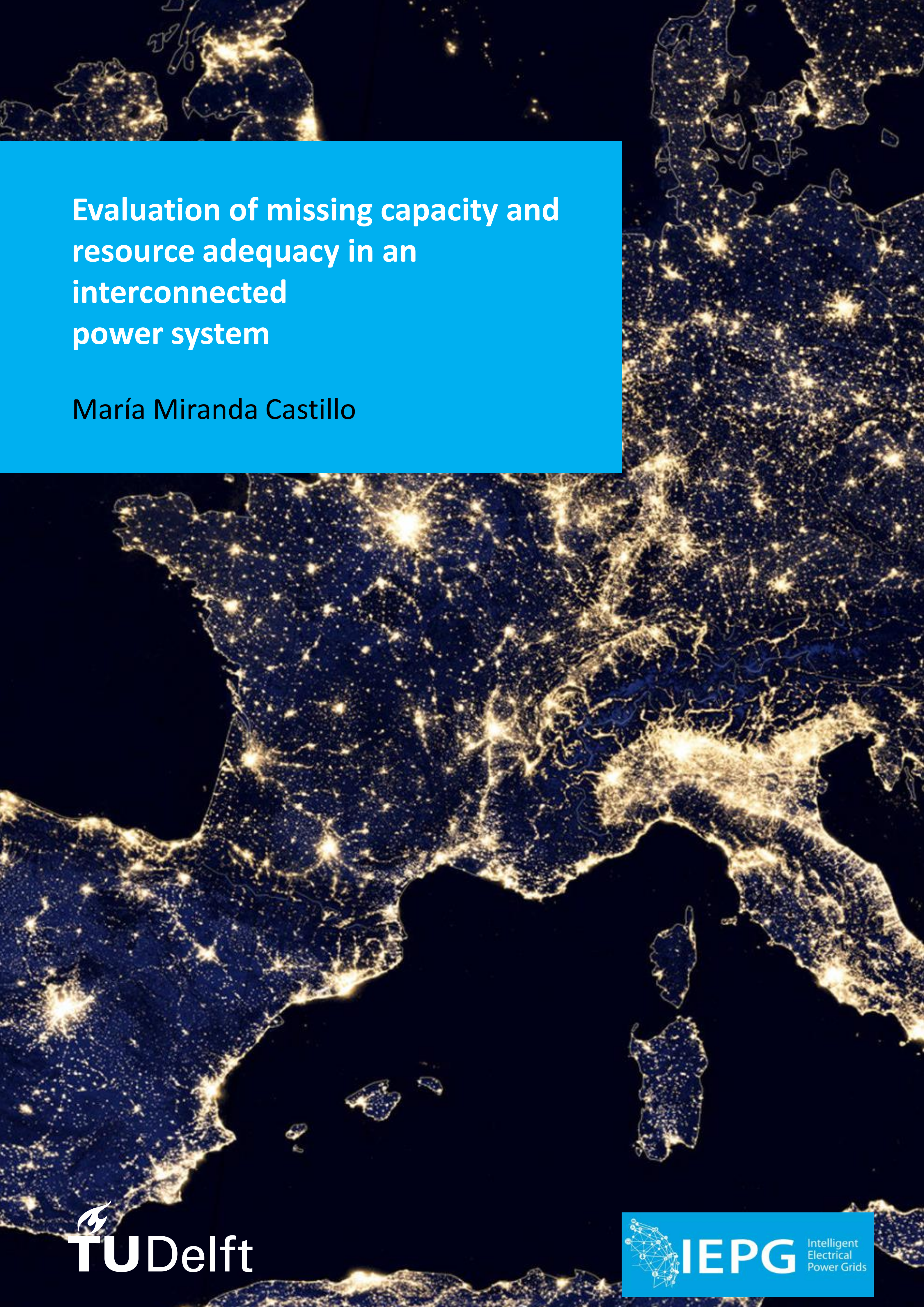

Evaluation of missing capacity and resource adequacy in an interconnected power system

María Miranda Castillo

TU Delft

IEPG Intelligent Electrical Power Grids

Evaluation of missing capacity and resource adequacy in an interconnected power system

by

María Miranda Castillo

to obtain the degree of Master of Science in Sustainable Energy Technology
at the Delft University of Technology,
to be defended publicly on Thursday September 26, 2019 at 9:00 AM.

Student number:	4734181	
Project duration:	January 7, 2019 – September 26, 2019	
Thesis committee:	Dr. Simon Tindemans,	TU Delft, university supervisor
	Dr. Laurens de Vries,	TU Delft
	Prof. Peter Palensky,	TU Delft
	Dr. Lazaros Exizidis,	ENTSO-E, company supervisor

TU Delft

Disclaimer
The views or opinions expressed in this thesis are solely those of the author and do not necessarily represent those of ENTSO-E, its Members or their respective employees. ENTSO-E and its Members shall bare no responsibility or liability for the correctness of the information used in this thesis.

Summary

Power system adequacy is the ability of the system to supply the load at all times considering scheduled and unscheduled outages of system components. Adequacy entails the balance between available generation and net load in the long term as it considers the future uncertainty of supply and demand. Resource adequacy is an increasingly prominent issue due to the uncertainties incurred by the current electricity market and power system. The decisions of generation expansion are driven by the market that operates under competitive rules, bringing uncertainty in the generation location and its availability. Besides that, the increasing penetration of renewable sources into the electricity mix also introduces uncertainty since the generation profiles become more volatile. This set of conditions presents a challenge when ensuring resource adequacy. It is in this framework where the present master thesis is placed, with the aim to answer the question "How to reach reliability targets in the interconnected European power system?". For that goal, a possible new adequacy indicator is introduced, proposing a methodology for its evaluation.

"Missing Capacity" is introduced as a possible adequacy indicator that quantifies the required capacity to reach a defined reliability target in a specific region. Focusing on the European power system different scenarios for the missing capacity evaluation have been investigated, using a reliability target expressed in the LOLE metric. The methodology is divided among the reliability target area, i.e. single or multi-area, and the capacity source, i.e. generation and/or transmission capacity expansion. For conducting the missing capacity evaluation two techniques have been identified: the integrated optimisation approach and the iterative approach. In a single-area study, the required capacity to reach the reliability target has been analysed by means of generation or generation and interconnection capacity expansion. Following the integrated optimisation approach, the generation capacity expansion has been computed bringing the optimal amount of capacity to reach the reliability target in a specific node. Two integrated optimisation techniques have been investigated, the introduction of a shortfall constraint and an economic optimisation. While both techniques can achieve a solution, the shortfall constraint approach introduces a limitation as the expectation nature of the reliability target is not preserved, and the solution answers the capacity requirements under the most severe scenario. On the other hand, the approach of generation and transmission capacity expansion is conducted, after computing the result of the previous method, by an iterative approach increasing the interconnection capacity. This method aims to present a sensitivity of generation capacity that can be replaced by interconnection capacity reaching the same adequacy level. However, the quantification of this metric is challenging and very sensitive to the base case conditions. A multi-area study has been conducted focusing on two interconnected areas. The evaluation technique applied is based on an iterative approach which brings two possible results: the achievement of the required reliability level in two areas by generation expansion in one node, or by sharing the extra capacity among the two nodes. Both solutions achieve the required reliability target and evidence the possible contribution of interconnectors to adequacy in sharing the benefits of capacity expansion. As included in the thesis scope, the contribution of interconnectors to adequacy has been investigated. As part of the generation and transmission capacity expansion approach, a previous study on how is the use of interconnectors in times of scarcity was conducted to find possible expansion candidates and analyse the role of interconnectors in adequacy.

To conclude, several methods to calculate the capacity needed to reach the required reliability target under several scenarios are presented. An optimal capacity solution has been reached either for a single-area or multi-area study. The results reflect the influence that, in a highly interconnected area, generation expansion in one node can have in the region, by lowering the LOLE and EENS results, thus improving the adequacy of the area. In the multi-area study, it is observed that sharing the additional capacity across both countries achieves a more efficient solution requiring less installed capacity to accomplish the reliability standard of the two countries. The interconnection contribution to adequacy is observed throughout all the results of the different studies. Moreover, a more in-depth study has brought the conclusion that the contribution of interconnectors to adequacy is highly dependent on the simultaneity of the scarcity periods among the interconnected countries, and the difference in their adequacy levels.

Preface

This master thesis would not have been possible without the assistance and support of several people whom I want to thank. I would like to acknowledge my supervisor, Dr. Simon Tindemans . His expertise in the field of resource adequacy helped bring a unique perspective to looking at this thesis topic, which was key in helping me overcome many challenges throughout this project. Thank you, Simon, for your detailed feedback and guidance in this process.

My most sincere thanks to Dr. Lazaros Exizidis for being my supervisor at ENTSO-E. His steering during all the thesis has been essential to me. I would like to thank you for taking out the time to support me in this topic, and for always being reachable and willing to help me in my most diverse doubts.

I would like to thank ENTSO-E and in particular, the entire System Development section for having welcomed me to the team during both my internship and thesis. It has been a very enriching experience from which I have learned something from all of you. Special thanks to Simón Norambuena for being so patient and always willing to help me with all the PLEXOS intrigues.

Finally, I would like to express all my gratitude to my family and friends who have supported me in many different ways, making all this master experience possible and unique. I truly believe we learn from all people we meet on the way, in that sense, these two years have been a master learning from you all. Thanks.

María Miranda Castillo
Brussels, September 2019

Contents

List of Figures

List of Tables

Nomenclature

Abbreviations

CONE	Cost of New Entry
CWE	Continental Western Europe
CY	Climate Year
DSR	Demand Side Response
EENS	Expected Energy Not Served
EFC	Equivalent Firm Capacity
ENS	Energy Not Served
FOR	Forced Outage Rate
LOLE	Loss of Load Expectation
LOLP	Loss of Load Probability
LT	Long Term plan
MAF	Mid-term Adequacy Forecast
MIP	Mixed Integer Programming
MIPL	Mixed Integer Linear Program
MOR	Maintenance Rate
MS	Member States
MT	Medium Term Schedule
NPV	Net Present Value
NTC	Net Transfer Capacity
PASA	Projected Assessment of System Adequacy
ST	Short Term Schedule
TSO	Transmission System Operator
UCED	Unit Commitment and Economic Dispatch
USE	Unserved Energy
VoLL	Value of Lost Load

Zone Codes and corresponding countries

AL	Albania
AT	Austria
BA	Bosnia and Herzegovina
BE	Belgium
BG	Bulgaria
CH	Switzerland
CY	Cyprus
CZ	Czech Republic
DE	Germany
DEkf	Germany KF
DKe	Denmark East
DKkf	Denmark KF
DKw	Denmark West
EE	Estonia
ES	Spain
FI	Finland
FR	France
FR15	France Corsica
GB	United Kingdom
GR	Greece
GR03	Greece Crete
HR	Croatia
HU	Hungary
IE	Ireland
IS	Iceland
ITcn	Italy Central North
ITcs	Italy Central South
ITn	Italy North
ITs	Italy South
ITsar	Italy Sardinia
ITsic	Italy Sicily
LT	Lithuania
LUb	Luxembourg

LUf	Luxembourg
LUg	Luxembourg
LUv	Luxembourg
LV	Latvia
ME	Montenegro
MK	FYR of Macedonia
MT	Malta
NI	Northern Ireland
NL	Netherlands
NOm	Norway Mid
NOn	Norway North
NOs	Norway South
PL	Poland
PT	Portugal
RO	Romania
RS	Serbia
SE1	Sweden
SE2	Sweden
SE3	Sweden
SE4	Sweden
SI	Slovenia
SK	Slovak Republic
TN00	Tunisia
TR	Republic of Turkey

1

Introduction

The current chapter will provide the context of the research project by formulating the motivation of the study, the objectives it aims to tackle, and the structure followed. Section 1.1 will present the research motivation, mentioning the role of ENTSO-E in this project. In section 1.2 the research problem and questions will be formulated. Next, section 1.3 will introduce the research approach, and will finalise with section 1.4 presenting the report layout.

1.1. Background & Research motivation

“Resource adequacy is an increasingly prominent issue that requires advanced methodologies to capture and analyse rare events with adverse consequences for the supply of electric power” [1]. Power system adequacy is defined as the ability of the system to supply the load at all times, considering scheduled and unscheduled outages of system components, i.e. generation and transmission facilities [2]. Adequacy entails the balance between available generation and net load, and it is placed in the long term as it considers the future uncertainty of supply and demand.

Originally, vertically integrated public or private electricity companies owned and operated the power generation and transmission in a specific area. With this configuration in which the utility acted as a regulated monopoly, the power planner had foresight on the future building of generation and transmission, being then relatively easy to forecast the needed generation and transmission capacity to meet the load [3]. Nowadays, the electric power sector in most of the European countries is a liberalized and competitive electricity market [4]. This reorganization in which centralized decisions no longer determined electricity production introduces a variety of challenges to ensure the adequacy of the power system. The generation capacity expansion and availability, either commercial or physical, are decisions driven by the market that operates under competitive rules, bringing uncertainty in the generation location, timing and future availability [5]. Uncertainty is also present in the complexity of power transactions and future demand, and regulatory constraints and rules [3]. Moreover, the current electricity mix with a high share of intermittent sources represents a major challenge when ensuring resource adequacy. The electricity share from renewable sources in the European Union reached 29.6% in 2016, more than twice the level in 2005 [6]. This increase in renewables makes the generation profile more uncertain and volatile, as renewable production depends on the weather conditions. Considering the same electricity generation from intermittent sources and dispatchable generation (i.e. thermal, hydro generation, etc.) the renewables still cannot ensure the same reliability level to the market as the dispatchable sources [4]. This volatile generation profile causes short-term balancing costs and long-term adequacy costs to the electricity market [4]. Under these conditions the ability to reliably serve the load takes new relevance, making the assessments of resource adequacy more important.

