



PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE  
SCHOOL OF ENGINEERING

**MULTI-PHASE RESILIENCE  
ASSESSMENT AND ADAPTATION OF  
ELECTRIC POWER SYSTEMS  
THROUGHOUT THE IMPACT OF  
NATURAL DISASTERS**

**SEBASTIAN ANDRES ESPINOZA**

Thesis submitted to the Office of Research and Graduate Studies in  
partial fulfilment of the requirements for the Degree of Master of  
Science in Engineering

Advisor:  
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Santiago de Chile, October 2015.

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*To my loving sister, mother and  
grandmother.*

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I finally hope this research is a small contribution to the disaster management and electric power systems fields. Chile and countries affected by major natural disasters need to improve their actions at the preparedness, response, recovery and mitigation stages while having a special care for those in need within the society, who are at the same time the most affected.

*”Pray as though everything depended on God. Work as though everything depended on you”. - Saint Augustine*

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## ABSTRACT

Around the world natural disasters, such as floods, ice and windstorms, hurricanes, tsunamis, earthquakes and other high impact and low probability events have affected countries' public security and economic prosperity. Furthermore, as a direct impact of climate change, the frequency and severity of some of these events is expected to increase in the future. This highlights the necessity of evaluating the impact of these events and investigating how man made systems can withstand major disruptions with limited service degradation and recover rapidly.

In this context, a multi-phase resilience framework is proposed here, which can be used to analyse any natural threat that may have a severe single, multiple and/or continuous impact on critical infrastructure, particularly electric power systems. Firstly, resilience assessment phases are presented: (i) threat characterization, (ii) vulnerability of the system's components, (iii) system's reaction and (iv) system's restoration. Secondly, multi-phase adaptation strategies, i.e., making the system more robust, redundant and responsive are explained to discuss different options to enhance the resilience of the network.

To illustrate the above, this time-dependent framework is applied to assess the impact of potential future windstorms and floods on a simplified version of the Great Britain's power system and to assess the impact of potential future earthquakes on a reduced version of the Northern Chilean Interconnected System. Finally the adaptation strategies are evaluated to conclude in what situations a stronger, bigger or smarter grid is preferred against the uncertain future.

**Keywords:** Adaptation strategies, earthquakes, electric power systems, floods, fragility curves, reliability, resilience, resiliency, windstorms.

## RESUMEN

Alrededor del mundo desastres naturales como inundaciones, tormentas de nieve y viento, huracanes, tsunamis, terremotos y otros eventos de baja probabilidad y alto impacto han afectado la seguridad pública y la prosperidad económica de los países. Aun más, como impacto directo del cambio climático, se espera un incremento de la frecuencia y severidad de algunos de estos eventos en el futuro. Esto remarca la necesidad de evaluar su impacto e investigar cómo los sistemas construidos por el hombre pueden soportar alteraciones mayores con una degradación limitada del servicio junto a una rápida recuperación.

En este contexto, se propone un marco multi-fase de la resiliencia, el cual puede usarse para analizar cualquier amenaza natural que tiene un gran único, múltiple y/o continuo impacto sobre infraestructura crítica, particularmente sistemas eléctricos de potencia. Primero, fases de evaluación de la resiliencia son presentadas: (i) caracterización de la amenaza, (ii) vulnerabilidad de los componentes del sistema, (iii) reacción del sistema y (iv) restauración del sistema. Segundo, estrategias de adaptación multi-fase, i.e., haciendo el sistema más robusto, redundante y responsivo son explicadas para discutir diferentes opciones para mejorar la resiliencia de la red.

Para ilustrar lo anterior, este marco tiempo-dependiente es aplicado para evaluar el impacto de potenciales futuras tormentas de viento e inundaciones en una versión simplificada del sistema eléctrico de Gran Bretaña y para evaluar el impacto de potenciales futuros terremotos en una versión reducida del Sistema Interconectado del Norte Grande de Chile. Finalmente, las estrategias de adaptación son evaluadas para concluir en qué situaciones una red más fuerte, grande o inteligente es preferida para enfrentar el incierto futuro.

**Palabras Claves:** Confiabilidad, curvas de fragilidad, estrategias de adaptación, inundaciones, resiliencia, sistemas eléctricos de potencia, terremotos, tormentas de viento.

## **1. INTRODUCTION**

Natural disasters around the world have affected the social and economic wellbeing of societies (P. Southwell, 2014). Furthermore, it is expected that some of these events may occur more often and with greater severity, mainly because of global warming and climate change (R. Pachauri and L. Meyer, 2014). Therefore, it is a necessity to develop techniques for assessing the impact of natural disasters in a comprehensive and systematic way, which will enable the enhancement of systems resilience against these catastrophic events.

### **1.1 Motivation**

Among critical infrastructure, electric power systems are particularly important because they are the backbone of several other key sectors, such as, health, traffic control, water supply, finance markets and others. Furthermore, while low-income and developing countries, like Chile, are the countries most affected by disasters (R. Pachauri and L. Meyer, 2014), their electricity systems are changing rapidly because of the high correlation between energy consumption and economic growth (as shown in Appendix A). Therefore, especially for developing and low-income countries, it is a priority to consider high impact low probability events in the design and operation of power systems.

### **1.2 Objectives**

In this context, the present research aims at fostering the resilience concept in electric power systems by achieving the following specific objectives:

- i) Formalize a resilience framework for studying particularly for electric power systems, which includes assessment and adaptation strategies.
- ii) Study the results of applying the resilience framework to the Great Britain's electric power system.
- iii) Study the results of applying the resilience framework to the Northern Chile's electric power system.

### **1.3 Research delimitations**

Given the complexity and size of the research objectives to achieve, the following boundaries were set to this study:

#### **a) Scenario building**

The hazard scenarios are simplified in order to represent only what is needed and what can be interpreted in the fragility curves available; all other aspects are assumed negligible and taken aside. Even though electric power systems are threatened by several risks, only windstorms, pluvial floods, intraplate and interplate earthquakes are modelled.

#### **b) Fragility curves**

Disastrous events may have direct and indirect impacts on systems. On the one hand, direct impacts are related to the stress applied to the components by the threat and on the other hand, indirect impacts reflect the probability of cascading, where failure of certain components may lead to the failure of others. In this research, only direct impacts are modelled.

Direct impact fragility curves are not developed in this research; they are taken from international literature and adapted to this research. Macro components identified and modelled as fragile to hazards are limited; consumers (demand) are modelled as unaffected to threats (invulnerable). In

reality, every system component is unique; however, components of the same type are modelled identically.

**c) Operation of the system**

In electric power systems, there are many considerations to ensure a coordinated efficient and secure operation. For instance, one week ahead of the operation a Unit Commitment is modelled to decide which units have to be turned on at each time. With the committed units, an Optimal Power Flow (OPF) is run to decide the actual dispatch of units. In this research, no Unit Commitment is included. Also, losses are considered only when running AC OPF. In the Chilean case study, the existing interconnection with the Argentinean system, SADI, is not included. Technology characteristics are not accounted for, except for wind power plants where wind profiles are used. For simplicity reasons, other considerations, such as start-up times, are included only when indicated.

**d) Restoration of the system**

An exhaustive central planning of the restoration procedure is not carried out; instead an individual perspective with interdependencies with other critical infrastructure through the magnitude of the event is taken into account.

**e) Socio-economic costs**

To compare adaptation strategies, cost-benefit analyses should be carried out. However, socio-economic costs are not considered in this study. Economic costs are only considered when deciding which generation units will be dispatched.

It is important to remark that given all the delimitations just presented, the results are conditioned to these boundaries. Therefore, to be able to have results

that may be taken into consideration for public policies and by decision-makers additional development of the current models is required.

#### **1.4 General methodology**

Before entering the topic in detail, three questions about the general methodology had to be answered to set the course of this research:

##### **a) Static vs dynamic analysis.**

Two time frames may be used to apply the resilience concept. On the one hand, a dynamic analysis, where the time frame may go from micro seconds to minutes, where tiny disturbances may be the studied scenarios. Frequency, reserves and protections would be the key variables. On another hand, a static or steady-state analysis, where multiple component failures may be the scenario. Grid topology, generation over capacity and generators operational constraints would become the most important variables. In this work, the latter analysis is used, where a time frame of one week is chosen with an hourly resolution.

##### **b) Analytical techniques vs Monte Carlo Simulations.**

In electric power systems, analytical techniques are very popular to evaluate the impact of weather hazards. But this is practical only for small systems and with limited number of variables. When large systems and many probabilistic variables are modelled, a simulation approach is recommended. Given the wide range of uncertainties considered in the analysis of resilience, including, for example, the hazard's probability of occurrence, its magnitude and probabilistic recuperation times, a Time-Series Monte Carlo Simulation approach is selected.

### **c) What software should be used?**

The complexity of the problem requires doing various analyses. Therefore, an environment with simulation, optimization and stochastic tools is required. MATLAB of Mathworks (2013) is chosen because of its versatility. Also MATPOWER (R. Zimmerman, C. Murillo-Sánchez and R. Thomas) is used for the system modelling.

## **1.5 Thesis outline**

The organization of the thesis is as follows: in Section 2, basic concepts used within the proposed resilience framework are briefly described. Then, in Section 3, the state of the art and the contributions of the present work are discussed. Thereafter, in Section 4, the multi-phase resilience assessment and adaptation framework is outlined along with the resilience metrics used and a model flow chart. In Section 5 and 6, the resilience framework is applied to windstorms and floods in a simplified version of the network of Great Britain and to earthquakes in a reduced version of the system of northern Chile, respectively. Finally, Section 7 summarizes and concludes the thesis and Section 8 proposes future work lines to develop new, better and more complete studies in order to achieve results that may be of guidance for public policy and decision-makers in disaster management and electric power systems fields.

## 2. BASIC CONCEPTS

The present chapter aims at briefly defining and classifying important concepts used within the research framework. These concepts are *threat*, *vulnerability*, *risk* and *resilience* definitions; the *system performance curve* throughout a disaster, the *electric power system* structure and a classification of analyses: *single-phase*, *system fragility*, *system serviceability* and *system resilience*.

### 2.1 Definitions

Disaster management and risk analyses require clarifying and defining the following concepts:

**a) Natural hazard or threat<sup>1,2</sup>:**

Naturally occurring events that might have a negative effect on people, environment or infrastructure. They are characterized by their location, severity and frequency (OAS, 2014).

**b) Vulnerability:**

Probability to suffer human and material damages of a community exposed to a natural threat, given the degree of fragility of its elements (infrastructure, housing, productive activities, degree of organization, waning systems, political and institutional development). It has to be remarked, that vulnerability is a precondition that reveals itself during a disaster (ECLAC and IDB, 2000).

**c) Risk:**

Combined probability of the two previous concepts: threat and vulnerability (ECLAC and IDB, 2000). This broad definition is the core of various definitions published in literature.

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<sup>1</sup> After the event occurs, if there is an overwhelming damage the concept changes to *natural disaster*.

<sup>2</sup> When human interests are not affected the concept changes to *natural phenomenon*.

**d) Resilience or resiliency:**

(The White House, 2013) has defined the concept as “the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions“.

**2.2 System’s performance curve throughout a disaster**

Given a system’s Performance Variable,  $PV(t)$ , a system’s performance curve may be drawn throughout a disaster as shown in **Figure 2.1**.

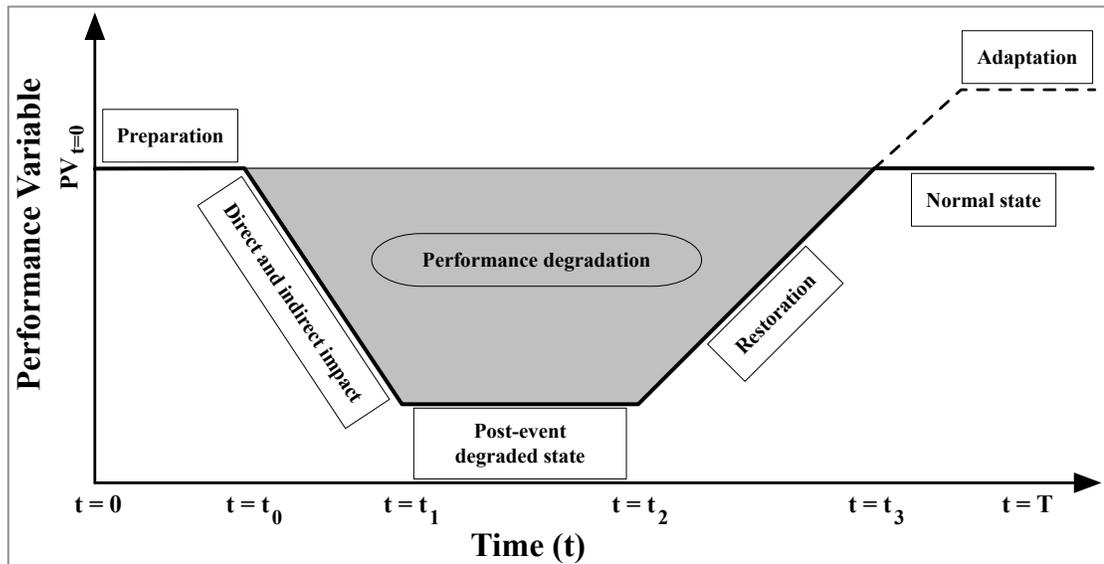


Figure 2.1. System’s performance curve throughout a disaster (own elaboration).

Within a time frame, defined by the time within  $t = 0$  and  $t = T$ , the performance curve starts in a normal pre-event state, where the main characteristic is preparation. When the event occurs at  $t_0$ , a direct and indirect impact to the system degrades the system to the post-event degraded state between  $t_1$  and  $t_2$ , which is followed by a restoration stage between  $t_2$  and  $t_3$ , that may return the system to a normal state or even, in a larger time-scale, to an even better adapted state that is more prepared to confront future disasters starting from  $t_3$ .

### 2.3 Electric power system's structure

Electric power systems are complex interconnected systems that are divided in three distinct segments: generation, transmission and distribution; a simple network presented in **Figure 2.2** illustrates this segmentation, present in this study. Currently, the development of new technologies is making power systems more complex by evolving to the smart grid concept.

The electricity generation is carried out by power plants (1) that may use a wide range of resources (e.g. solar irradiance, water, oil, wind and coal) to produce energy with different technologies. This is done at a medium voltage and connected to a local substation (2), which constitutes a node of the network.

The transmission segment starts at the substation (2) where voltage levels are increased in order to diminish losses, while it is being transported in transmission lines supported by towers (3) to another substation (5) in a different location where it is transformed to a medium or low voltage.

The distribution segment starts at the substations (5), where it may be transformed to a low voltage to supply residential consumers (7) or may be kept at medium voltage to supply industrial consumers (4,6), which depending on the size could also be connected directly to the transmission segment (4).

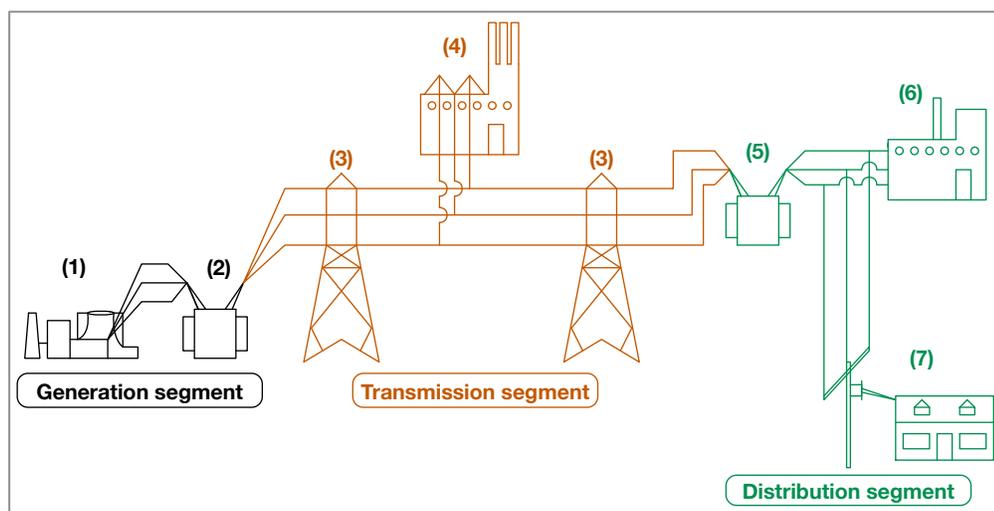


Figure 2.2. Electric power system's structure (adapted from (S. Blume, 2007)).

The main components considered in the diagram and in this study are power plants, towers, transmission lines, substations and consumers (or loads).

Power plants are composed of generation units, which are characterized by a number of technical parameters, such as their installed capacity, net (minus own consumption) active/reactive maximum/minimum generation, start-up times, variable costs, among others. Towers are vital components that support overhead power conductors, which are able to transport electricity constrained to their thermal capacity. Substations are facilities that are able to change the voltage from one level to another (with transformers), regulate the voltage, convert AC to DC and vice versa if required and is where safety/protection devices are installed, such as disconnect switches, circuit breakers, lightning arresters, etc. Loads are usually classified in industrial, commercial and residential consumers and represent the demand of the system.

## **2.4 Types of risk analyses**

Various system evaluations may be performed depending in what is included. As it is shown in **Figure 2.3**, in this work, a classification of four types of system analyses is proposed depending in what studies are included:

### **a) Single-phase analysis:**

Commonly, because of the complexity of the problem, researchers have gone deep into the understanding of the threat (e.g. (V. Kaistrenko, 2014)), the development of fragility studies of components (e.g. (M. Sadeghi, M. Hosseini and N. Pakdel Lahiji, 2012)), models and tools to understand the operation of electric power systems (e.g. (F. Noakes and A. Arismundandar, 1963)) and models to manage and optimize system's restoration (e.g. (N. Xu, et al., 2007)). These stages and their complexities are explained in more detail in Chapter 4. Even though these approaches might be useful, an

integral point of view can result in a better understanding of the whole problem.

**b) System fragility analysis:**

Some authors have integrated the threat analysis and the system topology. This fragility analysis enables to understand the capacity post disaster of the system after a disastrous event by identifying which are the components that will commonly fail and those that may continue working (e.g. (H. Yang, et al., 2013)).

**c) System serviceability analysis:**

Research groups have integrated in a single study the threat study, the system topology and the system operation. When this is carried out, it may be considered as a vulnerability analysis. This permits to know the actual capacity of the system to supply the demand over a time frame (e.g. (J. Buritica, et al., 2012)).

**d) System resilience analysis:**

In the past few years, a number of authors have started to integrate the threat characterization, the system topology, the system operation and also the system restoration. This analysis is the most complete study and the approach taken in the present research (e.g. (M. Panteli and P. Mancarella, 2015; K. Pitilakis, et al., 2014; M. Ouyang and L. Dueñas-Osorio, 2014; M. Shinozuka, et al., 2007)).

