mutual aid resources and non-traditional responders is a notorious disaster response challenge (US Fire Administration, 2015). As natural disasters overwhelm emergency response and recovery capabilities, TSOs/DSOs turn to neighboring utilities for help. These operations involve many diverse organizations and require interoperability among TSOs, DSOs, regulatory agencies and civil protection. As discussed in chapter 2 and Karagiannis et al. (2017a), mutual aid responses come with a wide range of challenges, including barriers to access, coordination and quality. Mutual aid agreements should address several issues, including:

- Initiation and termination of international assistance.
- Transportation and entry of repair tools, spare parts and telecommunications and information technology equipment.
- Qualification and credentialing of personnel. Engineering and technician professions are generally regulated in most EU Member States, and do not fall under the automatic recognition scheme of Directive 2005/36/EC ([12]). Directive 2006/123/EC ([13]) allows professionals, including those exercising regulated professions such as engineers and technicians, to provide services across EU Member States. Nevertheless, issues such as liability and malpractice insurance may not be addressed.
- Coordination with mutual aid crews and civil protection agencies.
- Telecommunications, including the use of radios.

One possible solution could be the standardization of repair crews and similar resources under the Union Civil Protection Mechanism. Resource typing has proven to facilitate efficient and effective deployment of resources in the emergency management and fire/rescue communities (FEMA, 2017; Mutual Aid System Task Force, Fairfax, VA, 2006). In the framework of the Union Civil Protection Mechanism, Modules are self-sufficient, standardized task forces, capable of being deployed overseas at a short notice to augment the response capabilities of a disaster-affected country ([14]). Several other types

([12]) Directive 2005/36/EC of the European Parliament and of the Council of 7 September 2005 on the recognition of professional qualifications (OJ L 255, 30.9.2005, p. 22-142)

([13]) Directive 2006/123/EC of the European Parliament and of the Council of 12 December 2006 on services in the internal market (OJ L 376, 27.12.2006, p. 36-68)

([14]) Commission Implementing Decision of 16 October 2014 laying down rules for the implementation of Decision No 1313/2013/EU of the European Parliament and of the Council on a Union Civil Protection Mechanism and repealing Commission Decisions 2004/277/EC, Euratom and 2007/606/EC, Euratom (OJ L 320, 6.11.2014, p. 1-45) of resources, including experts and equipment, can be requested via DG ECHO's Common Emergency Communication and Information System (CECIS). The system has proven to be versatile enough to manage various types of international assistance, including large power generators (DG ECHO, 2012). Therefore, mutual aid resources for electric power companies could be standardized under the UCPM. Analyzing this policy, including its effects, costs and feasibility, should be a joint endeavor of ENTSO-E and DG ECHO, while the JRC could have a supporting role.

Recommendation 5: *Plan for surge capabilities and external contractors.*

When disaster strikes, electric power companies often rely on contractors to augment their emergency repair and restoration capability on short notice. TSOs and DSOs should prepare for these operations before disaster strikes. Planning and preparedness should address resource management, documentation, finance, administration, insurance and other topics. Power companies should consider entering into standby contracts with local and regional contractors to minimize delays and administrative challenges. Staff need to be trained according to their duties and responsibilities. Last, these procedures need to be exercised together with external contractors, with a view to improving coordination and communications, and clarifying roles and responsibilities.

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List of abbreviations and definitions

AGL	Above Ground Level
DG	Directorate-General
DSO	Distribution System Operator
ECHO	Directorate-General for European Civil Protection and Humanitarian Aid Operations
ENTSO-E	European Network of Transmission System Operators for Electricity
FEMA	Federal Emergency Management Agency
GCM	Global Circulation Model
GDP	Gross Domestic Product
IAFC	International Association of Fire Chiefs
IEC	International Electrotechnical Commission
NPP	Nuclear Power Plant
OSCE	Organization for Security and Cooperation in Europe
RCM	Regional Climate Model
RCP	Representative Concentration Pathways
TSO	Transmission System Operator
UCPM	Union Civil Protection Mechanism

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Annex

This annex includes a list of the storms reviewed in this study, listed in Table 7 by continent.

Table 7. Storms reviewed in this study, by continent

Date	Country/Region	Storm type/name	Peak wind speed (km/h)
		Europe	
1 September 1996	France	Wind storm	116-179
25 December 1999	France	Cyclone Lothar	150-250
28 December 1999	France	Cyclone Martin	200
7-9 January 2005	Estonia	Cyclone Gudrun (Erwin)	135
7-9 January 2005	Sweden	Cyclone Gudrun (Erwin)	165
26 November 2005	Western Europe	Snow storm	65
17 January 2007	UK	Cyclone Kyrill	160
18 January 2007	Germany	Cyclone Kyrill	202
18 January 2007	Czech Republic	Cyclone Kyrill	200
23-27 January 2009	France	Cyclone Klaus	198
26 February-7 March 2010	Portugal	Cyclone Xynthia	228
26 December 2011	Finland	Tapani Storm (Cyclone Dagmar)	108
18-24 January 2013	Portugal	Cyclone Gong	140
1 October 2013	Finland	Cyclone Eino	120
13 December 2013	Sweden	Cyclone Ivar	
13 December 2013	Estonia	Cyclone Ivar	115
1 January 2018	France	Storm Carmen	130
3 January 2018	France	Storm Eleanor	140
18 January 2018	Germany	Cyclone Friederike	203

North America			
21 September 1989	US	Hurricane Hugo	260
4-10 January 1998	US	Ice storm	
4-10 January 1998	Canada	Ice storm	
25 September 1998	US	Hurricane Georges	175
30 January 2002	US	Snow storm	
22 July 2003	US	Wind storm	144
29 August 2005	US	Hurricane Katrina	201
24 September 2005	US	Hurricane Rita	290
22-25 October 2005	US	Hurricane Wilma	190
14 December 2006	US	Wind storm	183
1-4 December 2007	US	Wind Storm	235
2 September 2008	US	Hurricane Gustav	340
13 September 2008	US	Hurricane Ike	177
11-12 December 2008	US	Winter storm	
27-28 January 2009	US	Ice storm	
25 July 2010	US	Wind storm	96-112
26 August 2011	US	Hurricane Irene	230
28 August 2012	US	Hurricane Isaac	128
29-30 October 2012	US	Hurricane Sandy	155
22 December 2013	US	Ice storm	
22 December 2013	Canada	Ice storm	
29 August 2015	US	Wind storm	145
17 November 2015	US	Wind storm	122
25 February 2017	US	Wind storm	96.5
25 August 2017	US	Hurricane Harvey	120
10 September 2017	US	Hurricane Irma	215
20 September 2017	US	Hurricane Maria	250

Oceania			
10 January 1997	New Zealand	Cyclone Drena	130
28-29 February 2004	New Zealand	Cyclone Ivy	124
26 January 2011	New Zealand	Cyclone Wilma	260
2 February 2011	New Zealand and Australia	Cyclone Yasi	290
11-15 December 2012	Samoa	Cyclone Evan	210
7-17 March 2014	New Zealand	Cyclone Lusi	130
2-14 March 2015	New Zealand	Cyclone Pam	320
28 March 2017	New Zealand and Australia	Cyclone Debbie	263
9-14 April 2017	New Zealand	Cyclone Cook	200
8 November 2017	New Zealand	Storm with rain and snow	154
5 January 2018	New Zealand	Wind storm	128
Asia			
24 January 2008	China	Winter storm	

KJ-NA-29411-EN-N

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Publications Office

doi:10.2760/986436

ISBN 978-92-79-96403-9