As a result of the uncertainties incurred by the current electricity market, the topic of introducing mechanisms to secure enough firm electricity generation capacity has been raised across Europe [7]. As a response to reliability concerns, Capacity Mechanisms have been heavily debated across different European countries.

The discussion has been focused on the need or not of such mechanism, its detailed design and the third concern, the assessment of the amount to be procured [7]. In that respect, adequacy assessments play a major role, as well as the implementation and definition of reliability standards. The European Commission (EC), in this aspect, has introduced in the Clean Energy for All Europeans package, several requirements for the Member States (MS) in terms of their adequacy evaluations and adoption of capacity mechanisms. EC requires to the MS to monitor their resource adequacy situation based on a European resource adequacy assessment in which at least the adequacy indicators of expected energy not served (EENS) and loss of load expectation (LOLE) are applied. It also presents the framework for the implementation of a capacity mechanism, requiring to previously have in place a reliability standard that indicates the necessary level of security of supply. In particular, EC requests the European Network of Transmission System Operators for Electricity (ENTSO-E) to draft a methodology to calculate the mentioned standard, and to conduct the European resource adequacy assessment. ENTSO-E fosters the cooperation across Europe and develops adequacy assessment methodologies ensuring common standards and harmonization [1]. In the European context, ENTSO-E performs a pan-European analysis of resource adequacy. The Mid-term Adequacy Forecast (MAF) provides stakeholders with comprehensive adequacy information in the form of the reliability indices: expected energy not served (EENS) and loss of load expectation (LOLE). This information serves as a support to the stakeholders when making decisions regarding the development of the European power system. Nonetheless, the information provided by the metrics EENS and LOLE does not always serve the purpose of the stakeholders or it results difficult to understand and translate into decisions by institutions and stakeholders.

It is in this framework where the thesis "Evaluation of missing capacity and resource adequacy in an interconnected power system" is placed. The thesis has been developed at the Adequacy team of System Development Section of ENTSO-E, in the context introduced by the requirements of the Clean Energy package and with the aim to present a new adequacy indicator that provides comprehensive information on the amount of capacity needed to reach a specific reliability target

1.2. Problem statement & Research questions

As described in the previous section, the uncertainties incurred by the actual power system and electricity market, bring major importance to resource adequacy assessments. To ensure a reliable system, decisions of investments and developments of the grid should be taken, as well as considerations on the establishment of mechanisms to secure enough generation, capacity mechanisms. These topics of discussion represent the question of "how to reach a reliable system", and raise a request for tools that provide sufficient and comprehensive information to answer the question. Especially, in the European framework, the answer to how to ensure the reliability of the system cannot omit the interconnected nature of the power system, which brings specific characteristics to the problem formulation. Therefore, this research project aims to tackle these issues by formulating the main research question:

How to reach reliability targets in the interconnected European power system?

In order to answer the main research question, the following sub-questions are formulated, which guide the structure of this thesis:

1. *What is system adequacy and how is it regulated in EU countries?*
   Introduction of system adequacy, its definition and quantification through the reliability metrics. Adequacy framework and its regulation in Europe.

2. *How to assess system adequacy in an interconnected power system?*
   Identification of the research and industry practice in resource adequacy assessment.

3. *Which are the different approaches to ensure the required level of system adequacy?*
   Introduction of the concept of "Missing Capacity" as an indicator that provides the necessary capacity to reach a reliability target, and the different options for the achievement of such target.

4. *What is the role of interconnectors in contributing to system adequacy?*
   Study of the contribution of interconnectors to system adequacy.

1.3. Research approach

In order to answer the research questions previously defined, the following steps were conducted during this research project:

1. **Literature review and industry analysis.** Analysis of the definition and dimension of power system's adequacy and its regulation in Europe, as well as the analysis of the research and industry trends in the area of resource adequacy assessment.
2. **Definition of Missing Capacity and its requirements.** Introduction of a possible new adequacy indicator, its definition and scenarios for its calculation.
3. **Identification of Missing Capacity evaluation methods.** Identification of the correspondent methods for the evaluation of Missing Capacity in each scenario. The evaluation of Missing Capacity is conducted in the electricity market modelling tool PLEXOS as it is the tool implemented in ENTSO-E for performing the market and adequacy studies.
4. **Implementation of the Missing Capacity problem.** Identification and definition of the Missing Capacity problem implementation in PLEXOS, for the different scenarios.
5. **Analysis of results.** Analysis of the results achieved in each scenario to determine the different approaches to reach the reliability target in a specific region.

1.4. Report Outline

The report is structured as follows:

Chapter 2 introduces the concept of power system adequacy, and presents the reliability targets and their application and regulation in the EU countries.

Chapter 3 presents the research and industry trends in the area of resource adequacy assessment.

Chapter 4 explains the concept of Missing Capacity and the methodology for its evaluation.

Chapter 5 analyses the simulation results of the Missing Capacity method based on generation expansion.

Chapter 6 focuses on the contribution of interconnectors to system adequacy, analysing the use of interconnectors in times of scarcity and then, presenting the simulation results of the Missing Capacity method based on interconnection expansion.

Chapter 7 draws the conclusions of the research, answering the research question and sub-questions, and suggests the directions for future research.

2

Introduction to power system adequacy and its regulation in EU countries

In order to determine how to reach reliability targets in the European power system, is worth to first define what are the reliability targets and what is system adequacy. Through this chapter the previous topics will be presented, followed by the introduction of power system adequacy regulation in Europe. The definition of system adequacy and the reliability targets in Europe, will lead to the answer of the first sub-question: *What is system adequacy and how is it regulated in EU countries?*.

2.1. System Adequacy

There are three terms that are widely used in practice to describe power system reliability: reliability, adequacy and security. Therefore, in order to define system reliability, the previous terminology will be introduced.

Reliability is the ability of the system to deliver the required amount of electrical energy for all points of utilization over a long time period [8]. It represents the probability of the correct operation of the power system over the long term considering several disruptions. The level of reliability can be measured in terms of frequency, duration or magnitude of negative effects on consumers [2].

System security and adequacy are different dimensions of power system reliability, and both of them should be targeted to achieve a reliable system. Security refers to the power system's ability to withstand sudden contingencies such as short circuits [8], it represents the risk in the system's ability to overcome disturbances [2]. This term refers mainly to the short-term dimension of power supply, and it can be identified as Operational Security [9]. For a power system to be reliable it has to be stable and secure against contingencies.
In contrast, adequacy is placed in the long term, as it is defined as the power system's ability to meet demand considering scheduled and unscheduled outages of system components, and operating requirements [8].
Both security and adequacy are associated terms but not identical. While security covers the operational aspects of the power system, adequacy is part of the development and planning process [9]. Adequacy refers to the ability to meet demand in the long term considering the uncertainty of supply and demand, and the long execution time for capacity or network expansion. Otherwise, if system security is not ensured, the output of the generation sources cannot be delivered to the customers [9].

Adequacy evaluation can comprise generation adequacy, transmission adequacy, or both [9]:

- Power system's generation adequacy is the evaluation of the capability of the power system generation to meet the system's load, including the reserves[1] that allow the system to resist outages, dry periods or shortages of fuel.

[1] Operational reserves: primary, secondary and tertiary reserves.

- Power system's transmission adequacy is the evaluation of the capability of the power system to maintain the power flow between the generation and consumption centres.
- System adequacy is assessed considering generation adequacy and transmission adequacy simultaneously.

The previous classification of adequacy evaluation by functional zones, can be also identified as hierarchical level I – generation adequacy, hierarchical level II – transmission and generation adequacy, and hierarchical level III – transmission, generation and distribution adequacy [10].

In the frame of the European adequacy assessments, as it is the case of this research, generation adequacy is tackled while transmission is modelled in less detailed. Transmission adequacy evaluation is addressed by national studies lying on the Transmission System Operators' (TSO) knowledge of network management.

Therefore, the present study will assess reliability within the scope of generation adequacy evaluation, representing the transmission grid in a more simplified manner.

2.2. Adequacy metrics

To assess generation adequacy, a calculation procedure is conducted, using data from various sources as generators availability, wind and demand profiles, etc. According to the methodology adopted for the calculation, different indices for quantifying a power system's adequacy can be obtained: deterministic indicators (capacity margins) or probabilistic indicators.

By means of these metrics, the maturity of a system with respect to an adequacy standard can be measured. The use of the adequacy indicators allows the comparison among different systems and time periods. In order to determine if the level of adequacy presented by a power system is admissible, an adequacy standard, a reference value, is associated to each metric. The adequacy standards are defined by National Regulatory Authorities or energy agencies [9].

The European Commission in its identification of appropriate adequacy standards [9], provides an overview of the adequacy indicators used in the European electricity market, which will be presented in this section along with definitions introduced by other institutions.
The description and characteristics of the most common adequacy metrics will be presented in the following sections:

- Expected Energy Not Served (EENS)
- Loss of Load Expectation (LOLE)
- Loss of Load Probability (LOLP)
- LOL 95$^{\text{th}}$ percentile (P95)
- Capacity Margin

The first four indices can be estimated using probabilistic methods, while the Capacity Margin is calculated through deterministic techniques. The probabilistic indicators are based on expectations, they present the expected value of a probability distribution that is an approximation of reality [9]. However, the 95$^{\text{th}}$ percentile is based on a probabilistic model but its value is not an expectation.

<u>Expected Energy Not Served (EENS)</u> [MWh/year or GWh/year]

EENS is the expected energy not supplied per year by the generation system due to the demand exceeding the available generation and import capacity [11]. EENS is obtained through probabilistic methods, it is analysed in expectation over several Monte Carlo simulations. Its mathematical formulation is the following [11]:

$$EENS = \frac{1}{N} \sum_{j \epsilon S} ENS_j \tag{2.1}$$

Where ENS_j is the energy not supplied of system state $j(j\epsilon S)$ associated with a loss of load event of the jth Monte Carlo simulation and N is the number of Monte Carlo simulations considered, which is equal to the number of elements in S [11].

Loss of Load Expectation (LOLE) [h/year]

LOLE is the average number of hours per year when the available generation and imports are not enough to cover the load of a region. LOLE describes the duration of a loss of load event but not the severity nor the frequency. Despite these deficiencies, it is the most widely used probabilistic adequacy standard, used in generating capacity planning studies [10]. It is defined by the mathematical expression [11]:

$$LOLE = \frac{1}{N}\sum_{j\epsilon S} LLD_j \tag{2.2}$$

Where, LLD_j is the loss of load duration of the system state $j(j\epsilon S)$ associated with the loss of load event of the jth Monte Carlo simulation and N is the number of Monte Carlo simulations considered [11].

LOLE can also be expressed as the average number of days per year (or longer time frame) in which the available generation capacity is expected to be insufficient for meeting the daily peak load [10]. In the USA the LOLE is usually presented as days/10 years, where the daily peak load surpasses the available generation capacity.

Loss of Load Probability (LOLP)

LOLP is the probability that the load exceeds the available generation. This is often restricted to the ability to meet the peak load [9].

95^{th} Percentile (P95)

P95 is a LOL index calculated in a critical scenario. The critical scenario is represented by a cold winter (once every 20 years), and the P95 shows the number of hours for that year, when the generation supply plus imports cannot cover the load [9].

Capacity Margin

Capacity Margin is the percentage of the average excess of available generation capacity over peak load. The available generation capacity is represented by the installed capacity at peak load, adjusted by the derating factors (unavailability of plants due to outages). This metric is calculated by means of a deterministic methodology [9].

The previous metrics are different forms of characterizing the unserved energy presented in a system, depending on its duration, frequency of occurrence or probability [9]. Several differences can be noticed among the metrics, based on the information they provide and the different uses they can serve.

LOLE is one of the most used metrics because of its simplicity. However, neither LOLE nor LOLP indicate the severity of the problem, leading to obtaining the same number of hours for events of different dimensions. Moreover, these metrics do not provide enough information to optimal support economical decisions, thus LOLE and LOLP could lead to non-optimal definitions of capacity needs [9]. LOLP can be used to compare electricity systems of different size. EENS can serve to obtain a monetization of disruption costs, and in that way, compare different investment options to reach a reliability target. Despite EENS does not indicate the social value of adequacy, it still provides a more accurate indicator of the reliability of supply [9]. EENS is not the appropriate metric to compare electricity systems of different dimensions, as its absolute value depends on the system's size. For that purpose, the normalization of EENS with respect to the energy demand of each system is usually preferred.

The adequacy metrics can be used for the following purposes [9]:

- To assess the performance of an individual country or, for example, the European Union as a whole, in respect to the adequacy of its power system.
- To define adequacy standards by the establishment of a target value of a specific reliability metric.