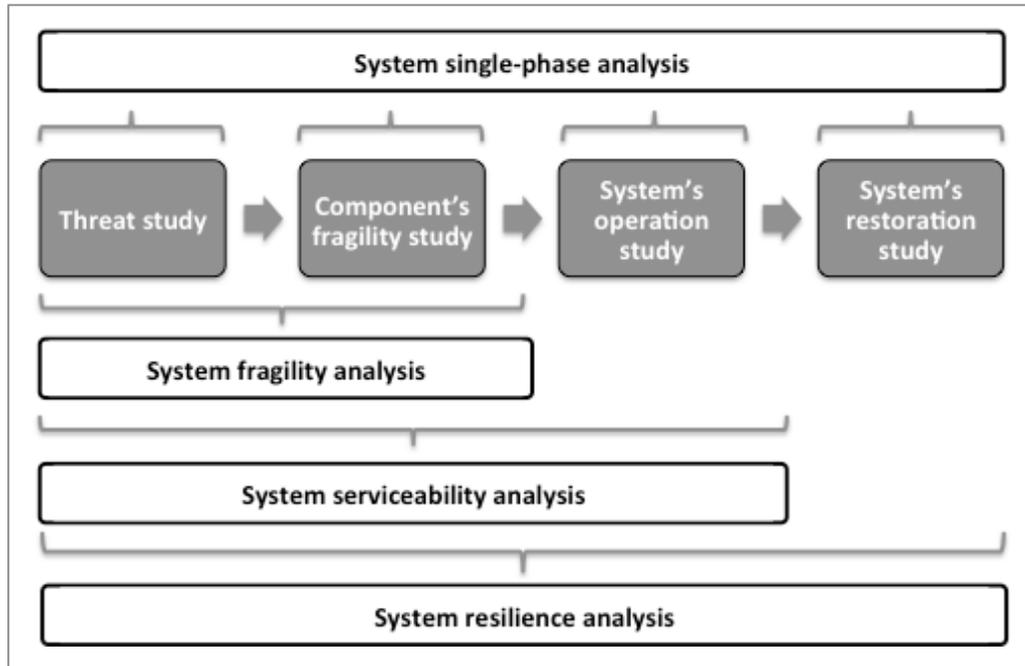


Figure 2.3. Types of system risk analyses (own elaboration).

### 3. STATE OF THE ART AND CONTRIBUTIONS OF THIS THESIS

Electrical power systems have been designed and operated to be reliable against abnormal but foreseeable contingencies. The concept of reliability<sup>3</sup>, defined as the ability to supply adequate electric service on a nearly continuous basis, with very few interruptions over an extended time period (R. Billinton and W. Li, 1994), has been extensively applied in the electric sector. However, dealing with unexpected and less frequent severe situations remains a challenge.

Resilience is an emerging concept and, as such, it has not yet been adequately explored in spite of its growing interest, particularly in power systems where there are almost no publications on the matter in IEEE periodicals (M. Panteli and P. Mancarella, 2015; H. Rudnick, 2011).

This chapter aims at explaining different perspectives researchers from the power systems community have taken to analyse this problem. Then different methodological advances in the topic are presented and finally the contributions of this thesis are listed.

#### 3.1 Different perspectives for the resilience concept

In 2014, the third number of the periodical *IEEE Power and Energy Magazine* covered the resilience concept with the title “Surviving with resiliency“. The same year, CIGRE released the report “Disaster recovery within a CIGRE Strategic framework: network, resilience, trends and areas of future work“. This reflects the fact that resilience has become a major topic in the area. However, there is no consensus on how to treat the concept.

Given the complexity of the problem and the system, it is understandable that different perspectives are taken. For example, within the mentioned IEEE PES Magazine issue, Article (G. Strbac, et al., 2015) is centred in how microgrids can enhance the resilience of the European megagrid. Here resilience is treated in a

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<sup>3</sup> Internationally, its main features are *adequacy* and *security* (R. Billinton and W. Li, 1994). In the Chilean technic normative *quality of service* is included as a third feature (CNE-Chile, 2015).

dynamic time frame, where microgrids can help specifically in the islanding and restoration procedures. Article (C. Marnay, et al., 2015) focuses on the same issue and methodology, giving as example the microgrids developed in Japan. Article (M. Shahidehpour, et al., 2015) discusses how does an integrated lightning system in a smart city improve resilience by strengthening the mesh and adding redundancy. Two more articles, describe projects where different strategies are being used, such as hardening the system components, the deployment of microgrids as well as distributed and renewable generation devices and the automation of the system.

With the exception of Article (M. Panteli and P. Mancarella, 2015), none of the above articles have developed an analysis of the system throughout the disaster in all of its stages. As (C.-C. Liu, 2015) suggests “a standardized definition of resiliency is needed to develop the requirements and procedures for (..) system planning and operation”.

### **3.2 Methodological advances of resilience assessment and adaptation in electric power systems**

There are a few works related to power systems that take as base the curve in **Figure 2.1** and have a system perspective. Nevertheless, studies published in other fields are briefly described below.

For instance, in (K. Pitilakis, et al., 2014), a joint effort of European universities analyses the impact of earthquakes on various cities and different critical infrastructures, including the power systems of Sicily. This study included the use of fragility curves and an object-oriented programme to assess the pre- and post-disaster performance of the network.

In (M. Panteli and P. Mancarella, 2015), the impact of windstorms is analysed using wind fragility curves, running DC optimal power flows on the IEEE-6 bus reliability test system and comparing different adaptation cases.

The resilience of the electric system of Harris County, Texas, US, is evaluated in (M. Ouyang and L. Dueñas-Osorio, 2014) by running four models: hurricane hazard model, components fragility model, power system response model and restoration model. The results are classified in technical, organizational and social dimensions of resilience.

In (Shinozuka, et al., 2007), micro-components of the transmission network under seismic stress are modelled to assess the resilience of the power system in Los Angeles, US. The vulnerability is also modelled, with fragility curves and risk curves developed as results.

Another notable effort, that has involved software developments, is Hazus, from the Federal Emergency Management Agency (FEMA) (2015). This platform has developed various fragility curves with damage states for many systems, some of them used in this research.

Even though the recent work on the topic has been a huge step towards understanding and measuring resilience, further research in this area remains a concerning issue given the consequences of these and other catastrophic threats to different systems around the world.

### **3.3 Contributions of the present work**

In the present work, the novel contributions are listed below:

**An integral analysis with a system perspective covering the whole disaster process is carried out to confront the problem of natural disasters and electric power systems.** It is common to find in literature that researchers studying disaster management and power systems choose single-phase approaches where the intention is limited to individual elements at risk.

**A novel multi-phase resilience assessment and adaptation framework is formalized** by identifying the best practices in recent international literature.

**Three different natural hazards and two electric power systems are modelled to apply the resilience framework presented.** Therefore, comparisons are possible. In all publications found about the topic, only a single hazard and system is modelled.

**The test systems are representative of national grids with focus on the generation and transmission system, where potential impacts are wider, but with fewer details.** In most publications the test system is focused on the distribution level, losing a national perspective and being unable to apply national strategies.

**Multi-disciplinary work was carried out, with people from public and private organizations and from different countries.** Due to the complexity of resilience studies, different fields have to be involved to be able to cover the whole process.

## 4. MULTI-PHASE RESILIENCE ASSESSMENT AND ADAPTATION FRAMEWORK

In this chapter, the resilience and adaptation framework presented in **Figure 4.1**, and given in detail in **Appendix B**, is proposed for evaluating the impact of natural disasters on the resilience of electric power systems<sup>4</sup> and the effect of possible adaptation strategies. This framework is presented in detail next.

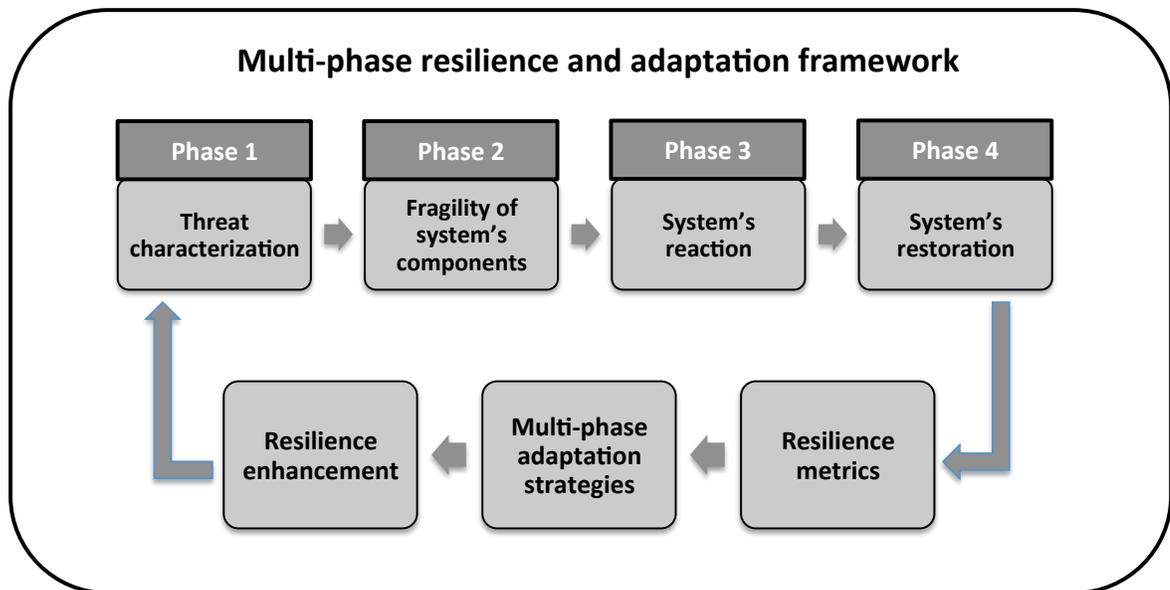


Figure 4.1. The multi-phase resilience and adaptation framework (own elaboration).

### 4.1 Multi-phase resilience assessment

The resilience assessment consists of four phases: threat characterization, fragility of the system's components, the reaction of the system and finally its restoration.

<sup>4</sup> Even though the resilience framework proposed can be extended to study any threat and any critical infrastructure, the study focuses in power systems so the phases do not incorporate aspects that may be of importance to other systems.

#### **4.1.1 Phase one: threat characterization**

The objective of this phase is to model the magnitude, probability of occurrence and spatiotemporal profile of a hazard. To this end, the causes, physical aspects and consequences of the threat must be understood. Two approaches can be taken, one is to build deterministic scenarios, where a historic event is modelled, and the other one is to build probabilistic scenarios, where potential future scenarios are projected.

For deterministic modelling, depending on the natural hazard under investigation, different tools can be used. For extreme weather events, generally the weather database needed may be acquired through Climate Models (CM), which can model the threat with a certain geographic and time resolution, or using real measurements with time a geographic features from weather stations. In the case of seismic and tsunami hazards seismographs and sea-level measurements database should be used.

For probabilistic scenarios, different projection methods can be used. The selected method has to be suitable to be applied to the specific event (e.g. earthquakes, tsunamis, floods, etc.) and be able to make an estimate of anticipated forces, possibly much greater than have ever been observed, using historical or model-generated data. For the case of data generated by CM, parametric studies are useful, where the parameters are modified by a certain factor (usually taking in consideration real extreme measurements or expert knowledge). For the case of instrumentally measured data, a first option is Power Law, which has modelled numerous natural phenomena, such as the Gutenberg-Richter number-size distribution of earthquake magnitude and other probabilistic predictions of data behaviour (S. Burroughs and S. Tebbens, 2001). Specifically for earthquakes, as developed by (B. Gutenberg and C. Richter, 1994) and explained in (A. Poulos,

2014), each seismic source has an annual amount of earthquakes that exceeds a given magnitude, which is represented by **Equation 4.1**.

$$\log_{10}(\lambda_M(m)) = a - bm \quad (4.1)$$

Where  $\lambda_M(m)$  is the mean annual frequency of the seismic events that exceeds magnitude  $m$ , and coefficients  $a$  and  $b$  are estimated by regressions. Given lower and upper bound magnitudes  $M_{\min}$  and  $M_{\max}$ , respectively, the cumulative distribution function (CDF) of the magnitude of an earthquake  $M_{\min} \leq M \leq M_{\max}$  is presented in **Equation 4.2** and its probability density function is presented in **Equation 4.3**.

$$F_M(m) = P(M \leq m) = \frac{1 - 10^{-b(m - M_{\min})}}{1 - 10^{-b(M_{\max} - M_{\min})}} \quad (4.2)$$

$$f_M(m) = P(M = m) = \frac{b \cdot \ln(10) \cdot 10^{-b(m - M_{\min})}}{1 - 10^{-b(M_{\max} - M_{\min})}} \quad (4.3)$$

A second option for instrumentally measured data, is Extreme Value Theory (EVT) (S. Coles, 2001), which is based on the distribution of the maximums (or minimums) by defining a return period  $T$  (e.g. 100-years) and estimating its return value  $X(T)$  (e.g. 60 mm). This would mean that an event of  $X(T)$  is estimated to happen every  $T$  years. EVT has two main approaches: Block Maxima Approach (BMA) and Peaks Over Threshold (POT). Both approaches have the aim of estimating  $X(T)$  for rare extreme events. In the case of BMA, this is done by a parametric modelling of maximums (or minimums) taken from large blocks of independent data. In the case of POT, this is done by a parametric modelling of independent exceedances above a large (or low) threshold. Both approaches then

use the Generalized Extreme Value (GEV) distribution (A. Jenkinson, 1955; J. Hosking, J. Wallis and E. Wood, 1985). GEV has the flexibility of combining the three types of extreme distributions, namely Type I-Gumbel, Type II-Fréchet and Type III-Weibull. GEV's cumulative distribution function (CDF) is as follows:

$$F(x; \psi, \beta, \xi) = e^{-\left(1 + \xi \frac{x - \psi}{\beta}\right)^{-\frac{1}{\xi}}}, \text{ for } 1 + \frac{\xi(x - \psi)}{\beta} > 0 \quad (4.4)$$

In **Equation 4.4**,  $\psi$  (location),  $\beta$  (scale) and  $\xi$  (shape) are the three main parameters of GEV. The particular cases of  $\xi = 0$ ,  $\xi > 0$  and  $\xi < 0$  are respectively equivalent to the distributions Type I, whose tails decrease exponentially; Type II, whose tails decrease as a polynomial and Type III, whose tails are finite. When the parameters are estimated to fit the dataset, a projection diagram can be drawn to visualize the return periods and return values (E. Gumbel, 1958).

#### 4.1.2 Phase two: fragility of system's components

The aim of this phase is to determine the damage level of each component of the system. To do this, the following three steps are considered:

- i. identify the vulnerable components
- ii. fragility modelling of the components
- iii. assign damage states

In the first step, the components identified are those that are vulnerable to the threat that could possibly have a high impact on the network resilience. Also, the type of component must be selected. In electric power systems, components can be classified in macro or micro components (K. Pitilakis, et al., 2014). For example, high/medium/low voltage substations/power plants, distributions circuits, transmission towers and lines can be classified as macro components. Circuit breakers, transformers, lightning arresters, switches and all those elements that

describe the internal logic of macro components are micro components. The use of one or another depends on the objectives of the resilience study being undertaken. Some studies also propose modelling people and communities from a physiologic perspective (M. Bruneau, et al., 2003; K. Bergstrand, et al., 2014).

The second step corresponds to modelling the fragility of the components to the natural threats. The concept of Fragility Curves has its origins as a structural reliability concept (JCOSS, 1981; F. Casciati and L. Faravelli, 1991), and is a useful tool for a stand-alone analysis of each component. A fragility curve, as shown in **Figure 4.2**, expresses the probability of failure of a component conditioned on the impact of the hazard. In practice, these failure probabilities are compared with a uniformly distributed random number  $r \sim U(0,1)$ . If the failure probability of the component is larger than  $r$ , then the component fails.

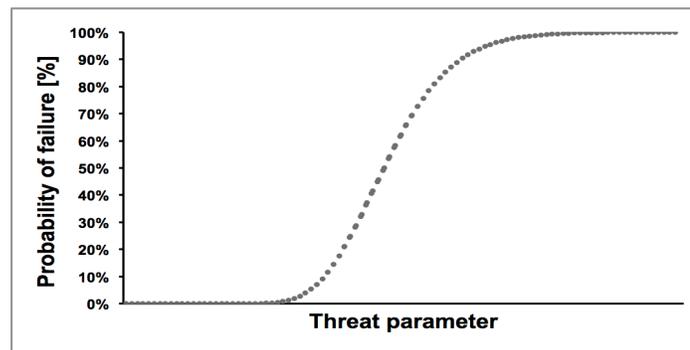


Figure 4.2. Generic fragility curve: probability of failure (%) vs threat parameter (own elaboration).

It is important to note that a “failure“ of the component does not necessarily imply a complete collapse of the component (i.e. removal from service). For example, after a seismic event a power plant that is composed of more than one generation unit might have just a portion of the units out of service, meaning that the power plant will be able to work at a degraded maximum generation capacity.

At the same time, other components such as transmission lines have a binary damage state: tripped or non-tripped.

Thus, as a third step, the damage state of the components must be addressed. In order to do this, two approaches can be used as shown in **Figure 4.3**, where (a) uses different fragility curves for different damage levels (as used by (FEMA, 2015)) and (b) relates the damage level to the zone of the fragility curve defined by percentiles (as used in Chapter 5).

Particularly for electric power systems, even though, most frequent faults happen at a distribution level, less common but with a higher impact occur at a transmission and generation level. Because of this, and to be able to have a nationwide perspective of resilience this research focuses on the generation and transmission level components.

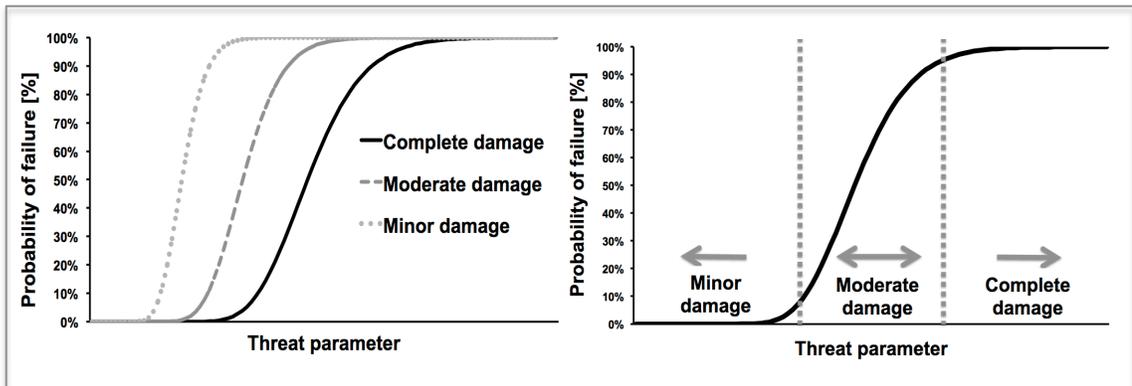


Figure 4.3 (a). Different fragility curves to assign damage states. (b). Different zones in the fragility curve to assign damage states. (Own elaboration).