- Once the standard is defined, the adequacy metric can be used to identify the proper value of that metric that maximizes social welfare. The optimal value of the metric would be such that the cost of the investments required to increase reliability plus the cost of unserved energy is minimized.
- To identify the optimal investment in capacity expansion, either generation or transmission, to meet the adequacy targets. The adequacy targets can be represented as a predefined value of an index, or the socially optimal value of the metric.
- To define instruments to stimulate investments in generation or transmission capacity in the cases when adequacy values are below the standards. This kind of instruments are represented by the Capacity Mechanisms which aim to secure enough firm electricity generation capacity to avoid low reliability levels [7].

2.3. Adequacy regulation in EU countries

Once the definition of adequacy has been introduced, as well as the existent adequacy indices, it is worth to describe the current situation of adequacy targets and requirements in Europe. First, an introduction of the adequacy standards across Europe will be presented, followed by the latest adequacy regulation introduced by the Clean Energy Package.

2.3.1. Adequacy targets in Europe

Several EU Member States (MS) have established adequacy standards to evaluate their national generation adequacy. Table 2.1 presents the different metrics used by each country. It can be noticed that LOLE (h/year) is the most extended metric, with values fluctuating between 3 to 8 h/year [11].

The setting of those standards is a sensitive topic for which there is lack of information about the methodology and criteria used for its establishment. Additionally, there is no common methodology across MS to determine the reliability target. To establish an adequacy target, economic and technical aspects should be considered, as the profitability to invest in new generation and transmission capacity compared to the value of loss load [9].

Table 2.1: Adequacy metrics used in EU Member States [11, 12]

Country	AT	BE	BG	CH	CY	CZ	DE	DK	EE	ES	FI	FR	GB	GR	HR	HU	IE	IT	LT	LU	LV	MT	NL	NO	PL	PT	RO	SE	SI	SK
Reliability Standard	No	Yes	NS[2]	No	Yes	No	Yes	No	Yes	Yes	No	Yes	Yes	Yes	NS	Yes	Yes	Yes	Yes	NS	NS	No	NS	No	Yes	Yes	NS	No	NS	No
LOLE (h/y)		3	13		3		5			0.2[3]		3	3	3			8	3					4		3	5				
LOL P95 (h/y)		20																												
LOLP																<1%														
EENS					0.001%														6.3 MWh/year											
Capacity Margin									10%	10%																				

2.3.2. Adequacy regulation in Europe

The most recent regulation of the electricity market has been introduced with the Clean Energy for All Europeans package. This package aims to update the energy policy framework to facilitate the clean energy transition. In the field of the electricity market, the directive presents a redesign of the market, adapting it to a higher share of renewables, increased efficiency, more flexibility, security of supply, decarbonization and innovation.

The Directives for Electricity Security of Supply 2003/89/EC and 2005/89/EC made mandatory for Member States the publication, every two years, of a System Adequacy Report with a time horizon of five to fifteen years [9].

Currently, with the Clean Energy package, Regulation (EC) No 5070/19, the following points related to system adequacy are presented [13]:

[2] Not specified reliability standard. The cases of NS where a standard is specified means that the TSO uses that value but there is no official reliability standard established.
[3] For non-peninsular regions, islands.

Article 18 states that MS shall monitor their resource adequacy situation based on the European resource adequacy assessment, and they may complement it by performing national resource adequacy assessments. "If a concern in the adequacy situation of a MS is noticed, the MS shall identify the regulatory distortions or market failures that caused the concern".

The European resource adequacy assessment is introduced by Article 19. The assessment shall be based on scenarios of projected supply and demand, economic assessment of power plants, energy efficiency and electricity interconnection targets, wholesale and carbon price changes, and sensitivity on hydrological conditions and extreme weather events. Each scenario should reflect different likeliness of generation adequacy concerns and the correspondent capacity mechanism designed to address such concerns. The assessment shall be based on market modelling, applying probabilistic calculations and using at least the adequacy indicators of expected energy not served (EENS) and loss of load expectation (LOLE).

The regulation also introduces the general principles for capacity mechanisms (Article 18a), stating that before introducing capacity mechanisms, MS shall analyze their possible effects on the neighbouring countries: "MS, before implementing another type of capacity mechanisms, shall assess first whether strategic reserves could serve as the capacity mechanisms to address the adequacy concerns."
As far as strategic reserves are referred, the regulation states that during imbalance periods, where the resources of the strategic reserves dispatched imbalances, the market shall be settled at least at the value of lost load.

Article 20 presents the framework for the implementation of capacity mechanisms. Member States applying capacity mechanisms shall have in place a reliability standard. "The reliability standard shall indicate the necessary level of security of supply of the MS. It shall be calculated using at least the value of lost load and the cost of new entry, and be expressed as expected energy not served (EENS) and loss of load expectation (LOLE)". ENTSO-E shall submit to the Agency (ACER) a draft methodology for calculating the mentioned reliability standard.

Finally, Article 21 describes cross-border participation in capacity mechanisms. "MS shall ensure that foreign capacity has the opportunity to participate in the same competitive process as domestic capacity. Moreover, Member States may allow direct participation of interconnectors, as foreign capacity, in the same competitive process".

This regulation presents the framework in which this thesis is placed. The necessity to create a methodology for a reliability target that allows calculating the necessary level of security of supply of a MS and the participation of foreign capacity and interconnectors in contributing to reliability, are topics that will be tackled in the following chapters.

2.4. Summary

This chapter introduces the theoretical framework of power system adequacy, intending to answer the subquestion one: *What is system adequacy and how is it regulated in EU countries?*.

As it has been reflected in section 2.1, adequacy of the system is a dimension of system's reliability. Adequacy is placed in the long term, as the ability of the system to meet demand in a long horizon considering the development of the power system. Adequacy evaluation can comprise generation and/or transmission adequacy. In the framework of European studies, adequacy is assessed at the generation level and a simplified representation of the transmission system, and thus this will be the scope of this research project. To evaluate the maturity of the system with respect to an adequacy standard, the adequacy metrics are applied. Loss of Load Expectation and Expected Energy Not Served are presented as the most widely used indices, with the LOLE being the most common in the planning operations. However, the purpose of the assessment should be considered when selecting the adequacy index, as each metric provides different information that can better serve the purpose. Member States lack in many cases the definition of a reliability standard, and wherever it is defined, LOLE is presented as the preferred one.
The Clean Energy package, Regulation (EC) No 5070/19, introduces some specifications for MS in terms of adequacy assessment and requirements when considering the implementation of capacity mechanisms. The national adequacy evaluations should be based on the European resource adequacy assessment. When con-

sidering a capacity mechanism the possible effects of neighbouring countries should be analysed, and the country should have in place a reliability standard that indicates the necessary level of security of supply for the Member State. Moreover, cross-border participation should be allowed in the capacity mechanism.

3

Methodology to assess adequacy

In order to evaluate the adequacy level of a power system, different methods can be applied. In this chapter, an introduction of these methods as defined and classified in the literature will be presented. Section 3.2 will summarize the methodology used by several industrial institutions. Specific focus will be paid to the procedure applied by ENTSO-E.
The content of this chapter aims to address the second sub-question set by this thesis: *How to assess system adequacy in an interconnected power system?*

3.1. Theoretical framework of adequacy assessment

The establishment of a level of acceptability of system failures is a complex process that implies a compromise between cost and reliability. By increasing investment in generation capacity, the probability of consumers being disconnected can be reduced. However, this can lead to overinvestment bringing extra costs to consumers. On the other hand, underinvestment can lead to lower reliability of the system. Thereby, the goal is to find a balance between reliability and cost-effectiveness.

To evaluate the adequacy level of a system, two different reliability criteria are applied: deterministic and probabilistic. The mentioned approaches will be introduced below with the aim of setting up a theoretical framework where the industry practices for evaluating mid and long-term system adequacy can be placed (described in section 3.2), and especially the ENTSO-E work.

3.1.1. Deterministic methods of reliability assessment

Deterministic methods are mainly scenario-based contingency calculations [9]. Only a small set of power system states can be evaluated. It does not account for the stochastic nature of power systems, not covering all system contingency configurations. For the analysis, the most significant states of the electricity system are chosen based on "worst case" studies, requiring a deep knowledge of the system [14].
The selection of the power system states is comprised by a discrete set of system configurations (network topology and unit commitment), system operating conditions (unit dispatch and load distribution), outage events (unavailability of generators, lines or transformers) and performance of evaluation criteria (voltage values, frequency) [9].

Deterministic criteria have been used by the industry for many years. Among the deterministic methods, the N-1 principle for transmission planning, and the capacity margin for generation planning, have been widely applied [14].

Two main deterministic approaches can be differentiated:

- The reserve margin method.

It is a widely used methodology to assess generation adequacy, often applied at a country level [15]. Reserve margin is defined as the difference between available generation capacity and the load to be supplied, without considering transmission constraints. It is expressed as a percentage of the excess quantity of supply above peak demand. Each of the supply sources capacity needs to be calculated by applying a de-rating factor that represents the likelihood to be technically available to generate at times of peak demand [16]. Neglecting transmission constraints or failures can lead to situations where despite having enough reserves in the system, some system areas present a lack of reserves, thus lower reliability level [9]. The reserve margins or capacity margins are computed for a set of specific time shots, the uncertainty can be considered by an additional margin that includes seasonal peaks or adverse weather conditions [15].

- The selected base incidents method.
  This method considers the transmission constraints by selecting a discrete set of contingency scenarios. The procedure of this method entails two steps [9]:
  1. Selection of one or more base cases that correspond to critical operating conditions.
  2. Exposing each base case to a series of generation and transmission incidents and analysing how the system responds to the contingencies.

Deterministic approaches required less data, reducing the computational time, thus allowing faster analysis and results. Nevertheless, the likelihood of each outcome is not assessed, as every outcome is considered with the same weight; also, deterministic approaches do not account for relevant aspects like the dynamic management of storages, variability of renewable energy generation, or power exchange constraints between countries due to the accomplishment of their own reliability targets [15]. The system risk cannot be calculated through deterministic criteria, presenting a limited application in modern complex power systems [17]

However, thanks to its quick implementation, deterministic methods are still in use, mainly at the dispatching level to evaluate the real-time security of the system. For the planning phase, like the long-term resource adequacy evaluation, probabilistic methodologies are preferred [9].

3.1.2. Probabilistic methods of reliability assessment

The behaviour of the power system is stochastic in nature, thus is logical to consider its assessment through techniques that answer to this behaviour, probabilistic techniques.

Probabilistic criteria examine all possible contingency situations, which are derived from unavailability factors linked to each element of the power system. As a result of probability methods, risk indices are obtained. This approach involves the random nature of weather data to take into account the variable behaviour of loads, intermittent generation and outages of generation and transmission equipment [9].

Probabilistic approaches require higher amount of data compare to deterministic ones, as there is no restriction on the selection of scenarios. Probabilistic methods overcome the main deficiencies of the deterministic approaches: they allow the representation of the probability of occurrence of each scenario by assigning weights to each case, also the consideration of the storage management and the network transfer capacity constraints [9]. Another feature provided by the probabilistic methods is the possibility of optimising the level of reliability by means of cost-benefit analysis (CBA), which can be used to find efficient investments to increase systems reliability [18].

To obtain the probabilistic reliability indices there are mainly two different sorts of probabilistic methods that can be applied [19]:

- Analytical method or convolution. This technique represents the system by a mathematical model and assesses the reliability indices using direct numerical solutions.
- Monte Carlo or Simulation method. In this approach, the reliability indices are estimated by simulating the real process and random behaviour of the electricity system.

The difference between the two approaches lies in the selection of the contingency events. In analytical methods the contingencies are chosen by screening techniques and then based on failure criteria. While in the

Monte Carlo method the selection of contingencies is based on random sampling [20]. Analysing the industry practice, the Monte Carlo method is generally preferred in Europe, while in the USA several assessments are conducted through analytical methods.

In the following sections the above-mentioned methods will be explained in detail.

Analytical methods

Analytical methods represent the power system by a mathematical model, and enumerates and combines the probabilities and frequencies of system states to obtain the reliability indices [21]. In order to generate an analytical tractable model of the system, a number of assumptions are necessary, which can result in a less meaningful analysis. Although, this use of assumptions and reduction of data, mainly in the case of complex systems, can provide expectation indices in relatively short time [19].

The calculation of the reliability indices by an analytical method, consist of three main steps [22]:

1. The creation of a load model. It represents the expected demand, considering the variation of weather and economic forecast.
2. The creation of a capacity model. It represents the generation of the system, including the intermittent generation and the outages affecting the generating units.
3. Calculation of the reliability indices using probabilistic mathematics and the combination of the load and capacity model.

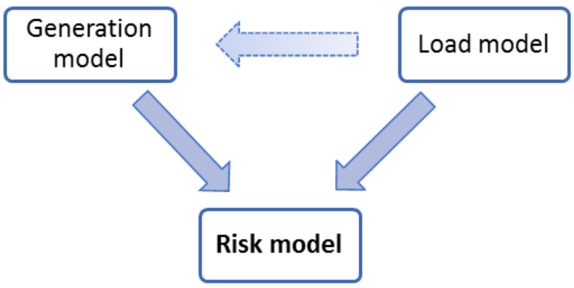

Figure 3.1: Steps for reliability evaluation following an analytical method.

In the following sections, the procedure for the calculation of the reliability indices applying analytical methodologies will be introduced, explaining as well, the construction of the capacity and load models.