### 4.1.3 Phase three: system's reaction

The objective of the third phase is to evaluate the performance of the critical infrastructure when it is exposed to the extreme event. In electrical power systems, to do this, numerous evaluation tools have been developed over the last decades; such as the CASCADE model, which studies the cascading mechanism of a blackout (I. Dobson, A. Carreras and D. Newman, 2003); the ORNL-PSERC-

Alaska (OPA) model, which is based on a DC optimal power flow and it is built upon Self-Organized Criticality (B. Carreas, V. Lynch, I. Dobson and D. Newman, 2002; I. Dobson, A. Carreras and D. Newman, 2001); the Hidden Failure model, which is based on approximated DC power flow and standard linear programming optimization of generation redispatch to represent hidden failures of the protection system (J. Chen, J. Thorp and I. Dobson, 2005); and the Manchester model, which is built upon AC power flow, uses load shedding and a power flow solution to determine the power system operation (M. Rios, et al., 2002; D. Kirschen, et al., 2003, D. Kirschen, et al., 2004).

When modelling the impact of extreme natural events, it is important to take into account the diverse impact of the weather front or geographic profile moving across the system, which is both spatial- and temporal-dependent. The resilience model used in this phase should thus be capable of capturing the spatiotemporal stochastic impact of the natural disaster on the resilience of power systems. It has to consider the flexibility of the system given by the installed technology and possible international interconnections. It should also be capable of providing a component and area criticality index, which will enable the resilience enhancement of the most vulnerable components. Furthermore, following the disaster, it is very likely that the system will be divided into multiple islands, which should be incorporated in the impact assessment model.

#### **4.1.4 Phase four: system's restoration**

The response to the disaster and the restoration times following the disaster are strongly related to the following three aspects:

- i. damage caused
- ii. amount of human and material resources available
- iii. accessibility of the affected area.

The restoration process can only be undertaken under the condition that both repair-teams and spare parts are available. The fast restoration and recovery of

critical infrastructure is a crucial feature of resilience (as discussed in Chapter 2). Therefore, proper and effective emergency and restoration strategies should be in place to restore the system to its pre-disaster state as fast as possible.

## 4.2 Multi-phase adaptation strategies

The probability of extreme weather events is relatively low, but their impact is so high that is vitally important to enhance the resilience of critical infrastructures. Particularly, for electric power systems, this can be achieved through a wide range of short- and long-term measures. Short-term measures are discussed in detail in (M. Panteli and P. Mancarella, 2015a; M. Panteli and P. Mancarella, 2015b). Long-term measures can be grouped in strategic adaptation cases that improve specific phases of the resilience of the system. Namely, the cases are: (i) Normal, which is the basic network; (ii) Robust, that improves the resistance of the system; (iii) Redundant, which includes backup installations or spare capacity enabling the diversion of the power flows to alternative paths of the network; and (iv) Responsive, that enables a faster response from the disruptive events. It can thus be seen that these adaptation case studies can improve, respectively, the 2nd, 3rd and 4th phases of the resilience framework.

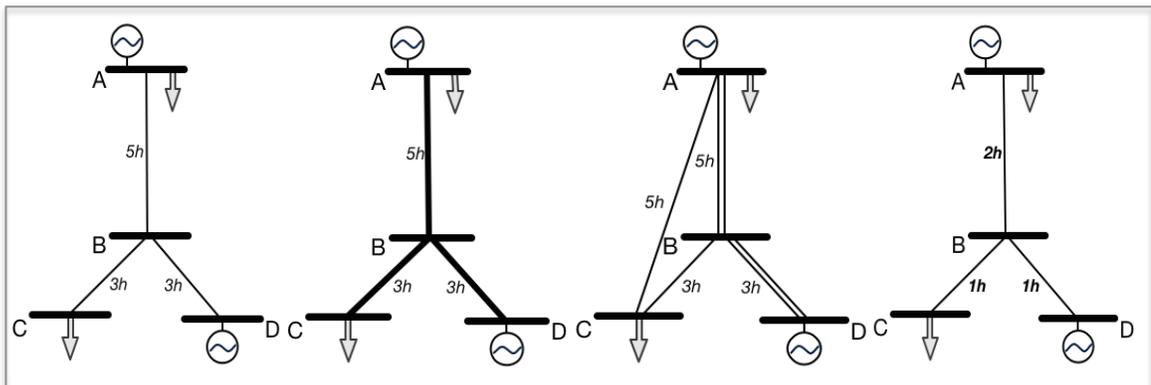


Figure 4.4 (a). Normal case. (b). Robust case. (c). Redundant case. (d). Responsive case.

(Own elaboration. Numbers indicate mean time to repair).

Explicative diagrams of the adaptation cases are presented in **Figure 4.4** (based on the examples in (C. Pickering, S. Dunn and S. Wilkinson, 2013), where (a) represents the normal network, which consists of four nodes and three links with their mean times to repair, (b) represents the robust case, having more resistant links that can be interpreted as a shift of the fragility curve. (c) shows the redundant case including alternative paths and (d) is the responsive case, where the mean times to repair are decreased.

### 4.3 Resilience metrics

Depending on the aim of the resilience study, the performance of electric power systems can be measured using numerous different metrics. Two measurements that are able to describe the impact of the extreme event within a time frame are the Expected Energy Not Supplied (EENS) and the Energy Index of Unreliability (EIU) (R. Billinton and W. Li, 1994, R. Allan and R. Billinton, 2000). The first, shown in **Equation 4.5**, indicates how much service (energy) was not provided during the studied time period as an absolute number (MWh or GWh). The second, shown in **Equation 4.6**, is directly related to EENS, which is normalized using the total energy demand in the studied time frame (%). In the following equations,  $E_k$  is the energy not supplied with a probability  $p_k$  of occurrence of scenario  $k$  during the time frame of the study.  $E$  represents the energy demand in the whole study period.

$$EENS [GWh] = \sum_{k=1}^{k=K} E_k * p_k \quad (4.5)$$

$$EIU [\%] = \frac{EENS}{E} * 100\% \quad (4.6)$$

#### 4.4 Resilience modelling

In the previous sections of this chapter, the framework concepts have been explained. In **Figure 4.5**, a flow chart of the resilience framework is displayed. The model is based on Sequential Monte Carlo Simulations, where every grey box represents one scenario and within every scenario an hourly sequential simulation is run. It has to be noted that the applications in following chapters may differ from the present flow chart.

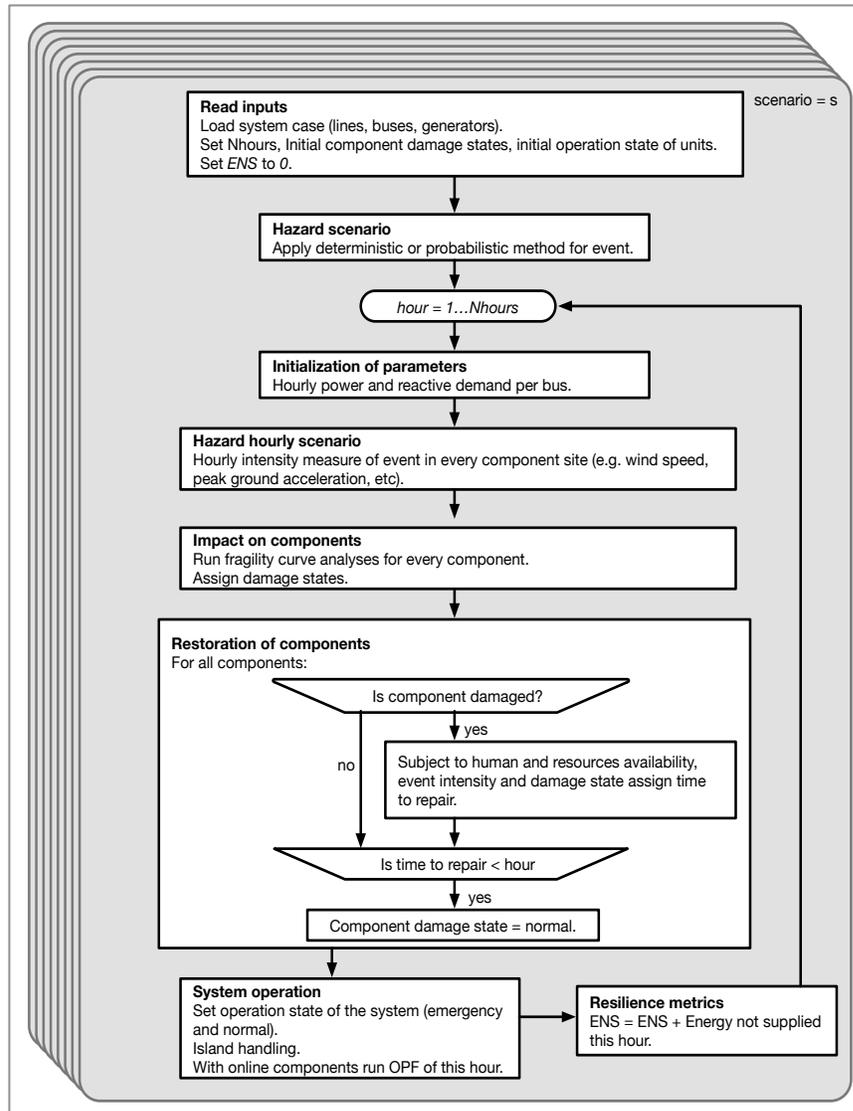


Figure 4.5. Resilience modelling flow chart (own elaboration).

## **5. APPLICATION TO WINDSTORMS AND FLOODS IN GREAT BRITAIN**

In the present chapter, the multi-phase resilience framework previously presented is illustrated by assessing the impact of potential future scenarios of windstorms and floods on a reduced version of the Great Britain's electric power system as it is explained hereafter.

### **5.1 Influence of extreme weather and climate change in Great Britain's power system**

In this Section, extreme weather events are described along with the influence of climate change and possible future scenario hazards.

#### **5.1.1 Extreme weather events**

A disruptive weather event can be classified into small, moderate, serious, major and extreme based on the number of customers disconnected, the duration and frequency (W. Associates, 2011). For example, in the USA, extreme weather-related events account approximately for 80% of the large-scale power outages from 2003 to 2012 (A. Kenward and U. Raja, 2014), with the annual impact ranging from \$20 to \$55 billion (R. Campbell, 2012).

Great Britain, in particular, is significantly affected by weather-related power outages. In (L. McColl, et al., 2012), it is reported that only from April 2008 to March 2009, 211 faults occurred on the transmission network in England and Wales and other 44 in Scotland, of which 23% and 95% were caused by weather, respectively. These weather-related faults can be categorized in one of eight causes: wind and gale; snow; sleet and blizzard; lightnings; ice; freezing fog and frost; heat waves; flooding and rain (L. McColl, et al., 2012; K. Murray and K. Bell, 2014). For example, several transmission substations and power stations are

at high risk of flooding, while high winds can cause transmission lines and towers to collapse. Also, in 2007, Great Britain suffered the wettest summer in its history. This produced extreme rainfall compressed into short periods of time that caused a series of destructive floods catalogued as the country's "largest peacetime emergency since World War II" (M. Pitt, 2008). Moreover, a few years later in 2014, an even more extreme weather-year took place. As described by the National Meteorological Office (MET), this was the wettest, 5<sup>th</sup> warmest and probably most disastrous winter in the UK (MET Office, 2014). Consequently, the Climate Change act of 2008 required the UK electricity industry to report on adaptation measures to deal with the effects of weather and the effect of climate change (United Kingdom Parliament, 2008). This motivates to analyse particularly windstorms and floods in this research.

### **5.1.2 Climate change and future hazard scenarios**

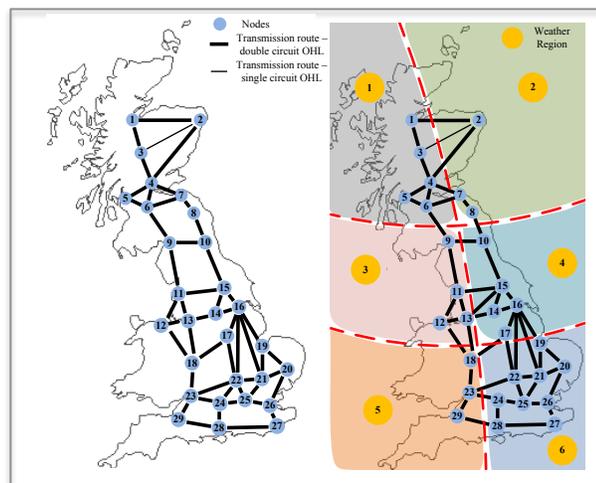
In 1992, the United Nations Framework Convention on Climate Change (UNFCCC) was created with the objective to "stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interface with the climate system" (R. Pachauri and L. Meyer, 2014). To achieve this, the Intergovernmental Panel on Climate Change (IPCC) supports UNFCCC producing reports of the scientific, technical and socio-economic aspects of global warming with its potential impacts and options for adaptation and mitigation. Until today, a series of five comprehensive reports have been published. The latest one, in 2014, stated that now, the IPCC, is "95% certain that humans are the main cause of current global warming" and that "climate change will amplify existing risks and create new risks for natural and human systems" (R. Pachauri and L. Meyer, 2014). Even though, mitigation of Greenhouse Gases (GHG) is crucial to constrain climate change, adaptation of infrastructure becomes essential, before mitigation measures can have any effect

(N. Stern, 2006). In consequence, possible future changes in natural hazards must be analysed.

According to the IPCC, climate change projections may vary from region to region, but generally it is likely that wet and dry extremes are going to become more severe (R. Pachauri and L. Meyer, 2014). In Great Britain, particularly for the variables studied here, reports indicate that while wind has a high uncertainty on how it will change (L. McColl, et al., 2012), flood risk will escalate because of the potential increase of rainfall volume and intensity (E. Evans, et al., 2008). Unfortunately, quantitative studies disagree on how will they scale up (L. McColl, et al., 2012).

## 5.2 The Great Britain’s simplified electric power system

The Great Britain network used in this study is a *simplification*<sup>5</sup> of the real one at the end of 2010 (M. Belivanis and K. Bell, 2011). As it is shown in **Figure 5.1** (a), the grid consists of 29 nodes, 98 overhead transmission lines in double circuit configuration and one single circuit transmission line between nodes 2 and 3, and 65 generators (with 81.5 GW of installed capacity) which are located at 24 nodes and include several technologies, such as wind, nuclear and CCGT.



<sup>5</sup> The components are not real; they represent a group of real components while trying to replicate the real AC power flows and operation of the actual system.

Figure 5.1 (a). Great Britain’s simplified system. (b). Weather regionalization of the system. (Own elaboration with M. Panteli).

Interconnections with external subsystems, i.e., France, the Netherlands and Northern Ireland are included. The demand, plotted in **Figure 5.2**, represents the winter peak week in 2010.

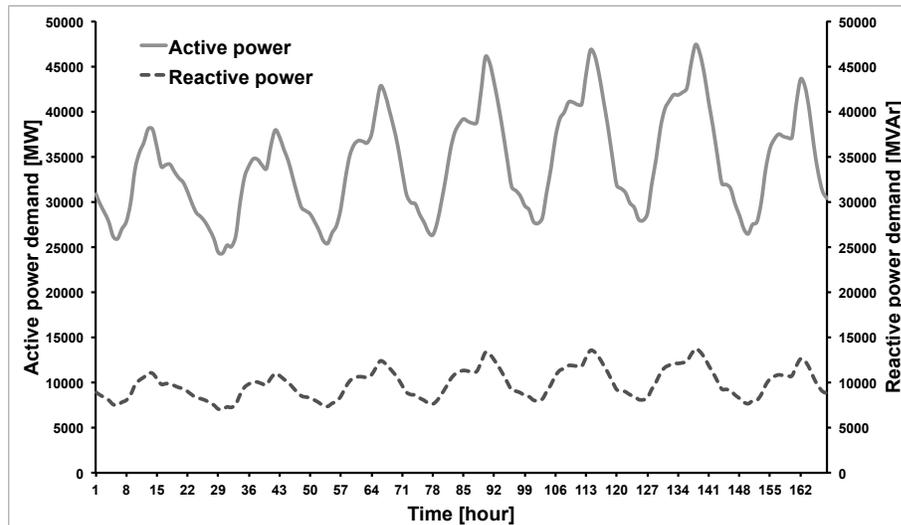


Figure 5.2. Winter peak demand week in Great Britain (Own elaboration).

### 5.3 Resilience assessment

The resilience of the test network is evaluated against windstorms and floods, which constitute severe threats to the Great Britain system.

#### 5.3.1 Phase one: windstorms and floods characterization

As explained in detail in Section 4.1.1, the threat characterization phase aims at defining the event’s probability of occurrence, magnitude and spatio-temporal profile. Therefore, in order to account for the spatial feature of the weather events, the “big island” is divided into 6 weather regions, as shown in **Figure 5.1** (b).

Weather conditions are assumed to be homogeneous within each region, so the fragility of each component is conditioned to the same stress across each weather region. Potential future scenarios were modelled as explained hereafter.

For the windstorms modelling, the main characteristic is the geographic mapping of the location and magnitude of wind speed. Therefore, hourly mean wind data for 33 years (1979-2011) was obtained using MERRA re-analysis (NASA, 2015). On the other hand, floods are more complex and affected by many factors, such as the capacity of drainage system, saturated ground, high river levels and accumulated rainfall. But in general, especially river and groundwater floods are strongly related to rainfall. For example, in (P. Guhathakurta, et al., 2011) flood is linked directly to accumulated rainfall. The hourly rainfall data for the same years, i.e., 1979-2011, was obtained from more than 17000 rain gauge stations all over Great Britain in that time frame, which was provided by the MET Office, UK (MET Office, 2006). This analysis altogether provides the temporal characterization of the threats: 33 years of wind and rainfall profiles with hourly resolution.

In order to deal with the uncertainty associated with the future weather conditions as a direct impact of climate change, five scenarios have been developed for evaluating the impact of windstorms, floods and both hazards together.

Given that wind speed was taken from a Climate Model, where the focus is on average measurements (with a maximum average of approximately 20 m/s), one suitable approach to use in order to model extreme winds that can damage the transmission components is to parametrically scale up the wind profiles. Therefore, the winds profiles of the 6 weather regions have been scaled up using a multiplication factor in the range [1,3] in steps of 0.5, resulting in five windstorms scenarios (meaning that x2 and x3 would represent approximately wind speeds of 40 m/s and 60 m/s, respectively). The wind profile is scaled up by the same factor

in the whole network, so the impact affects the entire network instead of specific areas.

For floods, given that the rainfall data was taken from real measurements, five levels were modelled by applying extreme value theory. Assuming the data is independent and identically distributed, the Block Maxima Approach (BMA) and the Generalized Extreme Value (GEV) distribution was used. Then the parameters of the GEV distribution were estimated to fit the dataset and a projection diagram was drawn for each region. An example of a projection diagram for Region 4 is shown in **Figure 5.3**.

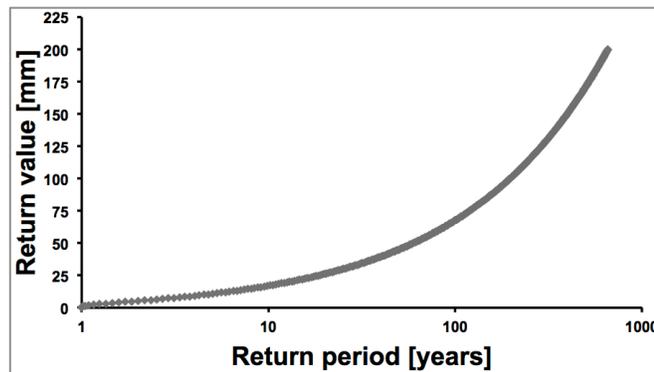


Figure 5.3. Projection diagram for Region 4 - horizontal axis in logarithmic scale - (own elaboration).

Thereafter, five return periods were chosen (i.e. 10-year, 33-year, 100-year, 150-year and 250-year), which provided five return values for the peak rainfall within one hour for every region. For example, for Region 4 the return values projected were: 17 mm, 32.9 mm, 59.7 mm, 74.1 mm and 97 mm, respectively (which is reasonable taking into account that the highest hourly rainfall recorded by Met Office was 92 mm in 1901 (MET Office UK, 2015)). Then, rainfall scale parameters are calculated with Equation 5.1, where given a return period  $\lambda$ -year, the scale parameter,  $\pi(\gamma, \rho, \lambda)$ , for the year  $\gamma$  and region  $\rho$  is equal to the return

value  $T$  ( $\lambda$ -year) [mm] divided by the peak rainfall value of the year  $\gamma$  in the region  $\rho$ ,  $P(\gamma, \rho)$  [mm].

$$\pi(\gamma, \rho, \lambda) = \frac{T(\lambda\text{-year})}{P(\gamma, \rho)}, \text{ for } \gamma \in [1979, \dots, 2011] \quad (5.1)$$

### 5.3.2 Phase two: fragility of electrical components

As detailed in Section 4.1.2, the component's fragility phase should follow three steps: first identify the vulnerable components, then use a fragility curve approach and finally assign damage states. Therefore, in the Great Britain study case, the key vulnerable macro components shown in **Table 5.1** were identified and modelled.

Table 5.1. Threats analysed with their correspondent key vulnerable components identified (own elaboration).

Threat	Vulnerable components	
Wind Storms	Transmission lines	Transmission towers
Floods	Substations	Power plants

Subsequently, the vulnerability of each identified component is analysed through fragility curves. Used lines and towers' wind fragility curves are presented in **Figure 5.4.(a)** (M. Panteli and P. Mancarella, 2015). Likewise, in **Figure 5.4.(b)**, the flood fragility curves used are shown. Floods are strongly related to the accumulated rainfall, which can be produced by an intense short event (less than three hours) or a prolonged event (less than ten hours). These imply that beginning with rainfalls of approximately 20 mm/hour for at least three hours, the risks of flooding exist (D. Houston, et al., 2011). To take into account the particularities of power stations and substations, when a flood occurs, a probabilistic assignation is done (i.e. 38% for power plants and 33% for substations) based on the report on the survey of electrical components at flood risk in (H. Wallingford, 2014). The accuracy of these curves can vary depending on the particularities of each

component. Consequently the accuracy of the assessment can be improved in further works by improving the methods to generate the fragility curves.

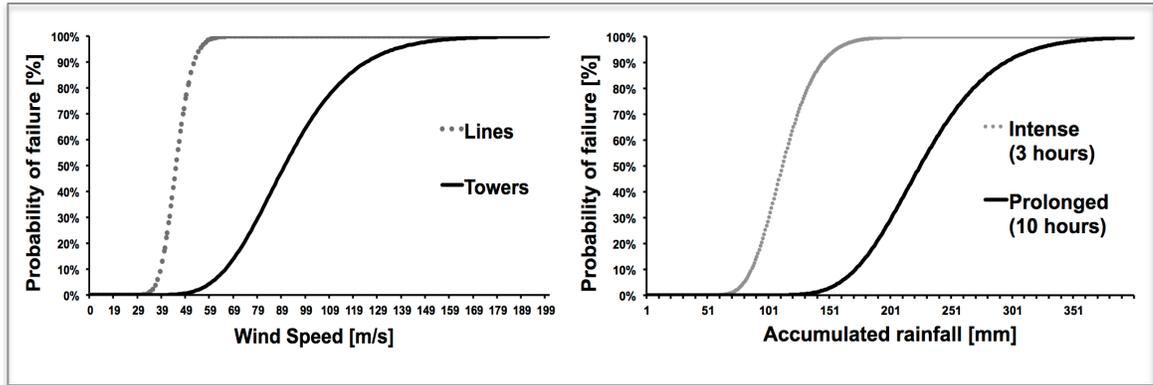


Figure 5.4. (a) Lines and tower’s fragility curves (M. Panteli and P. Mancarella, 2015). (b) Floods by intense or prolonged rainfall fragility curves (own elaboration with data from (D. Houston, et al. 2011)).

Finally, following the failure of a component, the damage state has to be assigned. The approach in this study is to establish the damage through zones in the fragility curve as shown in **Figure 4.3. (b)**. For example, power plants have four possible damage states: minor, moderate, extensive and complete. These states are determined by the percentiles 0-25<sup>th</sup>, 25<sup>th</sup>-50<sup>th</sup>, 50<sup>th</sup>-75<sup>th</sup> and 75<sup>th</sup>-100<sup>th</sup>, respectively. Lines, towers and substation’s potential damage are modelled with two states: operative and non-operative.

### 5.3.3 Phase three: power system’s reaction

As detailed in Section 4.1.3, the system’s operation phase consists in Sequential Monte Carlo Simulations with hourly OPF analyses. Also, in order to capture the spatiotemporal impact of the wind and rainfall fronts moving across the transmission network, a Sequential Monte Carlo-based time-series simulation model has been developed. This enables the representation of the weather and

electrical events in a chronological order as they happen in reality at different locations of the test system. An hourly simulation step is used, which is considered sufficient for modelling weather events. However, any time resolution can be used if desired and provided that the relevant information is available, e.g., weather profile. Further, one winter week is used as a simulation period, where extreme wind and rainfall events are expected considering that severe weather events do not usually last longer in Great Britain.

At every simulation step, the wind- and rainfall-affected failure probabilities of the electrical components obtained by the fragility curves are fed to the time-series simulation model as explained in the previous phases. Following this approach, the real-time weather-adjusted operation state of each electrical component is obtained. An AC Optimal Power Flow (OPF) is used for assessing the performance of the test network at every simulation step, which helps determine if load shedding is required for stabilizing the system. For solving the power flows the Netwon method was used, and for the optimization problem Matlab Interior Point Solver (MIPS) was employed. Finally, the model is also capable of island handling.

#### **5.3.4 Phase four: power system's restoration**

As explained in Section 4.1.4, three aspects should be taken into consideration for the components restoration: damage caused, human and material resources availability and the accessibility to the affected area. In this study, for simplicity reasons, the restoration curves are only related to the difficulties of the repair crew to enter the affected areas. The component restoration curves are defined by exponentially distributed curves with mean parameters as shown in **Table 5.2**. A Mean Time To Repair (MTTR) of 10 hrs and 50 hrs is assumed for lines and towers respectively, and 10 hrs and 30 hrs for power plants and substations respectively (referred to as  $MTTR_{base}$ ). The weather intensity is

classified here as follows: for windstorms, it can be Low (less than 20 m/s), Moderate (between 20 m/s and 40 m/s) or High (more than 40 m/s), while for floods it can be Low (less than 138 mm for intense accumulated rainfall or 280 mm for prolonged accumulated rainfall or High (more than 138 mm for intense accumulated rainfall or 280 mm for prolonged accumulated rainfall). As weather intensity increases, the repair crews need more time to enter the affected area and restore the damaged components, which is modelled here as a random increase in  $MTTR_{base}$  as can be seen in **Table 5.2**.

Table 5.2. Mean times to repair (hours) for different weather intensities (own elaboration).

Threat	Component	MTTR for different weather intensities (Wind speed (m/s) / Accumulated rainfall (mm))		
		Low	Moderate	High
Windstorms	Lines	$MTTR_{base}$	$MTTR_{base} \times \text{rand}[2,4]$	$MTTR_{base} \times \text{rand}[5,7]$
	Towers	$MTTR_{base}$	$MTTR_{base} \times \text{rand}[2,4]$	$MTTR_{base} \times \text{rand}[5,7]$
Floods	Power Plants	$MTTR_{base}$	---	$MTTR_{base} \times 2$
	Substations	$MTTR_{base}$	---	$MTTR_{base} \times 2$

#### 5.4 Resilience adaptation

In this study, the adaptation strategies discussed in Section 4.2 are applied to the critical transmission route shown in **Figure 5.5** from North to South Great Britain. Following extensive resilience studies (mainly focusing on the maximum power flows on the transmission lines), this corridor was identified as one of the critical transmission routes for preserving the resilience of the entire power system.

Particularly, for the normal case, the basic network was used with no resilience enhancement. For the robust strategy case, the fragility curves of the components (see **Figure 5.4**) in the critical path were shifted to the right a 15% of the 50<sup>th</sup> percentile of the curve. For the redundant strategy case, identical parallel lines have been added to the critical transmission path. Finally, for the responsive

strategy case, the mean times to repair of the components in the critical path were supposed unaffected by the severity of the weather.

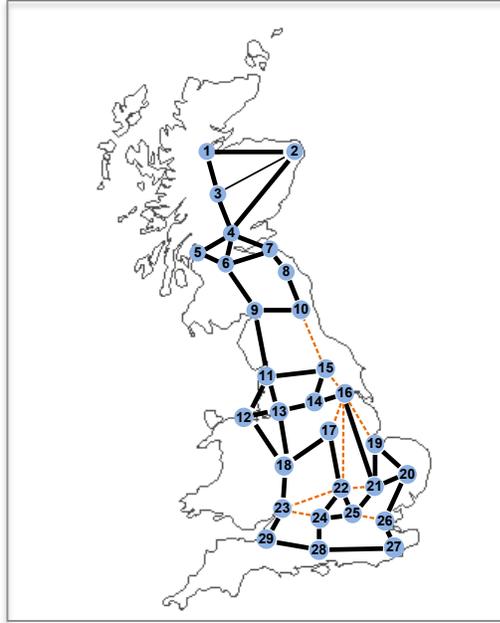


Figure 5.5. Dotted lines show the critical transmission corridor for which the adaptation case studies are applied (own elaboration with M. Panteli).

## 5.5 Results and discussion

The impact of windstorms and floods is first modelled independently, and then the combined impact of these threats is evaluated. In **Figure 5.6**, the comparison between these single and multi-hazards is represented using EENS for different intensities of the weather hazards. Where the impact increases with the intensity of the event and the combination of hazards is much more severe than the single threats. The impact of floods is greater than the windstorms mainly because the substations affected by floods are more important to the network than other components.

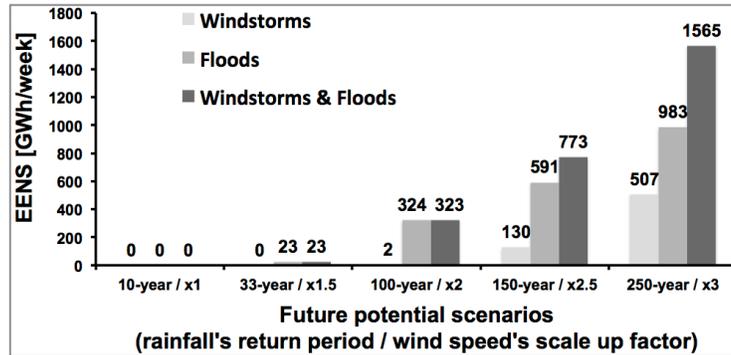


Figure 5.6. EENS [GWh/week] of different hazards in potential future scenarios (own elaboration).

Then, the EENS results for the strategic adaptation cases in the different future scenarios are illustrated in **Figure 5.7**. (a) and (b), for windstorms and floods, respectively. It can be seen that the best adaptation case for both hazards is robustness, followed by responsiveness and finally redundancy, where for floods this last strategic case has almost no improvement. This can be explained by the different components each hazard has impact on, where windstorms affect lines and towers, and floods affect power plants and substations. When the nodes of a network (substations) are impacted, alternative paths are also affected; hence redundancy of lines and towers enhances resilience significantly only for windstorms.

In **Figure 5.8**, the improvement of the strategic cases compared to the normal case of the three most severe scenarios can be seen through the percentage of decrease of EENS. As the intensity of the event increases, the improvement produced by the adaptation cases decrease; especially for robustness; hence having a better response plan or redundancy becomes more important.

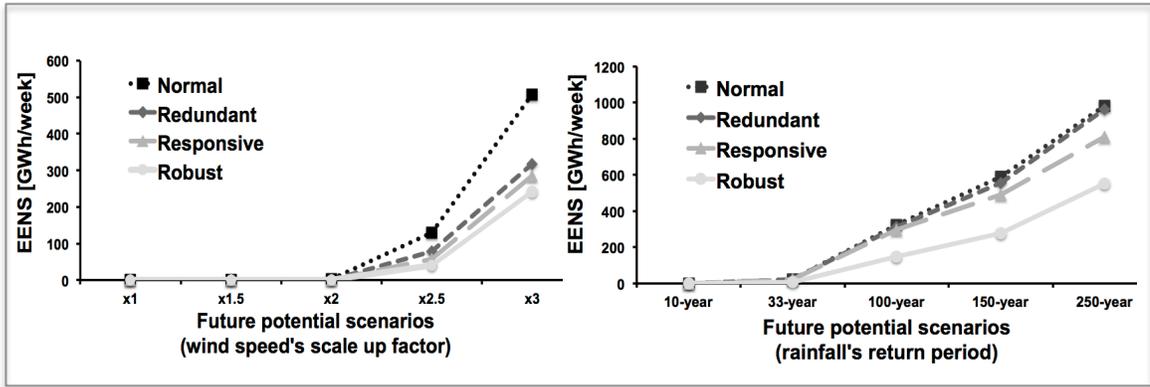


Figure 5.7. (a) Windstorms adaptation strategies results. (b) Floods adaptation strategies results. (Own elaboration).

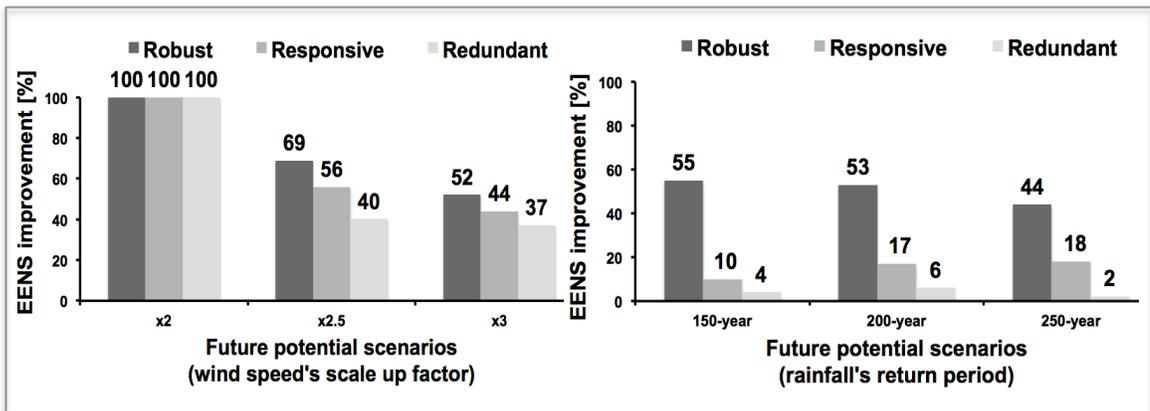


Figure 5.8. (a) Windstorms adaptation results improvements for the three most hazardous events. (b) Floods adaptation results improvements for the three most hazardous events. (Own elaboration).

Finally, in **Table 5.3**, the EIU results are presented. Here  $E$ , or total week-demand, is equal to 7193 GWh. It can be seen that the EIU results are relatively low except for the very extreme cases. This can be mainly due to the high reliability of the test network. However, this low impact when expressed through EENS or EIU can be very high in terms of financial losses, therefore a socio-economic analysis should be performed to correctly assess the resilience of the system and decide between different enhancement measures.

Table 5.3. EIU results (own elaboration).

<b>Comparison of hazards in different scenarios</b>			
<b>Scenarios</b>	<b>Windstorms</b>	<b>Floods</b>	<b>Windstorms &amp; Floods</b>
10-year / x1	0.00%	0.00%	0.00%
33-year / x1.5	0.00%	0.32%	0.32%
100-year / x2	0.03%	4.50%	4.49%
150-year / x2.5	1.81%	8.22%	10.75%
250-year / x3	7.05%	13.67%	21.76%

## 6. APPLICATION TO EARTHQUAKES IN CHILE

Chile is a long and narrow country in South America with a population of around 18 million people<sup>6</sup>. It is a fast developing country, currently with a GDP per capita of 23,165 USD<sub>2014</sub> (PPP)<sup>7</sup> and a Human Development Index (HDI) of 0.82<sup>8</sup>, which is classified as very high. At the same time, it has seen its electric power installed capacity grow 3 times between 1996 and 2012<sup>9</sup>. However, this socio-economic growth is challenged by the great amount and diverse natural threats, such as volcanic eruptions, wildfires, droughts driven by climate change, floods, landslides, earthquakes and tsunamis.

In this chapter, the influence of earthquakes and tsunamis in Chile is described, focusing on earthquakes and electric power systems. Afterwards, the northern electric power system modelled is presented and finally, the application of the resilience framework is developed.

### 6.1 Influence of earthquakes and tsunamis in Chile

The strongest earthquake registered in modern history took place in Valdivia, south of Chile, in 1960 with a magnitude of 9.5  $M_w$ <sup>10</sup>. The most recent mega earthquake in Chile, an 8.8  $M_w$  magnitude event, struck the central zone followed by a tsunami that hit the coastal areas on February 27, 2010. This earthquake, ranked as the sixth-strongest recorded in modern history, produced a loss estimated in US\$30 billion equal to a 18% of the country's GDP (more than twenty times greater than the most disastrous event in the US until now: hurricane Katrina in 2005) (M. Useem, et al., 2015).

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<sup>6</sup> INE, 2014.

<sup>7</sup> IMF, 2015.

<sup>8</sup> UNDP, 2014.

<sup>9</sup> Ministry of Energy of Chile, 2013.

<sup>10</sup> Mistakenly called Richter magnitude. The Richter scale was succeeded by the Moment Magnitude Scale (MMS) in the 1970s and is currently broadly used around the world.

At the same time, Chile has been host to a significant number of tsunami events. Three examples in the past five years are the large-scale tsunami of February 27, 2010, witnessed throughout the national territory, the tsunami in the north that struck Pisagua on April 1, 2014, after the same date earthquake magnitude 8.2  $M_w$  and while writing this thesis on September 16, 2015, a subduction earthquake magnitude 8.4  $M_w$  stroke nearby Illapel producing a tsunami along the central coast (more detail is given in Appendix C). Also, due to the geographical conditions in Chile, where the coast is closer to the earthquake generation zone, the first wave arrival times are significantly short<sup>11</sup>.

These events highlight the need for research in this topic.