The techniques applied in system reliability evaluation are generally presented in terms of their application to segments of the complete system, i.e. generation, transmission and distribution [21]. The adequacy evaluation of the following segments or functional areas will be presented:

- Generation.
- Interconnected systems (generation assessment).
- Composite systems (generation and transmission assessment).

Generating capacity adequacy evaluation

The adequacy of the generation system is assessed by the calculation of the reliability indices, once obtained the generation and load models.

1. Generation system model
To build the generation system model, first the availability of the generating units should be determined, and then the model can be built by creating the capacity outage probability tables.

- Generating unit unavailability
  Unit unavailability or forced outage rate is a basic parameter that accounts for the probability of finding the unit under forced outage at a specific moment in the future [19]. The unavailability of each unit is considered as independent from the rest of the generators. These concepts of unavailability or availability can be defined by the equations (3.1) [19]:

$$Unavailability\,(FOR) = U = \frac{r}{m+r} = \frac{r}{T} = \frac{f}{u} = \frac{\sum down\ time}{\sum down\ time + \sum up\ time} \tag{3.1a}$$

$$Availability = A = \frac{m}{m+r} = \frac{m}{T} = \frac{f}{\lambda} = \frac{\sum up\ time}{\sum down\ time + \sum up\ time} \tag{3.1b}$$

  Where r= mean time to repair= $1/\mu$
  μ= repair rate.
  m= mean time to failure= $1/\lambda$
  λ= failure rate of the unit.
  u= expected repair rate
  $m+r$= mean time between failures= $1/f$
  f= cycle frequency = $1/T$

  This simple two-state model that represents the unit up or down, can be used to represent a base load generating unit. In the case of peaking units, intermittent operating units or the start-up, shut-down states, a four-state model is required [19].

- Capacity outage probability tables
  The evaluation of the loss of load index requires a capacity outage probability table. This table is a simple representation of different capacity levels and its associated probabilities of existence [19]. The probability value that is presented in these tables, is the probability of exactly the indicated amount of capacity being unavailable. The cumulative probability can also be included, which is the probability of finding a quantity of capacity on outage equal or greater than the indicated amount [19].
  The capacity outage probability table can be used in combination with a load model to calculate the system risk level.

2. Load model
The generation system model can be convolved with a load model to produce the risk index [19]. There are different load models that can be used to generate different risk indices. One of the load models, that is extensively used in the USA, is the one in which each day is characterised by its daily peak load. From that load mode, by arranging the individual peak load in descending order, a cumulative load model can be produced, known as the daily peak load variation curve. If the individual hourly load values are used, the model is known as the load duration curve [19].

One of these load models can be used in combination with the system capacity outage probability tables and calculate the expected risk of loss of load [19]. These load representations do not follow a time sequential approach, neither does the capacity outages probability tables, thus a time independence is assumed.

Interconnected Systems adequacy evaluation

A particular case of generation adequacy assessment is the evaluation of an interconnected system, which is generally the case for the European assessments, both at a national or regional level, the system studied is analysed considering its interconnections. For this sort of evaluation, different probabilistic methods can be applied. The reliability is quantitatively presented by the risk indices, the loss of load expectation (LOLE) is the most commonly used indicator. There are two different methods for calculating the LOLE in an interconnected system: the probability array method and the equivalent assisting unit method [19].

1. Probability array method in two interconnected systems
In an interconnected system, a loss of load event is expected when there is not enough supply to meet the load in a specific area, and the assistance from the interconnectors is not sufficient, due to shortage situations in the interconnected regions. By using convolution equations the combined effect of the interconnected

systems in the whole area can be evaluated. The interaction between the systems is based on the premise that each system is independent and can assist its neighbouring systems when they are incurring a capacity deficiency. The assistance is to the extent that it does not jeopardized its own reserve situation, thus the existence of capacity surplus [23]. In this method, the above principles and the generating facilities of each system can be represented by a two-dimensional probability array representing all combinations of capacity outages in the two systems [19]. This representation can then be modified adding the load levels and the tie line constraints [19].

To obtain the risk index, first the assistance policy between areas should be defined. Second, the capacity model of each system should be developed, usually expressed as the capacity outage probability table. Third, from the individual tables, the probability array of the simultaneous outage probabilities can be obtained [19]. For obtaining the system risk, each system is evaluated separately taking into account the assistance policy established. Once the simultaneous outage probabilities are obtained the sum of those probabilities is the system risk of the studied system. The same procedure can be done with each region, obtaining an individual index for every interconnected system.

2. Equivalent assisting unit approach to two interconnected systems
The equivalent unit approach uses an equivalent multi-state unit to describe the ability of one system to accommodate capacity deficiencies in the other. In the case of two systems, one the assisted system and other the assisting system, the latter would have a capacity assistance level for a particular outage state dependent on the minimum of the tie capacity and available system reserve at that outage state [19]. The capacity assistance table can be translated into a capacity model of an equivalent multi-state unit which is added to the capacity model of the assisted system.

3. Linear flow network model
In this method the interconnections are modelled by a linear flow network in which the transmission lines are described by capacity states and the associated probabilities of existence. Each area is described by the probability distribution of available reserve margins. The critical minimal cuts of the network are found to determine the failure events. The failure probability is calculated by evaluating the combined probabilities of the critical minimal cuts. This method provides reliability measures for every area and the total system [24].

Composite system adequacy evaluation

Composite systems assess the level of adequacy of the generation and transmission system with the objective to evaluate the system's ability to supply the load and comply with the energy requirements at the major load points. Traditionally, the reliability of the transmission system and its capability to transfer the generated energy to the consumers' load points is not included in the resource adequacy studies [17]. However, the occurrence of different blackout events has made visible for the industry that in resource adequacy assessments, both generation and transmission characteristics should be accounted [5].
In order to evaluate the reliability of the overall system, the composite model at the load point is required [19]. This mode is the combination of the transmission model with the generation model. The input data required to evaluate a composite system, can be divided into deterministic data, as system components characteristics, and stochastic data such as outage information.

Simulation methods

Simulation or Monte Carlo methods model the actual process and random behaviour of the power system. The Monte Carlo method represents stochastic simulations using random numbers. There are two categories of Monte Carlo simulation approaches, "sequential" or "non-sequential". The non-sequential process does not follow a chronological order, it represents only snapshots of the system state at several time moments, without considering transitions between system states [21]. A sequential approach follows chronological simulation steps through the year simulated, recognizing the dependency of the events [22].

In both Monte Carlo approaches, sequential and non-sequential, the simulations are based on replications of historical data combined with future expectations of installed capacity and other system parameters [22]. The required number of simulations must be established in order to obtain an acceptable level of statistical convergence. The range of statistical convergence of a reliability index is calculated by the standard deviation of the measure of reliability [22]. For the desired accuracy level, the required number of samples is independent of the system size, making Monte Carlo methods suitable for large scale systems, contrary to analytical techniques [10]. Analytical techniques are more convenient for relatively small systems or low component outage probabilities, while Monte Carlo techniques are preferred for large size systems and high component outage probabilities, as it is a more flexible method to simulate complex requirements and states [25]. Therefore, for adequacy evaluation of wide areas, like is the case of a European assessment, and at a composite level, Monte Carlo simulation is the most suitable method.

The annual reliability indices are calculated as the average of the accumulated results (each simulation result) until the standard error of the mean is equal to or smaller than the selected convergence criteria [22], therefore the reliability index is provided as a mathematical expectation.

In this section the different simulation methods will be explained. First introducing the simulation techniques and then, the areas in which the adequacy assessment can be applied. Additionally, an introduction of several supporting policies in case of interconnected systems will be presented.

There are three simulation approaches in reliability evaluation, which can be classified under the sequential or non-sequential categories [10]:

- State sampling approach - non sequential.
- State duration sampling approach - sequential.
- System state transition sampling approach - sequential.

State sampling approach

This technique assesses the probability of a system component to be in a particular state. It considers that a system state depends on the combination of all component states. It can be described by equation (3.2) [10]:

$$E(F) = \sum_{S \epsilon G} F(S) \frac{n(S)}{N} \tag{3.2}$$

Where E(F) is the mathematical expectation of the index function.
$F(S)$= reliability index function, e.g. LOLE, EENS, etc.
N= number of samples.
$n(S)$= number of occurrences of state S, S being equal to 0 when is a success states, or to 1 when is a failure state.

This approach requires less input data than a sequential approach, however it cannot be used to calculate the frequency index.

State duration sampling approach

Through this approach, the state duration of each component is evaluated by sampling its probability distribution. First, the chronological state transition processes of all components are simulating by sampling. Then, those chronological state transition processes are combined to form the whole chronological system state transition process [10].

When considering a two-state component representation, these states are identified as the operating and repair state duration distribution functions, which are usually considered as exponential. However, other distributions can be applied [10].

System state transition sampling approach

This approach tackles the state transition of the whole system instead of each component state. State transition of any component in the system may lead to system state transition. In a system containing m components, with an exponential state duration distribution each, the system can perform a system state transition sequence. Therefore, given a present system state, the system with m components has m possible reached states. After several samples a long state transition sequence can be obtained and the reliability of each system state can be assessed [10].

Similar to analytical methods, the reliability evaluation can be applied to the generation system or the composite system. A differentiation between single area and multi-area in generation systems will be made. Moreover, various policies that should be considered when studying an interconnected system, will be explained.

Generating system adequacy assessment

Generating system adequacy assessment is applied to evaluate the generation system capacity to meet the total system load. This assessment is typically classified into two aspects: single area and multi-area generating systems. These two approaches will be introduced in the following sections.

1. Single-area generating system adequacy assessment
For assessing single-area systems, two simulation methods are applied: state duration sampling method and system state sampling method [10].

The general steps for applying the state duration sampling method are [10]:

1. Generation of chronological operating records of each generating unit by creating sample values of Time-to-Failure (TTF) and Time-to-Repair (TTR) of the unit.
2. Generation of the system available margin model by superimposing the system available capacity curve on the chronological load curve.
3. Calculation of the reliability indices based on N sampling years.

In the case of the state sampling method, it is based on the generating unit state probabilities. For modelling an annual load curve, the following method can be used [10]:

> Create a multistep model of the annual load curve: once having the load duration curve, approximate it by a multistate model. Compute the annual reliability indices by weighting the annualized indices for each load level by the load step probability.

2. Multi-area generating system adequacy assessment
Multi-area assessments involve not only generating capacity models and load models of each area, but also the tie line models and supporting policies between areas [10]. In order to assess adequacy considering assistance between areas and tie line constraints, two methods can be used: a maximum flow algorithm and a linear programming model.

The maximum flow algorithm method consists of three general steps [10]:

1. Creation of a generating capacity model and a load model for each area.
2. Combine the generating capacity and load models to get an available margin model per area.
3. Include the tie line network and assistance policy, and compute the reliability indices per area and the total system.

The maximum flow algorithm method considers each area separately and analyses the hourly available capacity margins obtained at step 2. In the hours where the available capacity margin is negative for at least one area, the flow algorithm is applied. By the application of the algorithm, the maximum available assistance through the interconnectors is found, and therefore the capacity margins are modified. Finally, after obtaining the modified available capacity margins, the reliability indices are computed per area and the total system over N sample years. These reliability indices show the adequacy level of the studied area considering interconnections.

For applying the linear programming model the next basic steps should be followed [10]:

1. Using sampling techniques, select a system state. The set of components that includes the system state represent the generating units and load levels of each area, and all the tie lines.
2. Calculate a reliability index by means of a linear programming model.
3. Calculate the expected value of the reliability index over the N number of samples.

Once selected a system state, the evaluation of the reliability indices using a linear programming model is conducted on a smaller fictitious system representing a generation-transmission system. The areas studied are divided into two sets of supporting (available generation capacity larger than the load), and supported areas (available generation capacity smaller than the load). The fictitious system is formed by generators, fictitious generator, a required load and the tie lines between areas. The generators are defined with a capacity equal to the difference between the available area generation capacity, and the load of each area in the supporting set. The required load is the area load and the available generation capacity of each supported area. The fictitious generator, defined in the supported areas, supplies the unsatisfied load when there is not enough capacity in the generators of the supporting areas or due to line constraints. The fictitious generator ensures the power balance in each area [10]. This representation of a smaller system allows the evaluation of the reliability indices of the areas by a linear programming model.

Composite system adequacy assessment

There are several simulation methods for assessing adequacy in composite systems: system state sampling methods, linear programming optimisation model and system state transition sampling technique [10]. Due to the thesis framework, the focus will be put on the Linear programming optimisation model. Regarding the business practice when assessing system's adequacy, the linear programming optimisation approach is extensively applied, it allows the evaluation of complex and large size systems, obtaining the reliability indices over a broad number of samples.

Linear programming optimisation model
In cases of contingency events, generation outputs should be rescheduled to maintain the energy balance and mitigate line overloads, and at the same time avoid load curtailment, or if it is not possible to avoid it, minimize it [10]. In order to minimize the total load curtailment, a minimization optimisation model can be used, where the power balance is satisfied, and the power flows and generation outputs are within their limits [10]:

$$min \sum_{i \epsilon NC} C_i \tag{3.3}$$

subject to

$$T(S^j) = A(S^j)(PG + C - PD) \tag{3.4a}$$

$$\sum_{i \epsilon NG} PG_i + \sum_{i \epsilon NC} C_i = \sum_{i \epsilon NC} PD_i \tag{3.4b}$$

$$PG^{min} \leq PG \leq PG^{max} \tag{3.4c}$$

$$0 \leq C \leq PD \tag{3.4d}$$

$$\mid T(S^j) \mid \leq T^{max} \tag{3.4e}$$

Where C= load curtailment vector.
NC,NG= set of load buses and generator buses respectively.
$T(S^j)$= line flow vectors under state S^j.
$A(S^j)$= relation matrix between line flows and power injections under state S^j.
PG, PD= generation output and load power vectors respectively.
PG^{min}, PG^{max},T^{max}= are the limit vectors of PG and $T(S^j)$.