### **6.1.1 Influence of earthquakes in Chile's power systems**

As explained before, Chile has faced many critical hazards, where the electric power systems have been tested. After the events on February 27, 2010, which impacted the SIC, central system of Chile<sup>12</sup>, efforts to collect information on how the system responded were carried out by (J. Araneda, et al., 2010; H. Rudnick, 2011; CIGRE, 2012).

Chile has a high standard of seismic requirements for its civil structures and for its electrical components<sup>13</sup>. That is one of the main reasons why (J. Araneda, et al., 2010; H. Rudnick, 2011; CIGRE, 2012) concluded that the electric power system responded well to the challenge (nevertheless, with space for improvements). Their assessment of the segments of the system that provides more than 93% of the national population is explained hereafter.

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<sup>11</sup> For example during the 2010 and 2014 Chilean tsunamis, wave arrival times were between 10 to 15 minutes following the seismic activity, while during Tohoku 2011, Japan, the first wave arrival times were between 30 to 40 minutes following the seismic activity (Cigiden, 2015).

<sup>12</sup> Currently, Chile has two large interconnected systems and two small isolated systems. The first two are the northern (SING) and the central one (SIC). They are going to be interconnected in 2017.

<sup>13</sup> The Chilean electric normative [20] indicates that high voltage facilities must fulfil the IEC 60071 standard or the IEEE 693-1997 standard at "High Performance Level".

#### **a) Impact on generation**

In February 2010, the installed capacity of the system<sup>14</sup> was 11,023 MW with a peak demand of 6,145 MW. At the time of the earthquake, the dispatched generation was 4,522 MW. As a consequence of the seismic event approximately 3,000 MW of generation capacity became unavailable immediately after the event. In the following 30 days 2,257 MW were put back into service and 693 MW remained out of service for up to six months requiring major repairs.

#### **b) Impact on transmission**

Tanselec is the main transmission company in Chile with 8,239 km and 50 substations in the two main systems: SIC and SING. Transelec's damage assessment revealed that in the SIC 12 of the 46 substations and 1.6 km of the 7,280 km of transmission lines suffered damages, representing 26% of substations and 0.02% of transmission lines.

#### **c) Impact on distribution**

At the distribution level, most of the damage was detected. 4.5 million people were affected by a blackout immediately after the event. However, the electric components did not suffer from design or construction seismic failures, but were mainly damaged because of nearby walls, landslides and the tsunamis. CGED is the main distribution company that serves the most affected area by the quake. The publications report that although 80% of the clients were without supply the day after the event, this was reduced to 0.4% two weeks later.

#### **d) Operation and restoration**

During the disaster, the country saw that one of the most weak critical infrastructure systems was telecommunications. These problems produced

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<sup>14</sup> This "over capacity" is due to the flexibility required by the system because of the high amount of hydro generation.

several difficulties to the operation and restoration of the electric power system.

(H. Rudnick, 2011) explains that given the impacts on the electric segments just presented the system operator had to plan the recovery in three stages. The first stage was to restore service where no facilities were affected by forming islands. In the particular case of the 2010 quake, the recovery experience started with a five-island scheme, which later was integrated into a two island-scheme that lasted for two days. The second stage consisted in the restoration of the principal equipment with limited material and human resources. In 2010, the efforts allowed the main transmission network to be restored to service in less than 13 hours, albeit in a weakened condition – no N-1 conditions and many breakers bypasses. The third stage, which took several months to complete, had the responsibility to restore the reliability criteria to the system.

One note that has been remarked is that the challenges from the generation and transmission perspective were not as severe as in a typical blackout, because the load demanded in the distribution level was reduced dramatically because of the quake.

### **6.1.2 Future hazard scenarios in northern Chile**

Since no major seismic event ( $> 8.5 M_w$ ) has occurred in northern Chile since the 1877  $8.6 M_w$  megathrust earthquake that was followed by a huge tsunami, the accumulation of elastic deformation is likely to be released in a future event (which if released at once it could correspond to a  $9 M_w$  earthquake). **Figure 6.1** suggests that this area is a mature seismic gap with a high seismic and tsunami hazard (M. Metois, et al., 2013).

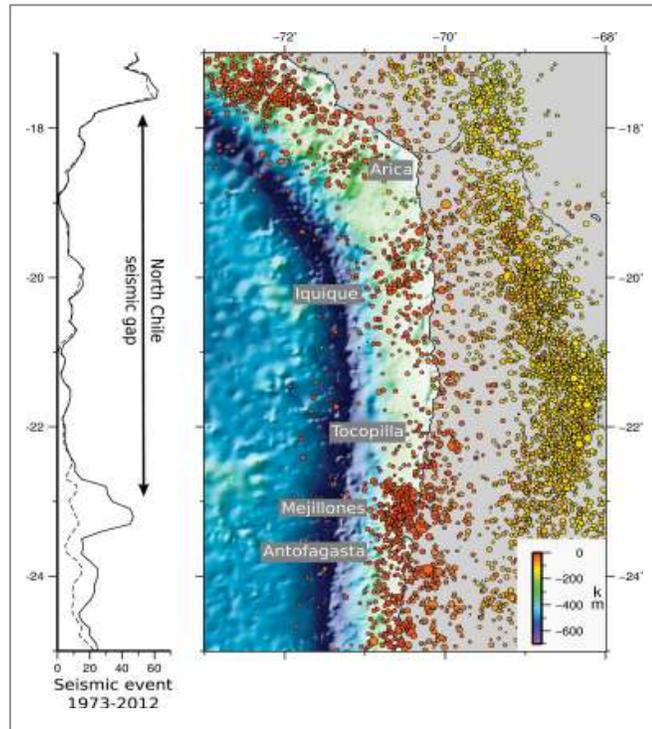


Figure 6.1. (a) Number of medium shallow earthquakes plotted against latitude (dashed curve removes aftershocks and the 2007 big event). (b) Map of all earthquakes registered by USGS from 1973 to 2012 (colour represents the epicentre's depth) (M. Metois, et al., 2013).

## 6.2 The northern Chilean reduced electric power system

The northern Chilean system (SING) serves the regions of Arica-Parinacota, Tarapacá and Antofagasta, which cover 24.5% of the continental Chilean territory. This system is characterized by the mining industry that accounts for almost 15% of the Chilean GDP.

**Figure 6.2.(a)** shows the real SING, while **Figure 6.2.(b)** is a diagram that presents the network in a very simplified way to show how most of the generation is at the coast and the mining consumers at the mountains only 200 km away. The system modelled is presented in **Figure 6.3**. It represents the grid as it was in the

beginning of 2014 with an installed generation capacity of 3744 MW, where 2100 MW is coal (56%), 1180 MW is diesel (31.5%) and 436 MW is GNL (11.5%). The peak demand in 2014 was 2363 MW. Finally, it is interconnected to Argentina through the substations Andes in Chile and Salta in Argentina.

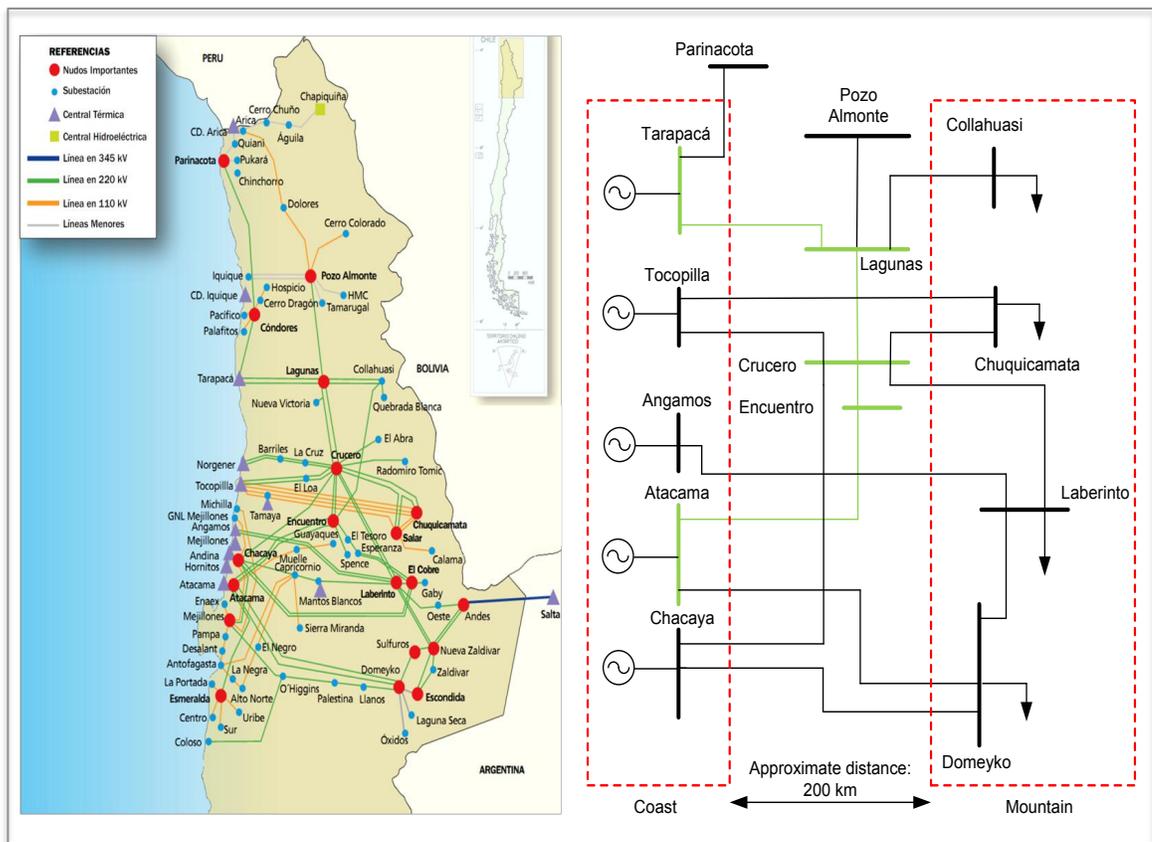


Figure 6.2. (a) Northern Chile real system. (b) Northern Chile explicative diagram. (H. Rudnick, 2013).

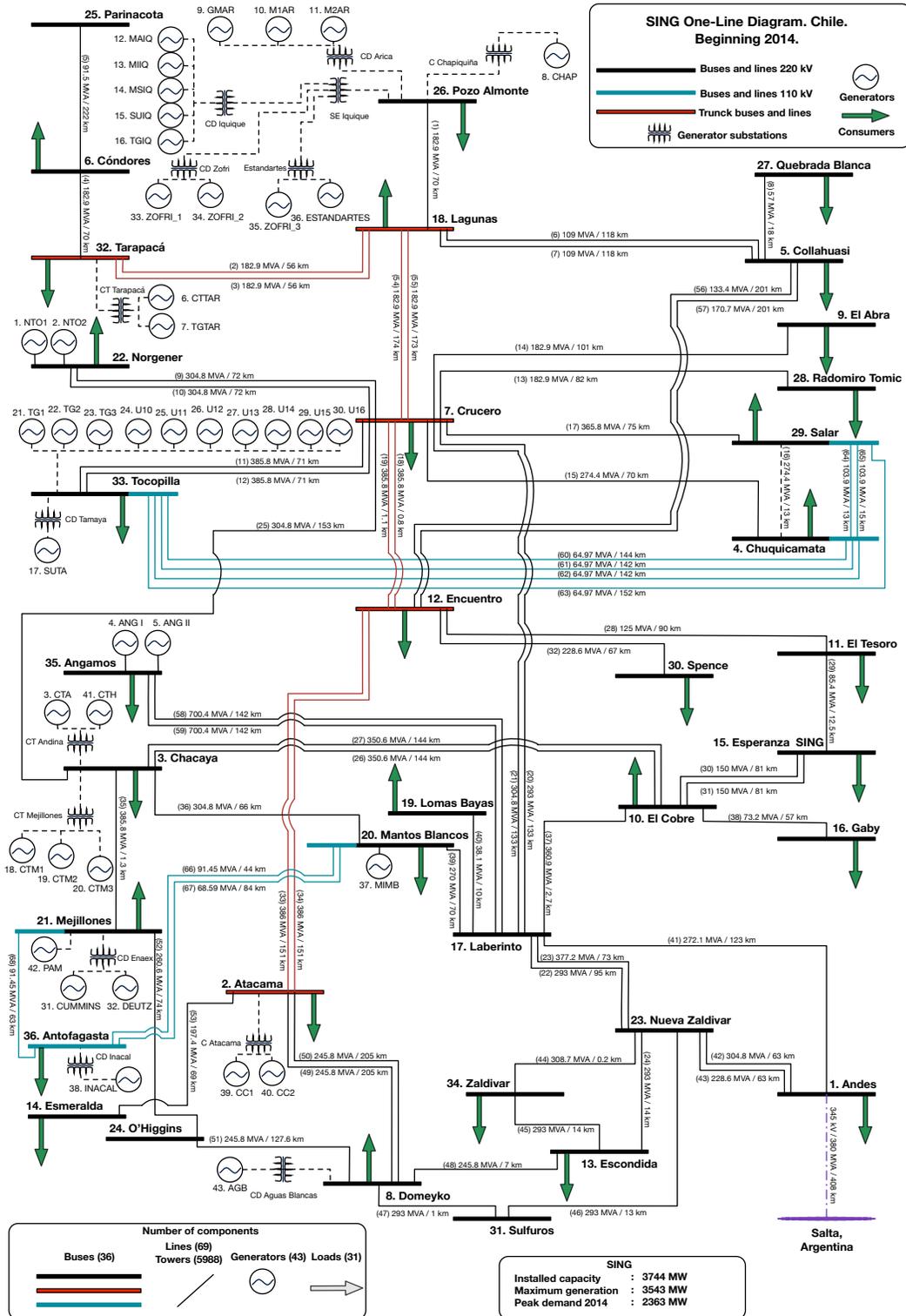


Figure 6.3. Northern Chilean reduced electric power system (Own elaboration).

## 6.3 Resilience assessment

The resilience of the test network is evaluated against earthquakes, which constitute a severe threat to the northern Chilean power system. In this study case, instead of simulating certain T-years events as in Chapter 5, here the simulation includes all possible seismic events following the technique presented in (C. Cornell, 1968).

### 6.3.1 Phase one: earthquakes characterization

As detailed in Section 4.1.1, the threat characterization phase aims at defining the event's probability of occurrence, magnitude and spatio-temporal profile. Therefore, as explained by (A. Poulos, 2014), calculating the mean annual frequency of events that generate a ground motion that exceeds a certain Intensity Measure (IM), conditioned to a magnitude  $M$  and source-to-site distance  $R$ , is required in order to estimate the probability of occurrence of all the possible seismic events at all the sites studied.

There are many IM possible to use, such as Peak Ground Deformation (PGD), Peak Ground Velocity (PGV), Peak Ground Acceleration (PGA), etc. The latter one is the most popular one and it is used in this study<sup>15</sup>.

For this research, the parameters of the equations presented in Section 4.1.1 are taken from the study in (M. Álvarez, 2001), which divides the interface between the subducting Nazca and overriding South American tectonic plates into planes and proposes the  $a$  and  $b$  coefficients of the Gutenberg-Richter law for each plane. Also  $M_{\min}$  and  $M_{\max}$  are defined as 5 and 9  $M_w$ .

Thereafter, to calculate the PGA in every site, Ground Motion Prediction Equations (GMPEs) are used. These attenuation relationships predict the intensity

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<sup>15</sup> This because the fragility curves selected in the next section are almost all describing the structural response with this Intensity Measure. In the future, to be more exhaustive, a correlation study should be carried out to decide which IM to use.

measure produced by an earthquake at a given site with its associated uncertainty. The GMPEs selected for this research were developed by (N. Abrahamson, et al., 2012), which require the earthquake characteristics defined before, the GIS information of the sites, along with its class of site, defined by its  $V_{s30}$ <sup>16</sup>, which is taken from USGS maps as shown in Appendix D.

### 6.3.2 Phase two: fragility of electrical components

As explained in detail in Section 4.1.2, the component’s fragility phase should follow three steps: first identify the vulnerable components, then use a fragility curve approach and finally assign damage states. Therefore, in the northern Chilean study case, the key vulnerable macro components presented in **Table 6.1** were identified and modelled. Given the seismic standard of constructions in Chile, all the facilities are considered as “anchored”.

Table 6.1. Hazard analysed with its correspondent key vulnerable components identified and modelled (own elaboration).

Threat	Vulnerable components	Classification
Earthquake	Transmission towers	Lattice steel
	Substations	Anchored medium voltage (150 to 350 kV)
		Anchored low voltage (34.5 to 150 kV)
	Power plants	Anchored large power plant
Anchored small power plant		

The seismic fragility curves of the identified components were retrieved from international literature (detailed in Appendix E). The used curves are presented in **Figure 6.4**, **Figure 6.5**, **Figure 6.7**, **Figure 6.7** and **Figure 6.8**. The

<sup>16</sup> Average shear-wave velocity in the upper 30 m of the site. It helps to define the site class, which is generally classified in hard rock, rock, very dense soil and soft rock, stiff soils, soft soils and others.

earthquake Intensity Measure used is PGA, which is measured in %g (percentage of the gravity acceleration).

To assign the damage states the random number  $r \sim U(0,1)$  is first sampled and compared to the “Collapse state“ fragility curve, if  $r$  is smaller than the probability of collapse this state is assigned, if its larger then  $r$  is compared with “Extensive state“ fragility curve. If  $r$  is again larger the procedure is repeated with “Moderate state“ and finally with “Minor state“. If  $r$  is still larger than the Minor state then the component did not fail. In the case of towers only two states are considered. Damage states are modelled as shown in **Table 6.2**.

Table 6.2. Components damage states (own elaboration with data from Hazus).

Vulnerable components	Classification	Minor damage	Moderate damage	Major damage	Collapse damage
Transmission towers <sup>17</sup>	Lattice steel	-	-	50% probability of line tripping	100% probability of line tripping
Substations <sup>18</sup>	Anchored medium voltage	5% of adjacent components are disconnected	40% of adjacent components are disconnected	70% of adjacent components are disconnected	100% of adjacent components are disconnected
	Anchored low voltage	5% of adjacent components are disconnected	40% of adjacent components are disconnected	70% of adjacent components are disconnected	100% of adjacent components are disconnected
Power plants <sup>19</sup>	Anchored large power plant	Out of service	Out of service	Out of service	Out of service
	Anchored small power plant	Out of service	Out of service	Out of service	Out of service

<sup>17</sup> When a tower collapses, the circuit supported by the tower goes out of service.

<sup>18</sup> Adjacent components refer to power plants and lines connected to the substation.

<sup>19</sup> The damage difference is seen in the mean times to repair explained in Section 6.3.4.

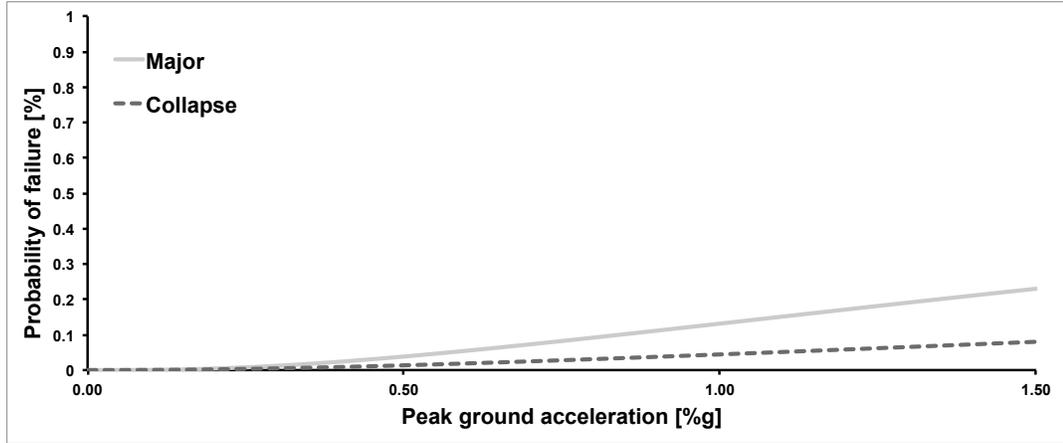


Figure 6.4. Transmission tower's fragility curves (L. Xie, et al., 2012).

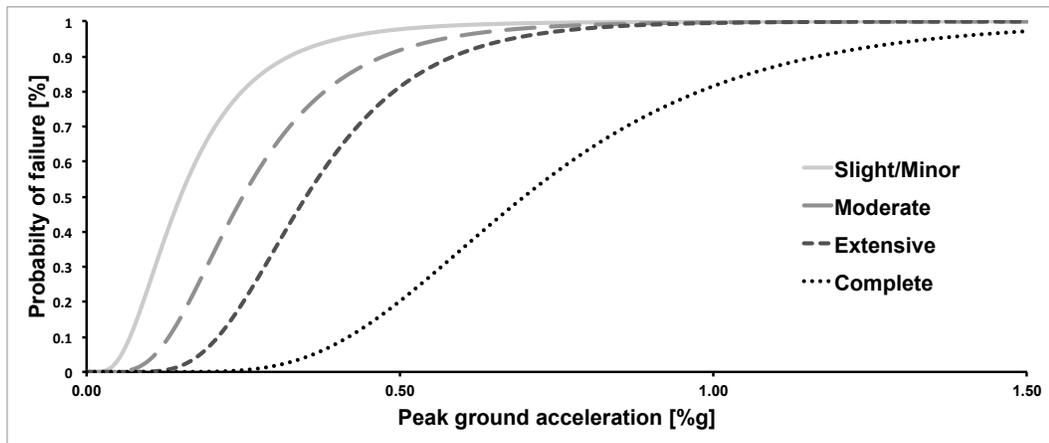


Figure 6.5. Anchored medium voltage substation's fragility curves (Hazus).

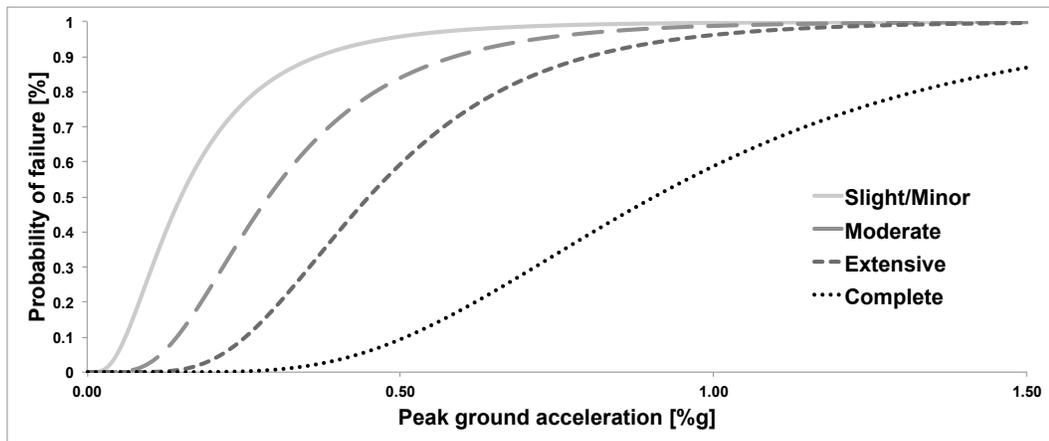


Figure 6.6. Anchored low voltage substation's fragility curves (Hazus).

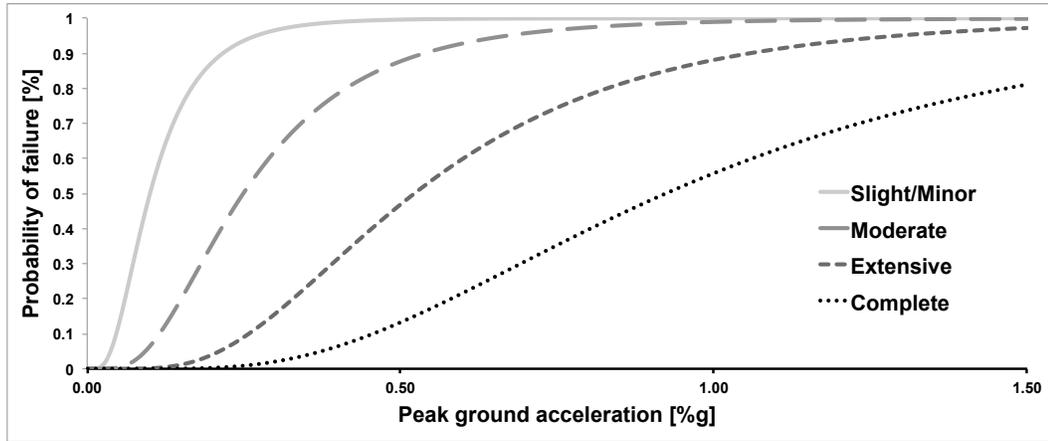


Figure 6.7. Anchored large power plant's fragility curves (Hazus).

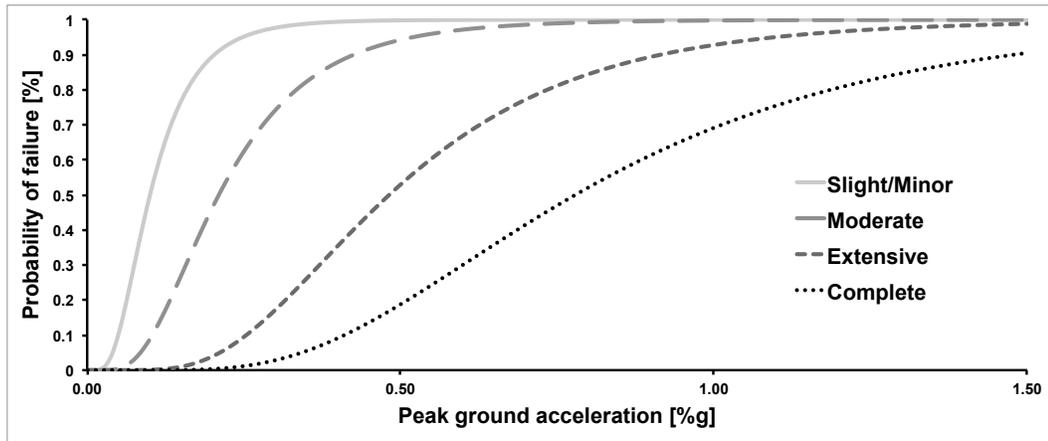


Figure 6.8. Anchored small power plant's fragility curves (Hazus).

### 6.3.3 Phase three: power system's reaction

As detailed in Section 4.1.3, the system's operation phase consists in Sequential Monte Carlo Simulations with hourly OPF analyses. Also, in order to capture the spatiotemporal impact of the earthquake scenarios along with the operation and recuperation of the system, a Sequential Monte Carlo-based time-series simulation model has been developed, similar to the one explained in the previous chapter. The resolution of every simulation step is hourly within a week.

The interconnection with Argentina is not considered. The total demand, plotted in **Figure 6.9**, represents the annual peak demand week in 2014.

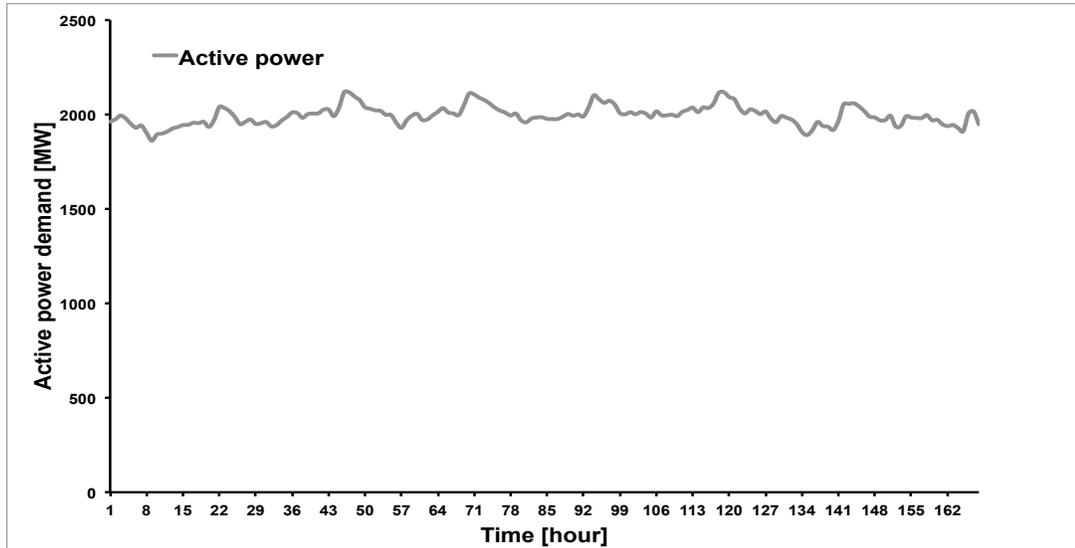


Figure 6.9. Annual peak demand week in the SING (Own elaboration from data of CDEC-SING).

Before the week’s simulation, an independent DC-OPF is run to identify which generators will be online during a normal week. Due to the generation mix in the northern system, which is mainly thermal hence very inflexible because of start up times; reserves of 70 MW are included as stated by (CDEC-SING, 2013). The results of the generation capacity for the first hour are presented in **Figure 6.10**.

Then in the first hour, when the event happens, an analysis is run to verify if the system should be run in emergency or normal state<sup>20</sup>, as defined by (CNE-Chile, 2015). Thereafter, in every simulation step an independent DC-OPF is run to analyse possible energy not supplied in the system.

<sup>20</sup> For instance, in normal state, facilities with voltages equal or over 500 kV must have their voltage levels within 0.97 and 1.03 pu, facilities with voltages between 200 kV and 500 kV must have their voltage levels within 0.95 and 1.05 pu and facilities with voltages below 200 kV must have their voltage levels within 0.93 and 1.07 pu. In emergency state, facilities with voltages equal or over 500 kV must have their voltage levels within 0.93 and 1.05 pu, facilities with voltages between 200 kV and 500 kV must have their voltage levels within 0.9 and 1.1 pu and facilities with voltages below 200 kV must have their voltage levels within 0.9 and 1.1 pu.

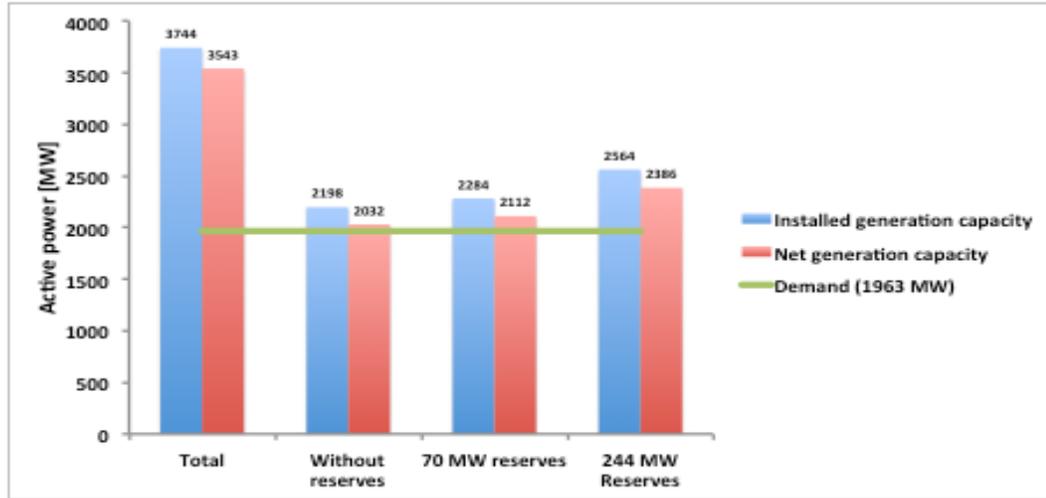


Figure 6.10. Generation capacity and reserves normative (own elaboration).

#### 6.3.4 Phase four: power system's restoration

As explained in Section 4.1.4, three aspects should be taken into consideration for the components restoration: damage caused, human and material resources availability and the accessibility to the affected area. In this case, restoration is modelled from an individual perspective with a probabilistic approach that depends on the damage caused and the accessibility to the affected area. For simplicity reasons, human and material constraints are not included.

The accessibility to the affected area is related directly to the magnitude of the earthquake as presented in **Table 6.3**. The component restoration curves are defined by exponentially distributed curves with mean parameters ( $MTTR_{base}$ ), as presented in **Table 6.4**.

Table 6.3. Delay in mean times to repair due to the event's magnitude (own elaboration).

Magnitude of the earthquake	Mean time to repair of components
$M \leq 6$	$MTTR_{base} \times 1.0$
$6 < M \leq 7$	$MTTR_{base} \times 1.5$
$7 < M \leq 8$	$MTTR_{base} \times 2.0$
$8 < M$	$MTTR_{base} \times 2.5$

Table 6.4. Mean Times to Repair (days) for different components (Own elaboration from adapted data of Hazus).

Vulnerable components	Classification	Minor damage	Moderate damage	Major damage	Collapse damage
Transmission towers <sup>21</sup>	Lattice steel	-	-	MTTR <sub>base</sub> = 3	MTTR <sub>base</sub> = 7
Substations <sup>22</sup>	Anchored medium voltage	MTTR <sub>base</sub> = 1	MTTR <sub>base</sub> = 3	MTTR <sub>base</sub> = 7	MTTR <sub>base</sub> = 30
	Anchored low voltage	MTTR <sub>base</sub> = 1	MTTR <sub>base</sub> = 3	MTTR <sub>base</sub> = 7	MTTR <sub>base</sub> = 30
Power plants <sup>23</sup>	Anchored large power plant	MTTR <sub>base</sub> = 0.5	MTTR <sub>base</sub> = 3.6	MTTR <sub>base</sub> = 22	MTTR <sub>base</sub> = 65
	Anchored small power plant	MTTR <sub>base</sub> = 0.5	MTTR <sub>base</sub> = 3.6	MTTR <sub>base</sub> = 22	MTTR <sub>base</sub> = 65

#### 6.4 Resilience adaptation

In this study case, the adaptation strategies discussed in Section 4.2 are applied to the Trunk transmission system, which is defined by the Decree 61 of the General Electric Chilean Law. In **Figure 6.2.(b)** the green components represent the Trunk system. In **Figure 6.3**, the Trunk system is represented by the red components.

Particularly, for the normal case, the basic network was used with no resilience enhancement. For the robust strategy case, the fragility curves of the components in the Trunk system were shifted to the right a 15% of the 50<sup>th</sup> percentile of the curve. For the redundant strategy case, identical parallel lines have been added to the Trunk transmission path. Finally, for the responsive strategy case, the mean times to repair of the components in the critical path were supposed unaffected by the severity of the earthquake.

<sup>21</sup> When a tower collapses, the circuit supported by the tower goes out of service.

<sup>22</sup> Adjacent components refer to power plants and lines connected to the substation.

<sup>23</sup> The damage difference is seen in the mean times to repair explained in Section 6.3.4.

## 6.5 Results and discussion

Before presenting the Chilean resilience results, two scenarios modelled are presented next. The northern Chilean system is drawn in **Figure 6.11.(a)**, where the blue dots, pink circles and green dots represent power plants, substations and towers, respectively. In **Figure 6.11.(b)**, the most hazardous scenario, with an EIU of 97%, is presented (i.e. earthquake magnitude 8.97  $M_w$ , which represent 180% of the energy released in Feb-2010) along with a scenario with an earthquake magnitude 7.64  $M_w$ , with an EIU of 1.5% (which is 55 times weaker in terms of energy release with the Feb-2010 earthquake).

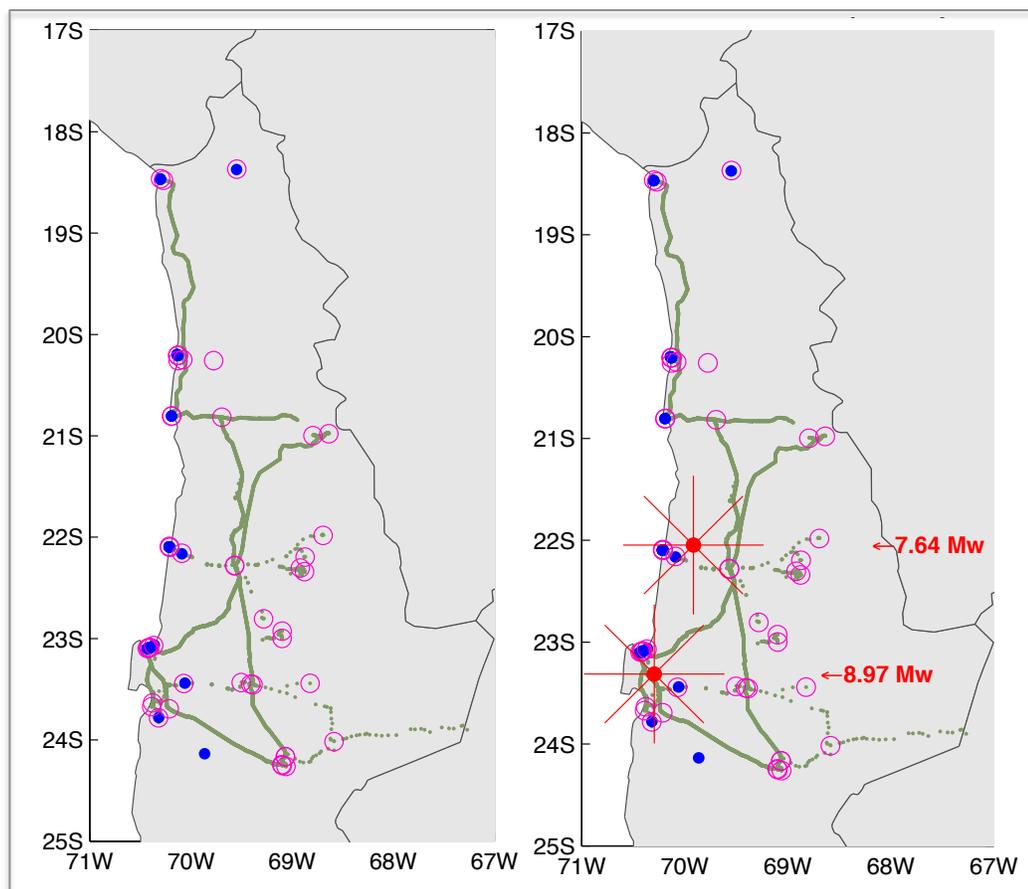


Figure 6.11.(a) Northern Chilean system with GIS information (b) Includes epicentres of two scenarios modelled (own elaboration).