The above model can have multiple solutions, therefore, to obtain realistic bus indices, a load curtailment strategy should be included in the model, i.e. loads curtailed at the closest buses to the outage, or according to the load importance, etc [10]. In the case of the adequacy study developed by ENTSO-E, i.e. Mid Term Adequacy Forecast, a cross-border charge on imports/exports is introduced to prioritize local use of available capacity and, therefore, outages within an area will first affect the adequacy of that area.

Policy implications

When developing the adequacy assessment of an interconnected system, a multi-area generating system, it is important to assess the reliability of the area, area indices. In order to obtain the reliability area indices, it is necessary to consider the supporting policies between systems and incorporate them to the assessment method, i.e. linear programming model [10].

In [26], considering two interconnected systems, A and B, four supporting policies are identified:

Veto each area satisfies first its own demand, and exports are made if there is net generation surplus. This corresponds with a no-load-loss sharing philosophy [10].

Share the shortfall are shared between areas, as a proportion of their demands levels, and to the extent of the available interconnector capacity. In other words, the load curtailments depend on the line capacity limits.

Assist A considering two interconnected areas A and B, interconnection capacity is used to mitigate the shortfall in system A, even if this induces shortfalls in system B.

Assist B the reverse of Assist A.

3.2. Business practice: methodology used in several institutions

From the industry perspective, the adequacy assessment is mainly performed based on probabilistic methods. Differences exist in terms of adequacy metrics applied, area of study, as well as input data considered. A review of the main adequacy studies of energy institutions worldwide will be introduced. Starting from national and regional level outside Europe, with the adequacy studies of the Australian Energy Market Operator (AEMO) and PJM Interconnection, to continue with the evaluation of adequacy at a European level, from the regional perspective of the Pentalateral Energy Forum (PLEF) and the national adequacy assessment of ELIA, and finalizing with the continental evaluation perform by ENTSO-E.

3.2.1. Australian Energy Market Operator – AEMO

AEMO is the institution responsible for operating the Australian gas and electricity markets and power systems [27].

In terms of adequacy assessment AEMO produces four deliverables [28]:

- Electricity Statement of Opportunities (ESOO): a ten-year projection to provide market information for planning purposes.
- Energy Adequacy Assessment Projection (EAAP): a two-year forecast of unserved energy (USE) over several energy-constrained scenarios, published once a year.
- Medium Term Projected Assessment of System Adequacy (MT PASA): USE forecast over two-years, published on a weekly basis.
- Short Term Projected Assessment of System Adequacy (ST PASA): capacity reserve forecast over a six-day projection.

Before going into detail about the method applied to evaluate reliability, is useful to introduce the reliability standard implemented in Australia. In order to measure the effectiveness of installed capacity to supply the load, the National Electricity Rules establishes a maximum expected unserved energy (GWh) of 0.002%, defined as a percentage of total energy in a region over a financial year [29].

AEMO applies this reliability standard in the different forecasts presented above. In the EAAP the reliability standard is implemented over two years, where the projected USE that exceeds the standard is identified. Special focus is made on the impact of potential energy-constrained scenarios like water shortages during summer [29]. The study assesses the supply adequacy in the National Electricity Market (NEM) which encompass the interconnected regions of Queensland, New South Wales, Victoria, South Australia and Tasmania [28].

EAAP study is based on a probabilistic, time-sequential model that simulates hourly Monte Carlo simulations to identify potential shortfalls in the projected scenarios. In the November 2018 EAAP model, 800 simulations were performed for each scenario, using two peak demand forecasts (10% and 50% Probability of Exceedance demand). Eight historical reference years to simulate variable patterns of intermittent generation and demand were used [28]. To evaluate whether the expected USE could exceed the reliability standard in each region, the model uses a probability-weighted USE. Therefore, to the results obtained from the peak demand scenarios, the following weights were applied to obtain the expected USE [28]:

- 30.4% for 10% POE.
- 39.2% for 50% POE.
- 30.4% for 90% POE.

Input data used in EAAP [29]:

- Generation capacity and planned outages obtained from the MT PASA offers.
- Intermittent generation based on historical meteorological data.
- Energy constraints (scenarios) tackling water availability during drought conditions and constraints on fuel supply.
- Hourly demand profile based on historical demand patterns.
- Network constraints.

Comparing the EAAP study with the MT PASA, the latter takes into account the influence of transmission outages, while the EAAP model uses system normal, considering any outage can be rescheduled to avoid capacity shortfalls. The same applies to generation outages, which are considered flexible in EAAP modelling [28].

3.2.2. PJM Interconnection (USA)

PJM is a regional transmission organization (RTO) that operates the wholesale electricity market, manages the high-voltage electricity grid, and procures the long-term regional planning of the grid in 13 American eastern states and the District of Columbia [30].

The generation adequacy standard established in the PJM regions is based on a loss of load expectation of one day in ten years. The "1 in 10" standard refers to the likelihood of having zero or negative reserve margin[4] [31].

PJM conducts a Resource Adequacy Planning Process that includes the establishment of reserve margin requirement, forecast of peak load and conduction of a Base Residual Auction. The PJM Reserve Requirement is defined as the required level of installed reserves needed to achieve the adequacy standard [32]. The Reserves requirement study evaluates the adequacy needs of the pool for the following five years, and it is conducted each year [31]. To calculate this Reserve Requirement PJM uses the Probabilistic Reliability Index Study Model (PRISM). This tool models two areas, the PJM area and a composite "World" representing some neighbouring states [32].

Input data used in Reserve Requirement Study [32]:

- Load: mean peak load data for 52 weeks and their correspondent standard deviation reflecting the forecasting error and weather variability.

[4] reserve margin= available capacity - load

- Generating capacity: 52 weekly mean values, and 52 available capacity distributions considering forces outages rates, planned outages, etc.
- Capacity Benefit Margin: deterministic value of the capacity between PJM and the external regions.

PRISM tool creates a probabilistic generation model and load model and combines the two models to obtain the probability of load exceeding available capacity. The load model does not consider the weekly load data chronologically, instead, it is ordered from highest to lowest within each season. The loads are then averaged over the five years forecasted. The capacity model simulates every generating unit in each area. The Capacity Benefit Margin, to determine whether the PJM transmission system is able to import energy under peak demand periods, is based on power flow analysis of the bulk electric power grid [32].

PRISM calculates a cumulative probability table of the availability of each generating unit's capacity for every week of the year. Then, it calculates the system LOLE for a particular load level. On a weekly basis, the probability of every load level occurring simultaneously with each possible generation availability level is evaluated [32]. When a combination of load and capacity presents a load level over the generating available level, there is probability of a negative capacity margin (LOLE). In the case of the two-area evaluation, the probability of the other area having an excess capacity margin within the tie value of the line, is then subtracted from the first area's probability of loss of load [32].

The tool does not apply Monte Carlo sampling because by using probabilistic distributions, the calculations consider every possible load and capacity state [31].

PRISM reaches a solution by adjusting the load distribution until the adequacy standard is achieved. It is an iterative method in which once obtained the LOLE of one day in ten years, the ratio of the installed generation to the annual load peak, is the required Installed Reserve Margin (IRM) [32].

3.2.3. Pentalateral Energy Forum - PLEF

PLEF represents the regional cooperation in Central Western Europe towards electricity market integration and security of supply. PLEF is formed by the Transmission System Operators of Austria, Belgium, Germany, France, Luxembourg, the Netherlands and Switzerland. Under the PLEF framework, the mentioned TSOs publish the Pentalateral Generation Adequacy Assessment which provides probabilistic analysis of the security of supply in Europe, obtaining the adequacy indicators LOLE and ENS for the Penta countries. The study is based on a projection of one year ahead and 5 years ahead [33].

The adequacy assessment is done by means of two market simulation tools, ANTARES and PowrSym which assume a perfect market. These tools apply a probabilistic approach in which the projected supply and demand levels are compared by simulating the operations of the European electricity system on an hourly basis for one year. The models solve a cost minimization problem known as "Optimal Unit Commitment and Economic Dispatch" (UCED), formulated as a large-scale Mixed-Integer Linear-Programming problem [33]. In order to assess adequacy, the two tools utilize a Monte-Carlo approach which involves many simulations with random combinations of stochastic variables (climate dependent) and unplanned outages, obtaining a representative probability distribution curve of ENS and LOLE [33].

Input data used by PLEF 2018 [33]:

- Load: hourly load data for each area taken from ENTSO-E MAF 2017. These profiles are based on data extracted from the Pan European Climate Database (PECD) which produces correlated chronological time series of weather-dependent variables based on historical weather over the period 1982-2015 (34 climate years).
- Demand Side Response (DSR): it is modelled as a generating unit with a maximum power and a strike price, with a limit on usage (number of hours per day).
- Thermal units and outages: thermal units defined by categories (coal, gas, etc.) with data such installed capacity, maximum power, fuel type and cost, efficiency, unavailability rate (forced outage and maintenance), etc. Unavailability is simulated through maintenance schedules on a seasonal basis and random draws to account for forced outages.

- Intermittent generation: renewable production is based on projected installed capacities and hourly profiles extracted from the PECD, including hydro-power production depending on the rainfall.
- Outages HVDC lines: forced outages of High Voltage Direct Current interconnectors in the Continental Western Europe perimeter (CWE) with a probability of 6% every 7 days.
- Fuel and CO2 prices: values taken from the International Energy Agency (IEA) World Energy Outlook (WEO) (2016).
- Balancing Reserves: Frequency Containment Reserves (FCR) and Frequency Restoration Reserves (FRR). The reserves on hydro units are modelled as a reduction of turbine capacity, and the reserves on thermal units are simulated as with a derating of the thermal capacity per category.
- System Adequacy mechanisms (SAM): consideration of the SAMs implemented in the PLEF countries that contribute to the assurance of generation adequacy.
- Grid modelling: for the short-term projection, one year ahead, a flow-based representation for the area of France, Belgium, Germany and the Netherlands was applied. While for the rest of the regions Net Transfer Capacities (NTC) were used to model the exchanges in the borders. In the case of the mid-term projection, five years ahead, the NTC approach was applied for all the perimeter. The NTC approach sets an interval for power exchanges between two countries without considering the exchanges with the rest of the countries. Contrary, a flow-based approach models the exchanges through domains which couple exchanges on all borders simultaneously per hour, reflecting the physical grid elements.
- Perimeter: the Penta countries plus neighbouring countries.

PLEF also analyses different sensitivities like the decommissioning of power plants due to economic or environmental reasons, reduce availability of nuclear power plants or sensitivity on the grid. The final result of PLEF is the EENS and LOLE indices for the Penta countries in the base case and the different sensitivities studied.

3.2.4. ELIA (Belgium)

Elia is the high-voltage transmission system operator in Belgium. Every year Elia publishes a probabilistic assessment of Belgium's adequacy for the next winter. In this report, the need for a strategic reserve is addressed.

The reliability standard implemented in Belgium is defined by a two-part loss of load expectation criterion [34]:

- LOLE < 3 hours.
- LOLE95 < 20 hours.

The calculation of the required volume of strategic reserves is made through a probabilistic simulation of the Western-European electricity market (20 neighbouring countries) on an hourly basis for the coming winter.

The market simulation tool utilized for the study is ANTARES, which performs sequential Monte Carlo multi-area simulations to assess generation adequacy. For every country within the perimeter many Monte Carlo years are created based on historical meteorological data (stochastic variables like renewables and demand), unavailability of generating units and HVDC links. Then, ANTARES performs the simulation of the electricity market operations, modelling the power plants' economic dispatch for a horizon of one year and with hourly resolution [34].

The input data for each country is the following [34]:

- Hourly demand profile.
- Thermal generation: projected installed capacities and availability.

- Intermittent generation: projected installed capacity of wind, solar and hydro generation and associated hourly profiles based on climate years.
- Interconnections are modelled using flow-based or NTC approach.

The data used and simulation procedure followed by Elia is the same or similar to the one applied in PLEF.

The output of the model that is analysed in the adequacy study, is an hourly time series showing the energy shortages for each country. From this output, the LOLE and ENS can be deduced. For calculating the required volume of strategic reserves, and iterative approach using the model is applied: first, the situation of the coming winter is analysed, the need for strategic reserves is identified whether the two adequacy standards (LOLE) are breached. Then once the need is identified, the margin is increased by 100MW blocks until the reliability standards are fulfilled [34]. The use of 100MW block resolution is also used in adequacy evaluations by other TSOs as well as ENTSO-E.

3.2.5. ENTSO-E

ENTSO-E is the European Network of Transmission System Operators for Electricity. It is an association that represents 43 electricity transmission system operators from 36 European countries. Its main objective is the setup of an internal energy market and to ensure its optimal functioning while following the European energy and climate agenda [35], acting as coordinator of TSOs.