These two scenarios produced several damages in the system as shown in **Table 6.5**. The consequences in the system are described by curves in **Figure 6.12**, where the red curve represents the hourly power demand curve, the blue curve the hourly power not supplied in the most disastrous earthquake scenario and the green curve the hourly not supplied by the 7.64  $M_w$ . It can be seen that the latter curve shows energy not supplied only in the beginning of the week, while emergency generators turn on and those with moderate/minor damage recover (**Figure 6.13**).

Table 6.5. Damages produced by earthquakes 7.64  $M_w$  and 8.97  $M_w$ .

Component	Total	Damaged by 7.64 $M_w$	Damaged by 8.97 $M_w$
Generators	43	Complete: 0	Complete: 18
		Major: 0	Major: 7
		Moderate: 5	Moderate: 4
		Minor: 10	Minor: 1
Substations	49	Complete: 0	Complete: 10
		Major: 0	Major: 7
		Moderate: 4	Moderate: 6
		Minor: 8	Minor: 9
Towers	5946	Complete: 3	Complete: 87
Lines	68	Major: 3	Major: 164
		Complete: 3	Complete: 21
		Major: 2	Major: 15

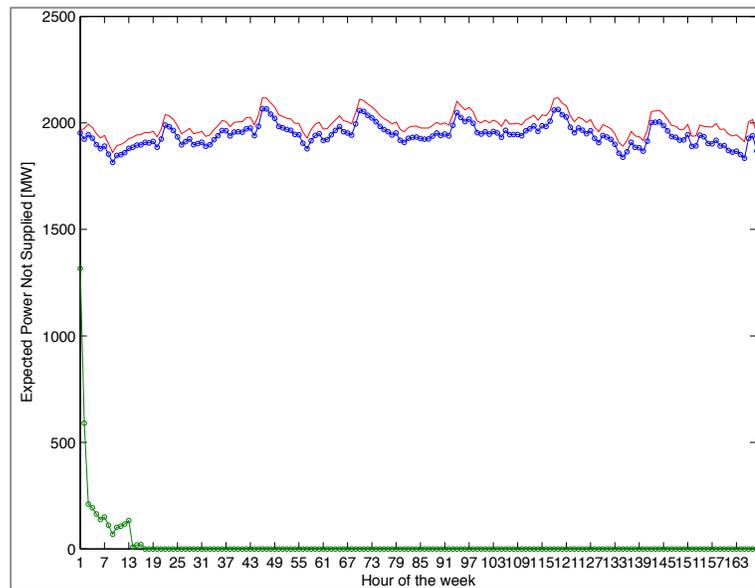


Figure 6.12. Hourly expected power not supplied [MW vs hour].

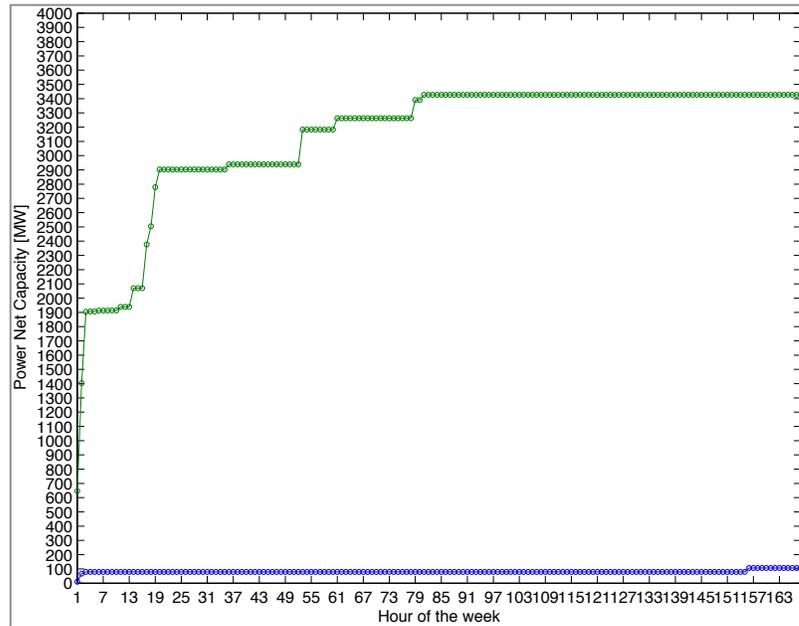


Figure 6.13. Hourly power net capacity [MW vs hour].

Its important to note that in this chapter all the probable events, including all magnitudes from 5  $M_w$  to 9  $M_w$ , of earthquakes are modelled together. Therefore, curves can be retrieved from the simulation results. In **Figure 6.14** the Expected Energy Not Supplied of the normal system (without adaptation strategies) is represented along with the total energy demanded during the studied week. As expected, as the event is less frequent and more severe the expected energy not supplied is higher.

Due to the form of the Gutenberg-Richter law, where earthquake with a low intensity measure are many and earthquakes with a high intensity measure are scarce, MCS results will have less density in the upper zone of the curve. Also it was detected that more scenarios are required since the results of the adaptation strategies presented in **Figure 6.15**, show inconclusive results. More scenarios for the simulation, clustering techniques and/or results factoring is required. However, it can be noted, that for the same return periods of Great Britain's hazards, the Chilean earthquake can produce a much larger impact. For instance, for an event that may happen every 100-years the combined event of floods and windstorms

produced a 4.5% of EIU and earthquakes could produce an impact as high as 60% of EIU. Also if the expected annual loss in terms of EIU is calculated; the results are 4.60% for the normal case, 4.44% for the redundant case, 4.51% for the responsive case and 4.10% for the robust case (this includes extreme events and low impact events).

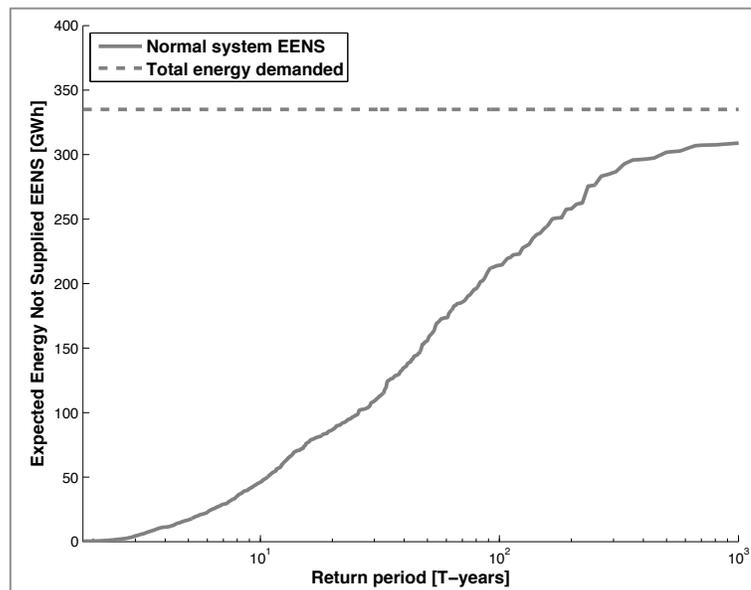


Figure 6.14. EENS [GWh/week] of the normal system under different scenarios.

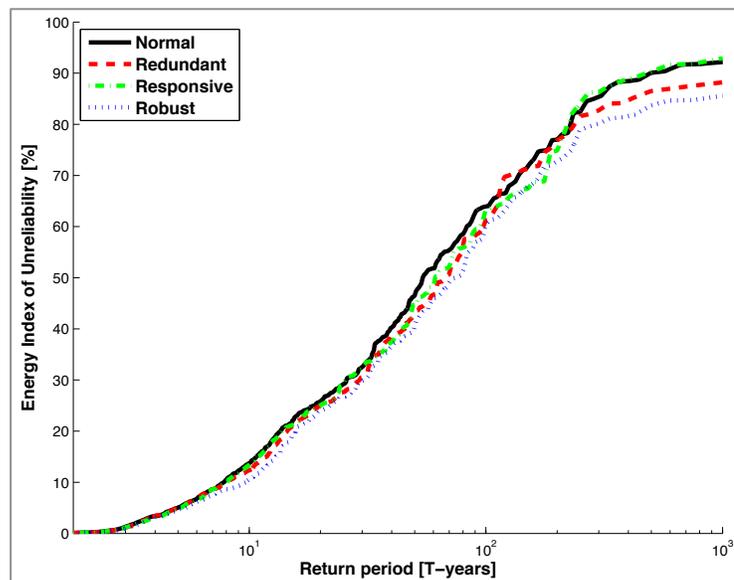


Figure 6.15. EIU [%] of adaptation strategies under different scenarios.

## 7. CONCLUSIONS

Resilience of electric power systems has emerged as a new concept after the recent catastrophic events around the world. It can be expected that the concept may represent for the future what reliability was in the past, but it has to be taken in consideration that resilience is far more complex, as the knowledge of many different fields and thus a multidisciplinary work is required. Currently, different research teams are working on defining the concept and developing tools to describe, measure and enhance resilience. As a contribution to the topic, this thesis presents a formalization of the resilience process and enhancement measures in a multi-phase approach and applies the framework to windstorms and floods in Great Britain and earthquakes in Chile. Specifically, the following conclusions respond to the specific objectives stated in Chapter 1.

Firstly, the proposed resilience framework consists in an assessment and enhancement procedure. The assessment procedure consists of four phases. These are (i) threat characterization, where the hazard's magnitude, probability of occurrence, spatiotemporal profile and future scenarios are defined; (ii) vulnerability assessment of the system's components, where the identification of the vulnerable components, the application of fragility curves and the assignation of damage states is done; (iii) system's reaction, where the performance of the system through sequential Monte Carlo Simulations and Optimal Power Flows is carried out, and (iv) system's restoration, where the component's recovery is related to the damage caused, human and material resources availability and the accessibility to the affected area. Finally, the whole process is measured in a time-dependent way with the Expected Energy Not Supplied index and Energy Index of Unreliability. The enhancement procedure consists of three adaptation strategies, which are based on the normal version of the test systems studied. These are (i) robust strategy, which is a more resistant network; (ii) redundant strategy, which is a version with more alternative paths and (iii) responsive strategy, which has a faster recovery process.

Secondly, the resilience framework was applied to analyse the impact of windstorms and floods on a simplified network of Great Britain. The results show that normal weather events do not represent a threat of major disruption, but when one models a flood event that may happen every 33 year or a windstorm where the normal wind speed is doubled, then the risk of blackouts becomes significantly higher. Regarding the effectiveness of the adaptation cases, for both windstorms and floods results seem to indicate that the best strategy is to improve the resistance of components, then to count with better restoration procedures and as a third option to invest in redundancy, whereas the last one implicates almost no improvement for floods.

Thirdly, the resilience framework was applied to analyse the impact of earthquakes on a reduced network of northern Chile. The results show that seismic events represent a severe threat for the system, where even events that may happen once every five or ten year may represent an energy index of unreliability of between 5% and 10%. Due to the number of scenarios needed, the adaptation cases outcomes were inconclusive. More scenarios for the simulation, clustering techniques and/or results factoring is required.

Finally, the aim of the comprehensive and systematic analysis exposed in this study is to help governments and disaster management related institutions to be better prepared for the uncertain future driven by natural disasters and climate change.

## 8. FUTURE WORK

As it has been said, resilience of electric power systems is an emerging concept. Therefore, there are many potential works to be done. In this chapter, future works regarding the research delimitations presented in Chapter 1 are proposed.

### a) Scenario building

The hazard models used in this study could be improved by considering more information. Also, deterministic scenarios could be modelled to calibrate and validate the model's parameters. Finally, more threats could be included, such as coastal floods in Great Britain and volcanic eruptions, landslides, tsunamis<sup>24</sup>, floods and wildfires in Chile.

### b) Fragility curves

Indirect impacts could be included to analyse the cascading effect of component's failures. Better event's descriptors could be chosen; even multi-variable descriptors may be used. Particular fragility curves for the case studies could be developed to have more certainty on the impact and damage states. Finally, more macro components could be included in the fragility analyses; moreover, including micro components.

### c) Operation of the system

A more detailed power system may be modelled, including Unit Commitment and using other power flow analysis, rather than OPF. Interconnections with other countries could be included in the Chilean case to be able to quantify how much does resilience improve with these actions. The SIC, which is hydro-thermal could be modelled to analyse the reservoirs protocols to confront natural disasters. Finally, the reserves normative, batteries and pump-storage could be analysed from this resilience perspective.

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<sup>24</sup> Currently, it is being included in the models with the aim to publish a second article that analyses the earthquake and tsunami hazard in northern Chile.

#### **d) Restoration of the system**

Central planning and individual restoration perspectives could be compared. Human and material resource limitations should be included. Consumer's prioritization and stocks protocols could be analysed. Finally, restoration optimization models could be developed.

#### **e) Socio-economic costs**

Socio-economic costs should be included, taking in consideration the potential errors due to the low probability modelling, assumptions and simplifications used. Finally, instead of using reliability indices (EENS and EIU), resilience metrics could be developed, such as criticality indices.

Future works are not limited to these topics. Research lines could be created inspired from the multi-disciplinary work and the real needs detected as major catastrophic events are happening every year. For instance, after simulation models are well developed and understood, engineering indicators and tools could be developed to improve the planning models of electric power systems. One example of the first efforts to integrate high impact low probability events in power system planning can be seen in (R. Moreno and G. Strbac, 2015). Lastly, interdependencies with other critical infrastructure could be modelled to have a more integral and realistic view of this complex problem.

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## **APPENDICES**

## APPENDIX A : CORRELATION BETWEEN ELECTRICITY CONSUMPTION AND ECONOMIC GROWTH

The following figure<sup>25</sup> was built with data from the International Monetary Fund and the World Bank Statistics, both from reports of 2015. It shows the correlation between energy and economic growth in the year 2011.

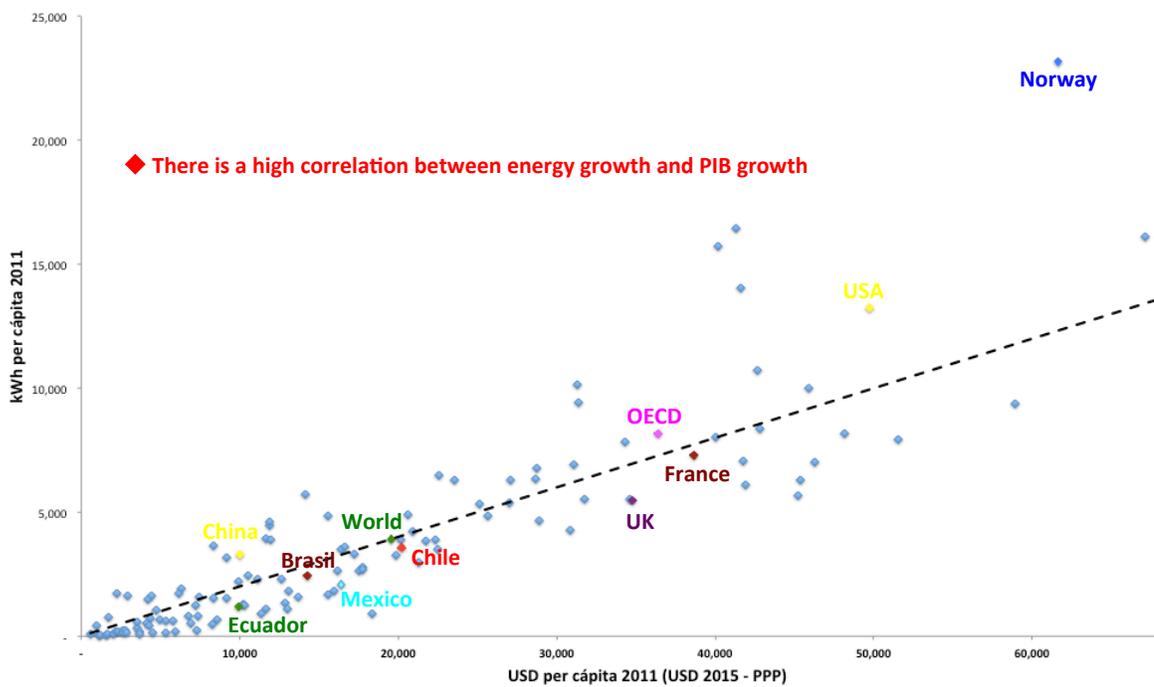


Figure Appendices.1. Electricity consumption 2011 vs GDP per capita 2011 (adapted from (H. Rudnick, 2013)).

<sup>25</sup> Adapted and updated from a presentation of Hugh Rudnick in London, 2013.

**APPENDIX B : MULTI-PHASE RESILIENCE AND ADAPTATION  
FRAMEWORK**

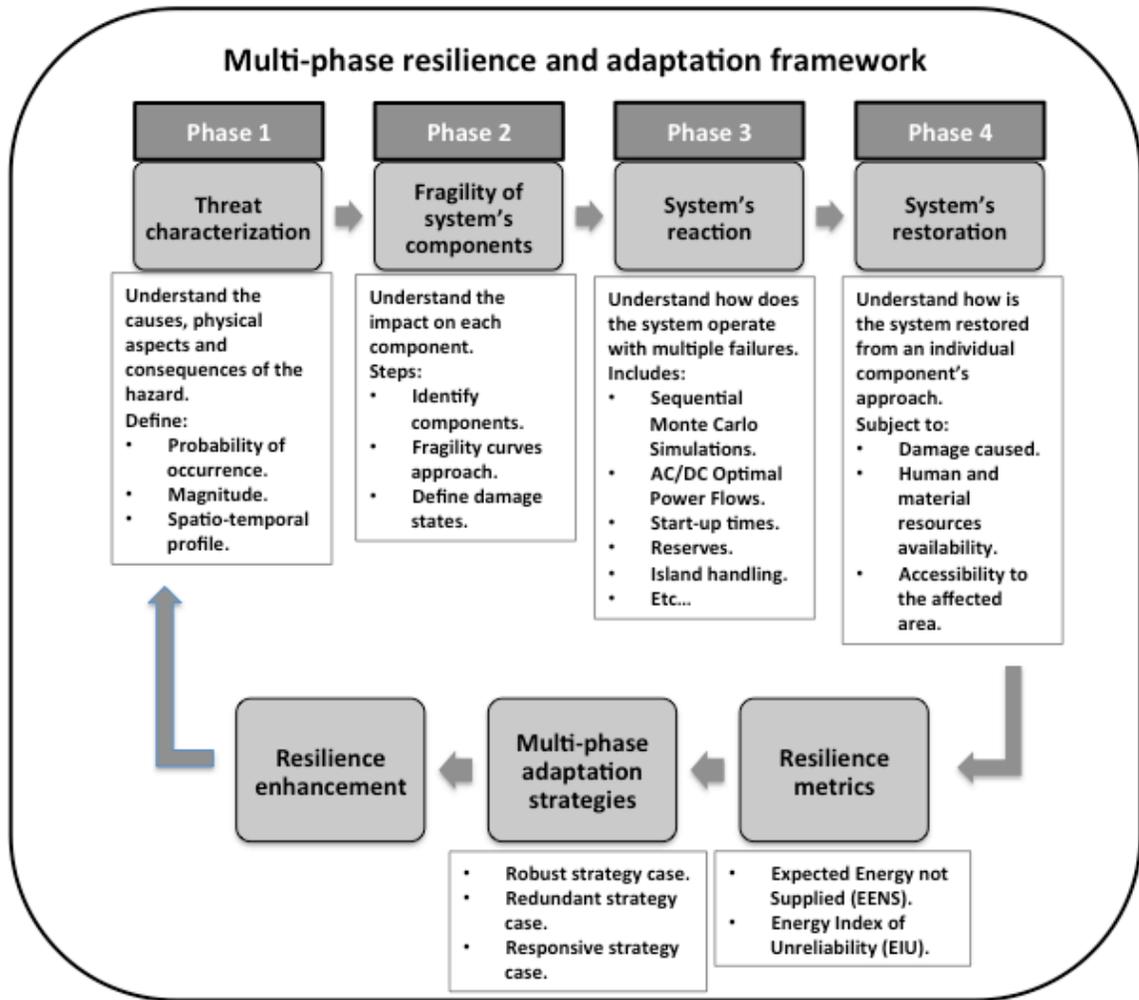


Figure Appendices.2. Multi-phase resilience and adaptation framework (Own elaboration).