Among its main deliverables is the Mid-term Adequacy Forecast (MAF). In this section the methodology applied in MAF to assess adequacy, as well as the input data used for the study will be explained in detail, as it represents the base for the development of the research project concerned. This section will summarise the procedure presented in [11].

Mid-term Adequacy Forecast 2018 edition

The Mid-term Adequacy Forecast (MAF) is a pan-European assessment of power system resource adequacy with a timeframe up to ten years ahead. It is based on probabilistic analysis by means of market-modelling simulation tools.

MAF analyses system adequacy in the pan-European area covered by ENTSO-E through five different modelling tools calibrated with the same input data and benchmarked against each other to increase the consistency [1]. As a result, the adequacy indicators LOLE and EENS are obtained for every country. The MAF 2018 targets the years 2020 and 2025, and it provides results for the base case, and several sensitivities such as the so-called low-carbon scenario and flow-based sensitivity [1].

MAF 2018 methodology

In order to assess adequacy, the methodology implemented in MAF compares supply and demand levels in the interconnected European electricity system by simulating the market operations over an entire year with hourly resolution. Supply and demand data are composed by a deterministic forecast, combined with stochastic variables. The deterministic side is represented by the ENTSO-E scenarios for 2020 and 2025 which entails the projected net generation capacity (NGC), cross-border transmission capacity and yearly load levels. On the stochastic side, the uncertainty is characterized by climate variables and unplanned outages, including:

- Ambient temperatures, which influence the demand level.
- Intermittent generation as wind and solar generation and hydro conditions.
- Unscheduled outages of thermal units and HVDC interconnectors.
- Maintenance schedules.

The geographical perimeter of study is depicted in figure 3.2.

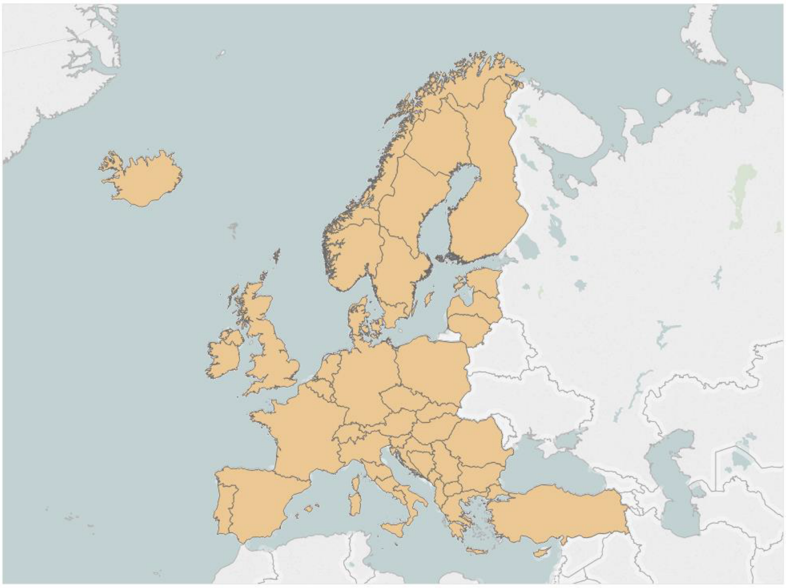

Figure 3.2: The European power system perimeter modelled in MAF 2018. Source: [11]

The modelling tools employed perform market simulations based on perfectly competitive market behaviour, simulating the marginal cost of the power system and each market node. The optimisation solved by the tools is a cost-minimization problem, the Optimal Unit Commitment and Economic Dispatch. It is formulated as a large-scale Mixed-Integer Linear-Programming problem, in which the objective is to find the least-cost solution while complying with all operational constraints (transfer capacity limits, ramping, etc.).

For evaluating the reliability of the system, the Monte Carlo method is followed, and incorporated to the simulations of the target years 2020 and 2025. To build these simulations the stochastic variables are combined, first, based on 34 historical climate years. Each climate year is a combination of demand, solar and wind hourly profiles and a correspondent hydro condition (wet, dry, normal), or for some nodes, a historical year-specific hydro generation time series. Every of these climate and hydro sets is later associated with a large number of Monte Carlo realizations[5] which randomly assign forced outage patterns affecting thermal units and interconnectors. The time horizon of the optimisation problem is one week, and the resolution of the simulation is hourly, meaning that the cost minimization problem is optimised for each week of the year on an hourly basis, thus reducing the computation time.

In terms of network representation, at pan-European level, market studies are based on Net Transfer Capacities. This means that the network constraints between the market nodes are modelled as limits only on commercial exchanges at the borders, not considering other grid constraints.

Data set and assumptions used in the MAF 2018:
The Pan-European Market Modelling Data Base (PEMMDB) is the centralized database for collecting the national generation data and outlooks provided by TSOs and then used in market studies. This database is the main source of data for the MAF, and covers elements as:

- Demand and DSR forecast.
- Thermal generation units' data (must-run, number units, etc.)
- Information on hydro generation plants.
- Renewable generation capacities.
- Reserves and exchanges with non-ENTSO-E countries.

[5]The number of Monte Carlo simulation performed differs among the five modelling tools.

Information about decommissioning of units is as well collected separately.

Apart from the data collected in PEMMDB, other information and sources are used in the MAF, these will be summarized in the following sections.

- Demand time series
  The demand input in MAF is based on a sensitivity analysis of demand and temperature, creating time series of electrical demand.

  The mathematical correlation between ambient temperature and consumption in a specific area is represented by a cubical polynomial approximation, which sets the basis for creating time series demand profiles per market node. The daily average temperature is calculated from historical meteorological data of 34 years. The next step is to up- or downscale the obtained time series to a specified demand (annual consumption) for the target year studied (2020, 2025). Finally, a synthetic demand profile is calculated considering the expected daily maximum and minimum consumption. Separately, considerations of changing consumption patterns due to electric vehicles and heat pumps are taken into account.

- PECD
  As previously mentioned in section 3.2.3, related to PLEF, PECD is a database developed by ENTSO-E which contains hourly weather data and load factors of climate-dependent variables for 34 historical years (1982-2015). The following data sets can be found in PECD:

  - Wind, speed, radiation and nebulosity time series.
  - Load factors time series of onshore, offshore wind, solar photovoltaic and concentrated solar power.
  - Temperature time series.

- Net Transfers Capacities
  For each scenario, 2020 and 2025 the NTCs included in the models are based on the TSO expertise about the expected transfer capacity between borders.
  The adoption of a flow-based approach is shown in MAF 2018 as an additional sensitivity analysis, but it is not included in the main results.

- Thermal generation maintenance profile
  Maintenance profiles represent the out-of-service state of thermal generating units. In PEMMDB the number of maintenance days and its distribution during winter/summer is collected. The maintenance schedule is calculated for each target year and it is defined based on the principle of “constant reserve”: for every week the difference between available thermal generation and residual load to be supplied is calculated and the maintenance of every generating unit is never broken into discontinuous weeks [11].

- Reserves
  Balancing reserves or ancillary services are agreements with producers and consumers to adapt their production or demand in certain moments and areas. Balancing reserves are not considered to contribute to long-term adequacy, therefore they are not included in MAF and are deducted from the available resources.
  This reduction in resources is implemented in the models in two ways:

  - Increasing the demand by the hourly reserved capacity.
  - In countries where reserves are provided by hydroelectrical generation, the maximum possible hydro generation was reduced by the reserved value.

- Demand Side Response (DSR)
  DSR is modelled as a set of generators with specific parameters as their hourly availability and price. The DSR generators are distributed in price bands with the activation price and a maximum hour of continuous availability. The price for the DSR assets is arbitrary set to 500€/MWh, ensuring that it will be activated before a loss of load event and without interfering in the merit order dispatch, while the

number of hours is defined as the typical DSR installations.

- Other parameters
  There are other parameters that constitute the input of the models and are collected as well in PEM-MDB, these are factors as the ramp-up/down rates, minimum up/down time or the availability of power system elements.
  The availability of power system elements includes the planned outages – maintenance, and the forced outages. The latter are defined by the Forced Outage Rate (FOR) parameter which specifies the annual rate of forced outage events of thermal generating units or interconnectors. Forced outages are simulated by the probabilistic Monte Carlo approach which generates random patterns of outages respecting the annual rate specified.

<u>MAF Model Results</u>

MAF delivers as output the LOLE and EENS for all the regions included in the forecast of 2020 and 2025, these results correspond to the average of all simulated results. In addition, different sensitivities are as well presented. Complementary to the LOLE and EENS, the 50th and 95th percentiles of their distributions are published, these values represent the risk of an extreme climate year of 1 in 2 years and 1 in 20 years respectively [11]. Moreover, a comparison of results per simulation tool is also shown.

To conclude this section of Business practices, table 4.13 presents a comparison of the different studies conducted by the previous institutions.

Table 3.1: Comparison business practice in adequacy assessment.

	Assessment	**Area studied/modelled**	**Reliability Standard Metric**	**Generation adequacy Evaluation Method**	**Horizon**	**Scenario**	**Output**
AEMO	Energy Adequacy Assessment Projection	Australia/Multi-area model	EENS [% of total energy/year]	Probabilistic. Sequential Monte Carlo method.	2 years	Several energy constrained scenarios. Outages not considered.	Probability-weighted EENS across scenarios.
PJM	Reserve Requirement	USA states/Two-area model	LOLE [days/10years]	Probabilistic. Analytical method.	5 years	One scenario. Generating units outages.	Required Installed Reserve Margin
PLEF	Pentalateral Generation Adequacy Assessment	Central Western Europe/ Multi-area model	LOLE [h/year]	Probabilistic. Sequential Monte Carlo method.	1 year & 5 years	Base case and sensitivities. Generation and transmission units outages.	LOLE & EENS
ELIA	Adequacy study and need of a Strategic Reserve	Belgium/ Multi-area model	LOLE [h/year]	Probabilistic. Sequential Monte Carlo method.	1 year	Base case and sensitivities. Generation and transmission units outages.	LOLE, EENS & volume of Strategic Reserves
ENTSO-E	Mid-term Adequacy Forecast	Europe/ Multi-area model	LOLE [h/year] & Capacity Margin	Probabilistic. Sequential Monte Carlo method.	2 years & 7 years	Base case and sensitivities. Generation and transmission units outages.	LOLE & EENS

3.3. Summary

Chapter 3 presents the different methods covered by the literature and applied in the industry, to assess system adequacy. The content of this chapter answers the second sub-question: *How to assess system adequacy in an interconnected power system?*

As it has been presented in section 3.1, in literature two main approaches are identified: deterministic and probabilistic methods. While deterministic methods required less data and computational time, they neglect several aspects of the power system, as variable generation, or probability of each outcome. Despite that, deterministic methods are still in used, mainly in the dispatch level; the reserve margin method and the selected base incidents method being the main deterministic approaches. Probabilistic methods are preferred for the planning phase as they account for the stochastic nature of the power system. To obtain the probabilistic reliability indices there are two approaches: analytical or simulation method. The analytical method represents the system by a mathematical model that includes a load and generation model for then calculate the risk indices. In the case of the simulation or Monte Carlo method, it models the actual process and random behaviour of the power system by stochastic simulations using random numbers. The Monte Carlo method can be applied in a sequential or non-sequential approach. Both analytical and simulation methods evaluate different system areas as generating system adequacy or composite system adequacy. The latter comprises the interconnected systems.

On the business side, the probabilistic methods are widely used for adequacy assessments. European institutions and AEMO make use of Monte Carlo simulations to evaluate the adequacy of their regions. They simulate the operations of the electricity market, performing the Unit Commitment and Economic dispatch problem. Contrary, PJM applies an analytical method for determining its Reserve Requirements. In each institution, different reliability targets and input data and assumptions are considered.
Overall, it can be stated that for assessing system adequacy of an interconnected power system, probabilistic methods are applied, and in particular Monte Carlo simulation is presented as the approach that can accurately reflect the power system and all its components and possible states, being widely used by the industry.

4

Missing capacity- concept and methodology

The focus of this research project is to introduce a new possible adequacy indicator, what is named “Missing Capacity" and the corresponding methodology for its evaluation, to the limit that has been investigated.

After the theoretical introduction to power system reliability, and how is it assessed in literature as well as in the industry, in this chapter several of those concepts will be applied to define the methodology for obtaining the Missing Capacity. In section 4.1, the concept of Missing Capacity will be introduced, describing briefly the different approaches for its calculation. Then, the simulation tool applied in the research process, will be presented, followed by the input data and assumptions used in the models. Section 4.4 will explain in detail the methodology found for evaluating Missing Capacity.

The content of this chapter will explore the possible answers to the sub-question three: *Which are the different approaches to ensure the required level of system adequacy?*

4.1. Missing Capacity as an adequacy indicator

As it is introduced by the Clean Energy package, when considering the implementation of a capacity mechanism, the Member State shall have a reliability standard in place that indicates the required level of security of supply for the region. It is specified that the reliability standard has to be calculated using at least the value of lost load and the cost of new entry [13].

Within this framework is placed the investigation of Missing Capacity. This concept is introduced with the aim to provide a possible adequacy indicator which assesses the security of supply in a more comprehensive manner. Whether EENS and LOLE indicate the adequacy level of a country, that then can be compared with the reliability standard in place, they do not provide information or tools to resolve the difference between the calculated state and the standard. A quantification in terms of capacity that would be required to reach the reliability standard, cannot be derived from the information provided by metrics such the LOLE or EENS. This lack of information is crucial when considering investments and instruments to ensure security of supply, like capacity mechanisms. For that purpose, an indicator that explicitly states the capacity required to reach a specific target can provide more thorough information. With this purpose, the Missing Capacity concept is introduced.

Missing capacity is defined as a quantitative indicator that represents the extra capacity needed to reach a defined reliability target in a specific region. It shows the installed capacity that a region would need in a given future scenario to fulfil the adequacy criteria established. Missing Capacity can be defined regarding two main aspects:

- The capacity source considered.

- The area of the assessment.

The capacity required is defined as firm capacity and technology-neutral. Therefore, it is presented as capacity which is guaranteed to be available at a given time. Moreover, in the definition of Missing Capacity no real parameters of generation sources are used. Neither technical or economic parameters that characterize a generation technology are implemented, thus the nature of the Missing Capacity indicator is set as technology-neutral.

For the quantification of missing capacity, two main capacity sources can be considered, generation and transmission. The capacity required can be provided either by generation capacity or transmission capacity. In both cases expansion of resources is required, either the local generation or the interconnection capacity is increased.

When developing an adequacy assessment, like the Missing Capacity, the study area where the reliability target wants to be achieved should be defined. In the case of study two target areas are identified:

- Single area.
- Multi-area.

When evaluating the missing capacity of a single area, only the reliability target of the country of study is considered. Therefore, the required capacity to reach the target in that country is calculated, without assessing the adequacy levels of the neighbouring regions. Contrary, when the perimeter of study expands to a multi-area level, the Missing Capacity is defined as the required capacity to reach the reliability target in each of the studied countries. In this case, an area formed by several neighbouring countries is assessed, and the reliability targets are computed separately. Thus, the missing capacity is the capacity that fulfils each target simultaneously. It should be noted that this division refers to the areas where the achievement of the reliability target is studied and thus the additional capacity is installed. For all the assessments a pan-European perimeter is modeled.

In both perimeters, single or multi-area, the capacity required can be computed as generation capacity, transmission capacity, or a combination of both. On one hand, the case of single area local generation expansion can produce indirect effects on the adequacy levels of neighbouring countries. Despite that it is not an approach that directly aims to assess the adequacy on a multi-area level. On the other hand, when evaluating the adequacy of a multi-area, the knock-on effects in bordering regions, caused by the additional capacity are considered. Accounting for the interconnected nature of the areas allows to share the capacity required and can achieve more efficient allocations of capacity. When considering transmission capacity, even in a single area approach, the contribution of other regions to the adequacy of the country studied is accounted. This increment in cross-border capacity accounts for the contribution of interconnectors to adequacy to the extent of available generation in the regions.

Despite the meaningful information for resource adequacy evaluation that the Missing Capacity metric could bring, its definition and evaluation is not a straight forward process, relying on the boundaries and assumptions needed for its calculation. The interconnected nature of power systems is one of the challenges in the definition of Missing Capacity. Either the interpretation of the missing capacity and its effects on neighbouring regions, along with the problem formulation, are affected by this interconnected nature. The influence of flexible resources as hydro and its intertemporal constraints (e.g. reservoir levels), also brings some challenges when implementing the Missing Capacity problem. Moreover, the definition of economic parameters for the problem implementation is a sensitive topic influenced by the lack of clarity and unification of reliability standards, value of lost load or cost of new entry.

The Missing Capacity indicator has to be calculated with respect to a reliability standard expressed as LOLE or EENS. It should be defined using probabilistic methodology and be based on a regional assessment. The contribution of interconnectors should be considered, allowing the share of capacity across regions by means of the interconnection capacity.

The calculation of Missing capacity is based on a simulation method, using an electricity market model that performs Mixed-Integer-Linear Programming optimisation, following a time-sequential approach. The model incorporates the adequacy indicator defined by the national regulation of each region. In the European framework that is usually expressed as loss of load expectation, as it is reflected in table 2.1. Therefore, in this study, the reliability target used for the calculation of the Missing Capacity is the LOLE metric. If no adequacy target is placed in the region a standard of LOLE = 3h/year is applied.

Let us consider a power system with a $LOLE > TLOLE$, where $TLOLE$ is the reliability target of the system. The Missing Capacity problem can be formulated as follows:

$$minimise(\text{ Total System Operation cost} + \text{Cost of additional capacity } K) \tag{4.1}$$

Subject to,

$$\text{Total System supply} = \text{Total System demand} \tag{4.2a}$$

$$LOLE \text{ after addition of } K \leq TLOLE \tag{4.2b}$$

Where K represents the firm capacity added to the system.
Equation (4.2a) presents the system energy balance, and equation (4.2b) establishes the reliability target to be achieved by the system.
The formulation can be modified when considering a multi-region perimeter and the reliability target is applied to more than one system.

Missing capacity methodology: introduction of different approaches

As previously mentioned, Missing Capacity can be calculated within different scenarios. Hence, how that capacity is calculated, between which boundaries and therefore how it is defined, can change for each case.

The different approaches analysed in the framework of this thesis, for the calculation of Missing Capacity will be introduced, presenting later in section 4.4 a detailed explanation of the methodology and concepts.

Given a power system that consists of multiple interconnected regions with independent adequacy targets. When in some of these regions the required level of reliability is not reached, the study of Missing Capacity can be conducted. The methodology to determine the extra capacity needed to reach the adequacy level can be classified considering the area of the assessment, the area where the reliability target has to be reached and thus the addition of capacity, or the capacity source.

Area of the assessment:

- Single-area approach.
- Multi-area approach.

Capacity source:

- Generation capacity expansion.
- Interconnection capacity expansion.

Following the previous classification, the approaches investigated in the present research project are introduced below:

1. Single-area approach, local generation: evaluation of the missing capacity considering a single region and local generation capacity expansion. The reliability shortage of the region assessed is solved considering only national resources.
2. Multi-area approach, generation expansion: calculation of the missing capacity in order to fulfil the reliability target of two or more neighbouring regions. In this case, the extra capacity is shared among areas, being able to reach the adequacy standard by imports/exports as well as local capacity.
3. Single-area approach, generation/interconnection capacity expansion: assessment of the missing capacity of a single region, considering both expansion options, capacity and interconnection.

In this chapter the three approaches will be explored, presenting the methodology for its evaluation.

Once identified the area of the assessment and the capacity source, the methods analysed for calculating the missing capacity, are the following:

- Integrated optimisation approach: Missing Capacity - capacity expansion problem.
  - Shortfall Constraint: implementation of the reliability target as a constraint in the area of study.
  - Economic Optimisation: definition of a build cost for the new generators that constraints by itself the hours of unserved energy in the area.
- Iterative approach: iterative increment of generation/transmission capacity to reach the LOLE target.

The investigation of different methods is required due to the computational complexity of the problem depending on the areas and capacity sources analysed. These methods will be applied in section 4.4 in function of the area considered.

4.2. PLEXOS® Simulation Software

The study of Missing Capacity has been conducted by a linear programme optimisation model built upon a market simulation engine. The simulation tool applied in the research has been PLEXOS.

PLEXOS is a power system modelling tool developed by Energy Exemplar. It is presented as a problem-solving engine that tackles a variety of problems within the electricity industry, such as long-term capacity planning, system reliability, portfolio optimisation, etc [36]. PLEXOS solves optimisation problems as generator unit commitment and economic dispatch by applying Mixed Integer Programming (MIP). It determines the least cost unit commitment and dispatch decision to meet the load, across each step of the simulation [11]. PLEXOS is a software utilized by different companies like consulting firms, utilities or system operators, as it can be employed in different business areas such as operations, planning, market or transmission analysis.

Focus on the application of PLEXOS® for Power Systems, the current section will introduce the basic architecture of the tool, the different simulation phases and other characteristics of the tool that have been used in the research project.

PLEXOS architecture

The optimisation problems are built as an "extensible object model", a set of building blocks with characteristics that can be extended if needed in the future.
The energy system, formed by electric components, is described as a set of *objects* that belongs to *collections*, and are defined by several *properties*. Therefore, a model is built upon three core elements [37]:

- Objects: an object can be a generator, fuel, emission, storage, reserve, region, node, line, transformer, constraint, horizon, etc. Each of these objects belongs to its correspondent class, which defines how objects behave and what data can be defined in each type of object.
- Memberships: they represent the hierarchy and relationship between objects.
- Properties: the data that defines the objects.

Each model is described by a System object, which is the root object to which all other objects belong, and it has a group of collections, one per class of object.

Simulation Phases

The model input data that defines a power system, can contain any combination of short-term to long-term data. PLEXOS allows selecting suitable algorithms for each analysis depending on the time-frame and detail required. There are four possible simulation phases, LT Plan, PASA, MT Schedule and ST Schedule, each with different features and capabilities.

Long Term Plan (LT)
LT simulation phase performs a capacity expansion problem, it finds the optimal combination of generation and transmission new builds or retired. LT optimises the expansion decisions while minimizing the net present value of the total system cost over a long-term planning horizon of 10 to 30 years [37]. It is subject to system constraints such as emission limits, prices, reliability constraints, etc. Long Term Plan is the only simulation phase that performs the capacity expansion problem over a long-term horizon. LT is generally used to provide solutions over a reduced chronology in which the dispatch periods are combined into blocks. Moreover, LT does not perform the simulation of random outage events.

The following types and characteristics of expansion or retirements are performed [37]:

- Building or retiring of a generation plant.
- Building or retiring AC and DC transmission lines.
- Multi-stage projects.
- Deterministic or stochastic optimisation.

Projected Assessment of System Adequacy (PASA)
PASA simulation models and schedules maintenance and random outages of generators and transmission lines. The maintenance schedule is performed in a way that available generation capacity is optimally shared across interconnected regions [37]. PASA has also the capability to calculate LOLP reliability index.

The outages that are modelled by PASA can be classified in [37]:

- Discrete maintenance: planned maintenance events.
- Distributed maintenance: maintenance events generated by the simulator.
- Forced outages: unplanned outages generated by the simulator.

Medium Term Schedule (MT)
MT simulation represents the system based on temporal simplifications, it can apply partial or full chronology and handles the constraints to the required level of detail [37]. It can simulate long time horizons and large systems in short computational time. MT results can be used alone or to decompose medium-term constraints, objectives and hydro release policies, to then be used by the full chronological simulation, ST.

MT manages the constraints ranging from weeks, months or years, like [37]:

- Energy limits.
- Long-term hydro storage limits that account for inflow uncertainty.
- Emission limits.

The temporal simplifications introduced in MT are controlled by the chronology setting that defines the level of detail used to represent the horizon. It can take different values like Partial, Fitted or Sampled chronology [37].

Those three types of chronology define the load profile employed in the simulations. Under Partial chronology a load duration curve is created for each day, week, month or year, each with a specific number of blocks [37]. The block correspondent to peak and off-peak demand moments are represented in more detail than the block of the average load conditions.
In case of Fitted chronology, the demand series is fitted to the number of blocks per day, week, month or year, defined by the user. This approximation is done by applying the weighted least-squares technique [37].
In Sampled chronology, a certain number of samples defined by the user are taken of days, weeks or months. Sampling is done statistical, obtaining a representative variation of the original load series [37].
Fitted or Sampled options provide a more accurate simulation as unit commitment and other intertemporal

constraints (rump up, etc.) are preserved.

Short Term Schedule (ST)
ST performs a full detailed unit commitment and economic dispatch based on mixed-integer programming. It can handle time periods of minimum one minute. It performs a chronological simulation over a horizon ranging from minutes to years. Some application in which ST is used are the following [37]:

- Solve market-clearing dispatch and pricing optimisation problems.
- Large scale transmission studies.
- Portfolio optimisation.
- Thermal unit commitment problem.
- Stochastic unit commitment.

ST Schedule can get information from MT Schedule, allowing a correct treatment of long-term constraints in shorter time-frames [37].

The different simulation phases can be run alone providing independent solutions, or they can be integrated. The integration of simulation phases provides broader solutions, making use of the particular features of each phase. In case of integration of phases, the information of each phase will be feed into the next one, following the order depicted in figure 4.1.

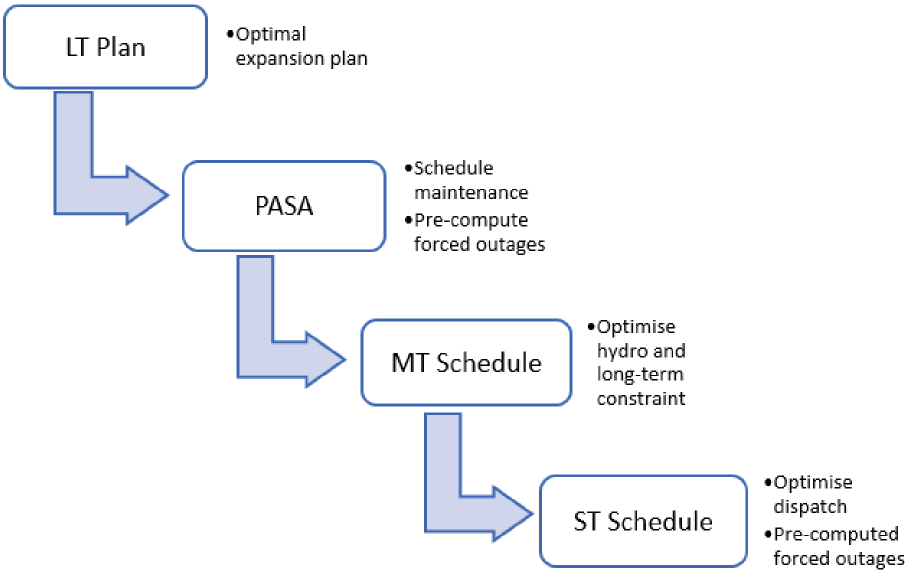

Figure 4.1: Integration of PLEXOS simulation phases.