## **APPENDIX C : EARTHQUAKE AND TSUNAMI 2015**

At 19:55 on September 16, 2015, while finishing this thesis an 8.4  $M_w$  earthquake occurred offshore from Illapel, Coquimbo region, Chile. A tsunami followed the quake, 10 to 15 minutes after. 15 fatalities in Chile and 1 fatality in Argentina were reported. The material damage was limited, and mostly produced by the tsunami waves. Hereafter, preliminary reports of the central dispatchers (CDECs) with the electric power systems reactions are remarked.

### **SING (Northern interconnected system):**

September 16, 2015.

20:30: The system operates normally; the earthquake did not affect generation nor consumers.

21:00: Interconnection with Argentina's system (SADI) was activated without energy transfers as a preventive action<sup>26</sup> to have more backup.

### **SIC (Central interconnected system):**

September 16, 2015.

20:00: An estimated of 600 MW of loads was lost in distribution consumers.

September 17, 2015.

08:00: Power plants Ventanas 1, Ventanas 2 and Nueva Ventanas out of service.  
Wind power plants Canela 1, Canela 2, Arrayán and Punta Palmeras out of service due to step up transformers failures.  
Line 66 kV Los Molles – Ovalle 1 out of service.

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<sup>26</sup> The event may be only a foreshock. In 1960 four foreshocks bigger than magnitude 7.0  $M_w$ , including a magnitude 7.9  $M_w$  on May 21 preceded the magnitude 9.5  $M_w$  great earthquake on May 22.

Line 220 kV Las Palmas – Totoral out of service due to failure in Las Palmas Substation.

Substation Las Palmas, switch 52JR out of service.

September 18, 2015.

08:00: Wind power plants Talinay Oriente and Talinay Poniente still offline.

Wind power plants Canela 1 and Canela 2 back to service.

Wind power plant El Arrayán, online under assessment.

Wind power plant Totoral online.

## APPENDIX D : SOIL CLASSIFICATION OF NORTHERN CHILE

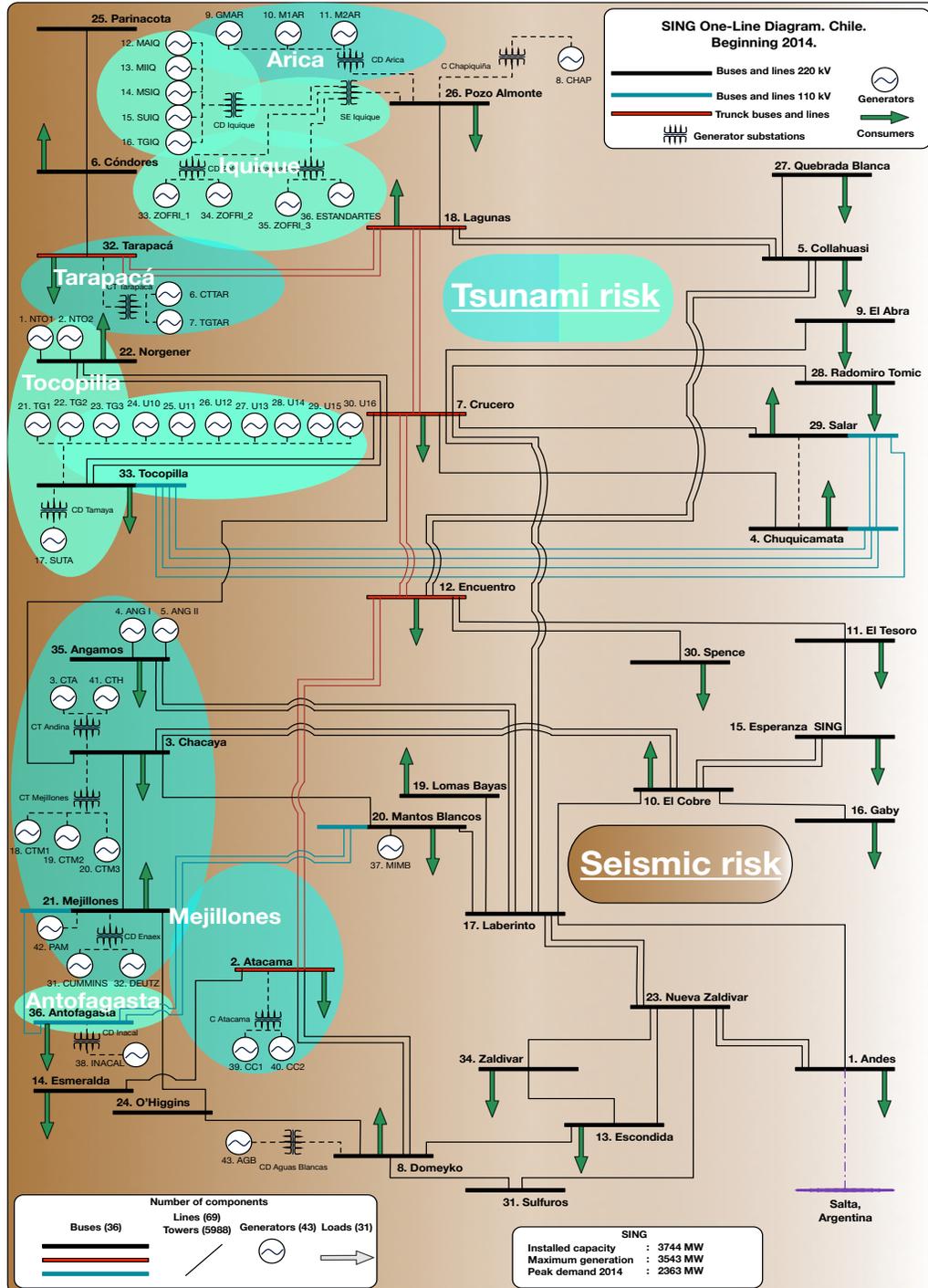
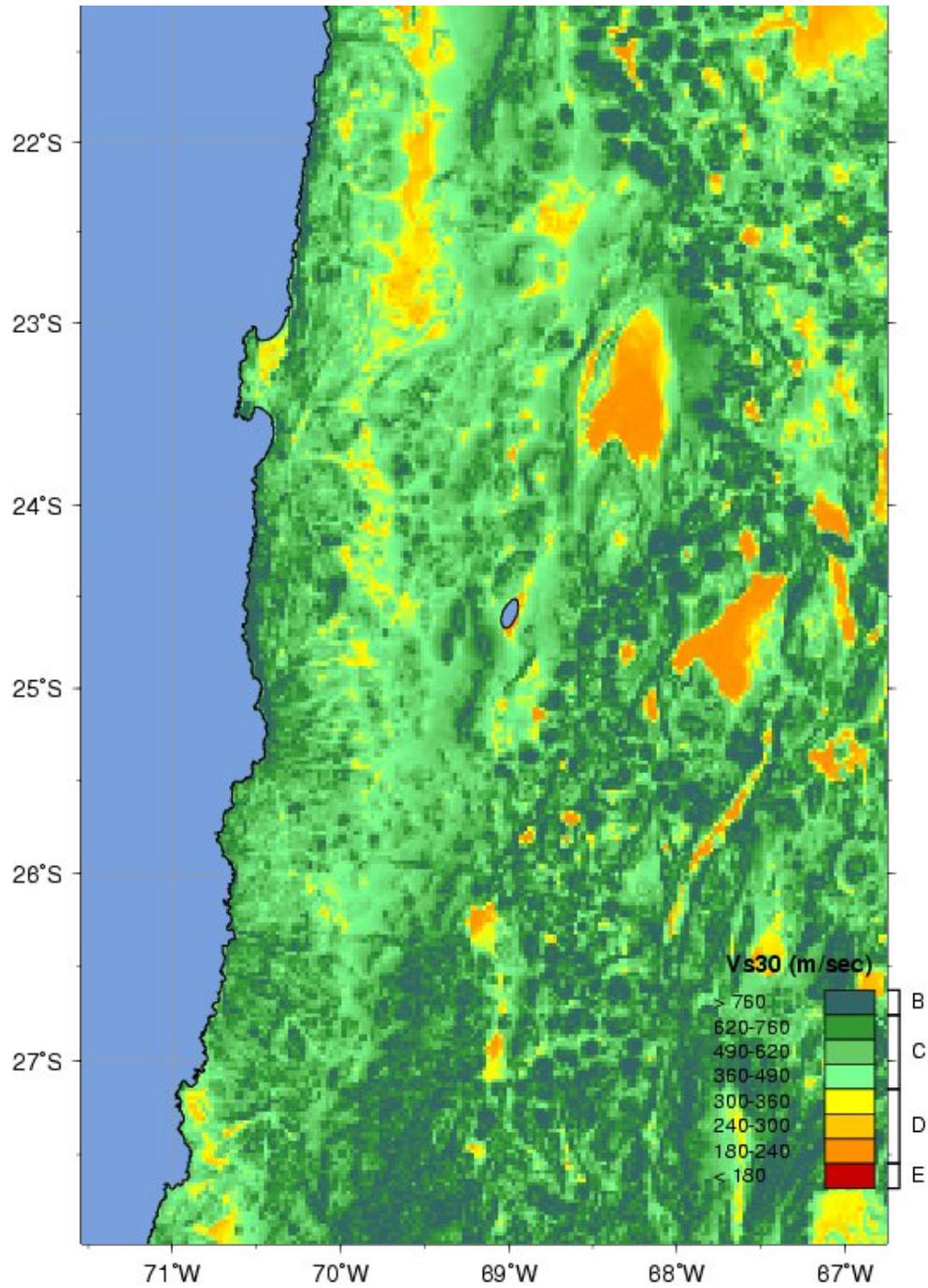


Figure Appendices.3. Reduced northern Chilean electric power system (own elaboration).

## APPENDIX E : NORTHERN CHILEAN HAZARD MAP



GM 2015 Jul 27 19:24:34

Figure Appendices.4.  $V_{S30}$  in northern Chile (USGS).

**APPENDIX F : INTERNATIONAL LITERATURE OF SEISMIC  
FRAGILITY CURVES FOR ELECTRICAL COMPONENTS**

Fragility curves found were presented in WCEE, the World Conferences on Earthquake Engineering, and in the Syner-G project. The detailed publications reviewed are presented in **Table Appendices.1**.

Table Appendices.1. Seismic fragility curves for electrical components presented in WCEE and Syner-G project.

<b>Reference</b>	<b>Elements studied</b>	<b>Earthquake intensity measure</b>	<b>Damage states used</b>
Sadeghi, et al. 2012.	Tubular steel towers.	Peak ground acceleration.	Failure.
XIE, et al. 2012.	Lattice steel towers.	Peak ground acceleration.	Minor, Major and Collapse.
Anagnos. 1999.	6 microcomponents.	Peak ground acceleration.	Failure modes depending on the component.
Anagnos and Ostrom. 2000	500 kV circuit breaker and 230 kV horizontal disconnect switch.	Peak ground acceleration.	Failure modes depending on the component.
Ang, Pires and Villaverde. 1996.	6 microcomponents and 500 kV-230 kV substations.	Peak ground acceleration.	Failure.
Bettinali, et al. 2004.	11 microcomponents.	Peak ground acceleration.	Failure.
Dueñas-Osorio, Craif and Goodno. 2007.	Electric power grid.	Peak ground acceleration.	Failure based on substation functionality (20, 50 and 80%).
Giovinazzi and King. 2009.	Medium voltage substation.	Peak ground acceleration.	Minor, Moderate, Extensive and Complete.
Hwang and Huo. 1998.	9 microcomponents, pothead structure and 115/12 kV transformer.	Peak ground acceleration.	Failure.
Hwang and Chou. 1998.	6 microcomponents and substation.	Peak ground acceleration.	Failure.

Liu, et al. 2003.	500 kV – 230 kV three-phase transformers.	Peak ground acceleration.	Failure.
Rasulo, et al. 2004.	11 microcomponents and substation.	Peak ground acceleration.	Failure.
Straub and Kiureghian. 2008.	1-phase 230 kV transformer, 230 kV live tank circuit breaker and systems of these components	Peak ground acceleration.	Failure.
Vanzi. 1996.	11 microcomponents and 4 macrocomponents	Peak ground acceleration.	Failure.
Vanzi. 2000.	Distribution substation	Peak ground acceleration.	Failure.
Vanzi, et al. 2004.	420 kV circuit breaker	Spectral acceleration.	Failure.
Shinozuka, et al. 2007.	Transformer, circuit breaker, disconnect switch and bus	Peak ground acceleration.	Failure.
Hazus, FEMA. 2003.	Substation, distribution circuits and power plants.	Peak ground acceleration.	Minor, Moderate, Extensive and Complete.

## APPENDIX G : SING'S RECUPERATION ZONES

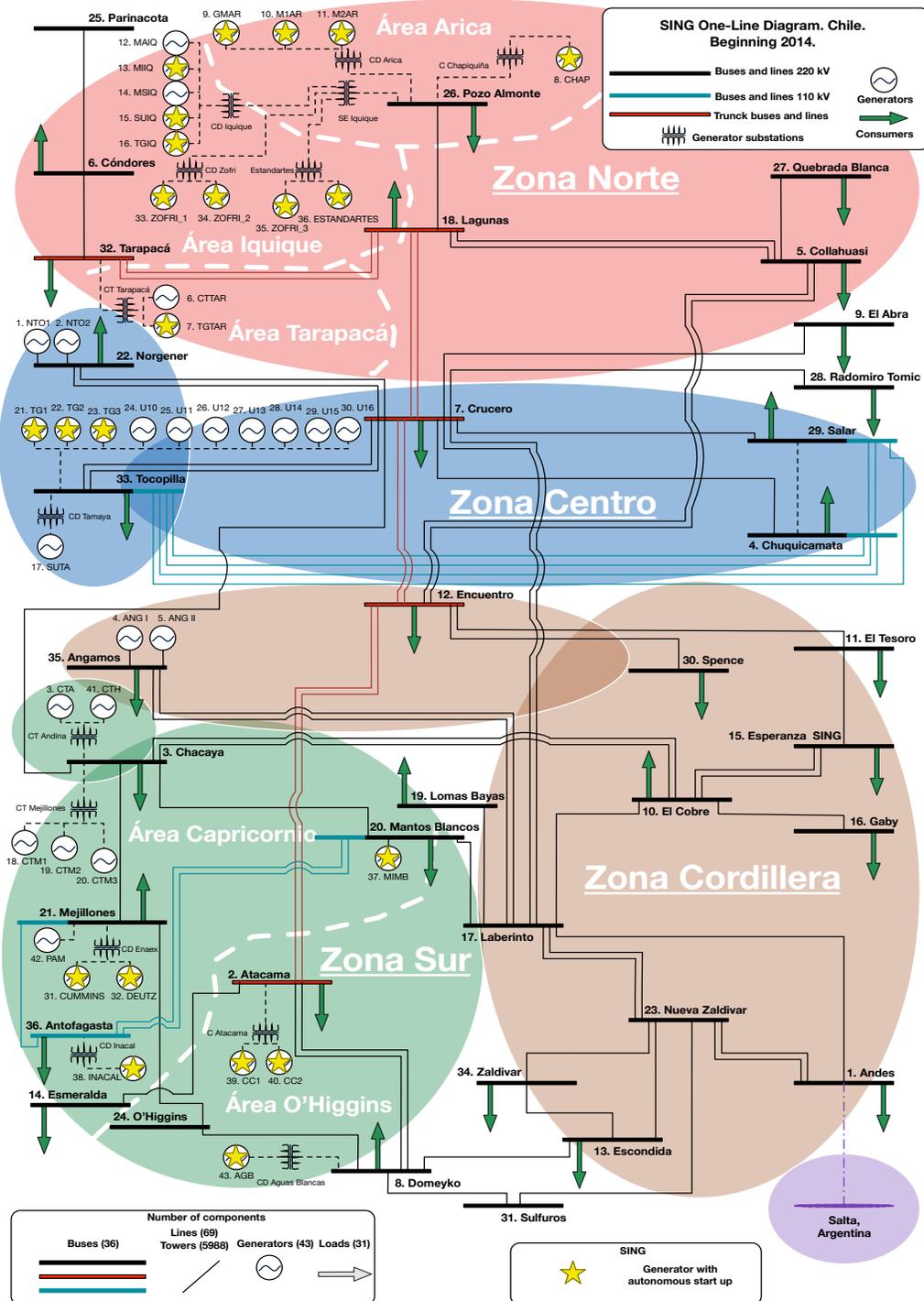


Figure Appendices.5. Reduced northern Chilean electric power system (own elaboration).

## **APPENDIX H : LIST OF PUBLICATIONS AND PRESENTATIONS**

### **SUBMITTED JOURNAL PAPERS**

S. Espinoza, H. Rudnick, M. Panteli and P. Mancarella, "Multi-phase assessment and adaptation of power systems resilience to natural hazards," Under revision, *Electric Power Systems Research*, Elsevier. August 2015.

### **TO-BE-SUBMITTED JOURNAL PAPERS**

S. Espinoza, H. Rudnick, A. Poulos, J. Gonzáles, M. Panteli, P. Mancarella and R. Moreno, "Multi-phase assessment and adaptation of power systems resilience to earthquakes and tsunamis," To be submitted, *IEEE Transactions on Power Systems*.

### **PRESENTATIONS**

S. Espinoza, H. Rudnick, M. Panteli and P. Mancarella, "Resilience assessment of electric power systems after the impact on natural disasters," poster presented in PGR Poster Conference, Manchester, UK, May 2015.