Aside from the simulation phases, it should be introduced the Stochastic capabilities of PLEXOS, and the unit commitment and economic dispatch problem.

Stochastic variables and optimisation.

PLEXOS provides the possibility of performing stochastic modelling across all simulation phases. There are two classes of stochastic inputs [37]:

- Planned or unplanned outages.
  The number of outage patterns generated is defined by the user. Monte Carlo method is applied considering the outages patterns as independent samples.

- Random variables.
  This feature creates randomized sample data for different input data like load, wind and solar generation, hydro inflows, fuel and electric prices. Sample data can be predefined by the user and introduced into the model, or it can be automatically generated during the simulation, based on the probability distribution specified by the user.

The stochastic method includes a stochastic optimisation mode, “Scenario-wise decomposition”, which differs from the Monte Carlo technique. In the Monte Carlo method, the simulation phase runs a certain number of times, one time for each sample, selecting the appropriate values for each. In scenario-wise decomposition, the simulation phase runs a single optimisation, including all samples into the optimisation problem, and obtaining a single optimal solution of hydro storage in MT phase, capacity expansion decisions in LT phase, or unit commitment decisions in ST phase [37].

Unit commitment and Economic Dispatch

PLEXOS performs the generator unit commitment and economic dispatch optimisation using mixed-integer programming, as long as it is a chronological simulation phase.

The unit commitment and economic dispatch algorithm includes both problems. On one hand, unit commitment represents the sequence of generating unit on and off decisions across the optimisation horizon. The unit commitment solution is the optimal combination of these on/off decisions in terms of the total system cost while complying with system constraints. On the other hand, economic dispatch refers to the optimisation of generator dispatch levels for the given unit commitment solution. The UCED algorithm co-optimises the cost of unit commitment decisions, like start costs, dispatch costs like fuel, and operations and maintenance costs, such all system costs are minimized [37].

The general formulation of the UCED problem is as follows [38]:

$$minimise_{u_i,P_{G_i}} \sum_{i=1}^{n} C_i(u_i, P_{G_i}) \tag{4.3}$$

Where the cost (C_i) of the operating status of a generating unit is represented by (u_i, P_{G_i}), being u_i a binary variable taking value of 1 if the unit is on-line and 0 if it is off-line.

4.3. Study framework

This research project is based on the data set and assumptions used in the ENTSO-E Mid-term Adequacy Forecast 2018 edition (see section 3.2.5). The Missing Capacity study, models the European electric power system represented by the MAF data, which has been collected from the TSOs, based on their information and expectations for the future electricity supply, demand and grid status. This study is therefore based on assumptions and should not lead to statements on whether or not the market works properly, neither as a reference for future investments.

As explained in section 3.2.5, the MAF 2018 assesses adequacy for different scenarios such as the base case, and various sensitivities. One of those sensitivity studies is the low-carbon scenario that represents the reduction of installed capacity caused by the acceleration of low-carbon policies. The Missing Capacity research has been performed based on the mentioned scenario, low-carbon, using the same data set and assumptions, and for the time horizon of the year 2025. Hence, the adequacy assessment has been modelled for the time frame from 01-01-2025 till 31-12-2025 using the input data of the low-carbon scenario.

The evaluation of missing capacity is subject to the existence of scarcity situations in a region that leads to an adequacy level below the reliability standard established in that region. Therefore, in order to have study material and region candidates where to perform the evaluation, the low-carbon scenario was chosen. This scenario represents a stress case on generating capacity where more European countries face scarcity, thus it is more meaningful for performing the missing capacity calculation.

As it is presented in section 3.2.5, the projected years, being 2020 and 2025 in the MAF 2018, are based on hourly weather data and load factors of 34 historical climate years. This means that for the target year 2025, 34 projections of 2025 are simulated, each based on the expected installed capacities for 2025 and the climate year that influences the stochastic variables (wind, solar, hydro and demand). In the case of the Missing Capacity study, due to the time-frame for the realization of the thesis and the computational time required for the simulations, the study is based on three climate years. The selection of climate years has been based on the existence of severe weather conditions in the given year. The reason behind this selection is, as well as for the low-carbon scenario, that in such conditions, there are more regions that present scarcity, and the adequacy levels are significantly reduced, hence it is more suitable for calculating the missing capacity.

The climate years selected are 1985, 1986 and 2012. These years represent critical weather conditions which impact the adequacy results. The year 1985 presents the most extreme conditions among the PECD collected years, as it can be seen in the representation of the cold spells in France:

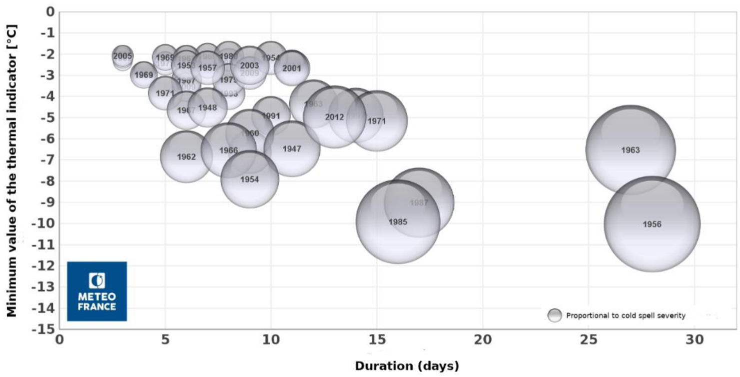

Figure 4.2: Cold spell waves in France between 1947 and 2016. Source: [39]

It should be noticed that the results presented, based on three climate years, do not represent the real probabilities of having extreme weather conditions in 2025, but it serves the goal of this study of finding a methodology for the evaluation of missing capacity.

Perimeter of study

The countries represented in the data and models used for the Missing Capacity study are the same as the ones covered by MAF 2018, figure 3.2. However, the study is focused on the area of Central Europe: Belgium (BE), Germany (DE), France (FR), United Kingdom (GB), Luxembourg (LU) and the Netherlands (NL). This selection is due to the LOLE results shown in that region, as it can be observed in the figure 4.4, which makes it suitable for the calculations of missing capacities. Moreover, Central Europe is a highly interconnected area, contrary to other isolated regions that present LOLE, which allows the study of the contribution of interconnections in times of scarcity, being also in the scope of this thesis.

Outage patterns

When conducting Monte Carlo simulations, as it is the case for obtaining indices like LOLE and ENS, the number of simulations that should be performed can be established by the degree of statistical convergence of the reliability index, having this confidence interval to reach an acceptable level. In the case of the MAF 2018 this confidence interval was reached with 34 climate years and 20 outage patterns per year when using PLEXOS. The outages patterns represent the random outages that are generated by the simulator. In the case of this study, when conducting the Monte Carlo method, the same number of outage patterns is applied.

Low-carbon scenario 2025

This scenario analysis the adequacy results in case low-carbon national policies drive an accelerated reduction of thermal capacity. This capacity reduction can answer either to environmental legislation or indirectly by lower profitability of thermal plants due to environmental actions [11]. The scenario represents a stress test, as the carbonized generation that is decommissioned is not replaced by any other generation source. In total, 23.35 GW are removed from the 2025 base case scenario of MAF 2018. Figure 4.3 shows per country, the capacity reduced from the base case:

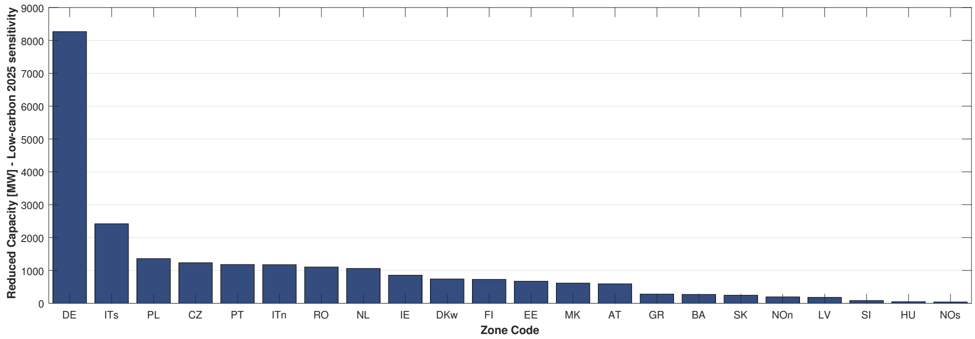

Figure 4.3: Reduced generation capacity in low-carbon 2025 scenario. Source: [11]

Table 4.1 presents the detailed results of low-carbon 2025 scenario, in terms of EENS and LOLE for the countries in the perimeter of study. The results shown were adjusted to the scope of this research, thus they were obtained for the projection of 2025 based on the three climate years and modelled in PLEXOS.

Table 4.1: EENS and LOLE results for low-carbon 2025 scenario by zone.

Zone Code	EENS [GWh]	LOLE [h/year]
AL	0.01	0.03
AT	0.00	0.00
BA	0.00	0.00
BE	133.44	48.87
BG	0.17	0.43
CH	0.00	0.00
CY	152.43	1244.78
CZ	13.71	16.90
DE	9.63	4.18
DEkf	0.00	0.00
DKe	2.35	8.28
DKkf	0.00	0.00
DKw	1.01	3.67
EE	1.04	2.95
ES	0.00	0.00
FI	1.45	5.15
FR	262.86	45.67
FR15	1.87	30.47
GB	47.56	17.13
GR	0.06	0.20
GR03	2.61	55.83
HR	0.00	0.00
HU	0.00	0.03
IE	34.35	96.12

Zone Code	EENS [GWh]	LOLE [h/year]
IS00	0.00	0.00
ITcn	13.92	24.93
ITCO	0.00	0.00
ITcs	0.22	0.47
ITn	59.07	24.43
ITs	0.00	0.00
ITsar	0.47	2.60
ITsic	0.12	0.62
LT	0.93	2.63
LUb	1.91	66.67
LUf	8.92	65.37
LUg	33.95	38.32
LUv	0.00	0.00
LV	0.08	0.32
ME	0.00	0.00
MK	0.06	0.38
MT	0.70	15.40
NI	6.74	42.65
NL	7.65	8.08
NOm	0.00	0.00
NOn	0.00	0.00
NOs	0.00	0.00
PL	12.01	12.87
PT	0.00	0.00
RO	0.00	0.00
RS	0.00	0.00
SE1	0.00	0.00
SE2	0.00	0.00
SE3	0.00	0.00
SE4	0.96	1.28
SI	0.01	0.07
SK	1.64	2.50
TN00	0.20	1.03
TR	0.00	0.00

In figure 4.4, an overview of the LOLE results for the countries studied can be observed. It is seen that the area of central Europe is particularly affected under this scenario and assumptions, hence it represents the focus area for the Missing Capacity evaluation.

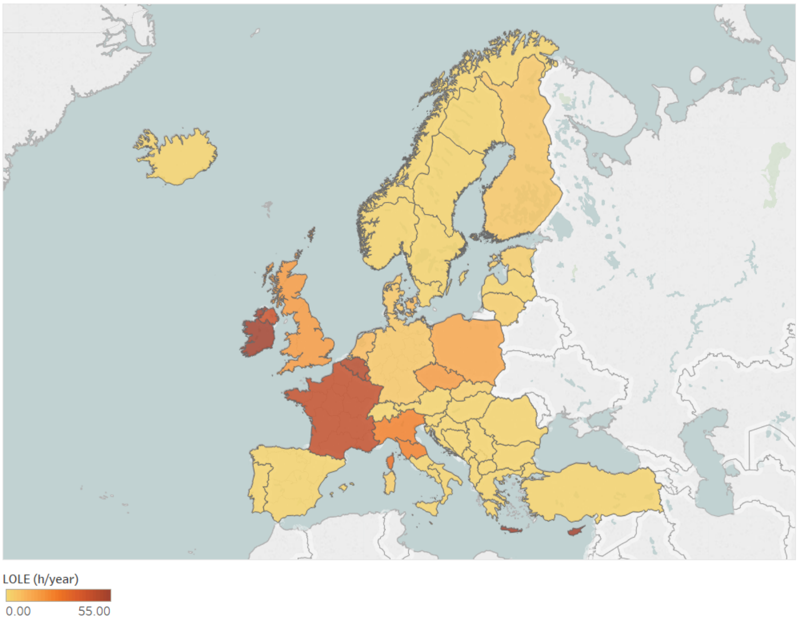

Figure 4.4: LOLE results for low-carbon 2025 scenario by country.

Table 4.2 shows the summary of the study framework and input parameters utilize in the study.

Table 4.2: Summary study framework Missing Capacity evaluation.

Target year	2025: 01/01/2025 – 31/12/2025
Data set and assumptions	Low-carbon scenario 2025, MAF 2018
Climate years	1985, 1986, 2012
Outage patterns	20

4.4. Missing Capacity methodology

In this section, the methodology and processes applied in order to calculate the missing capacity will be presented. First, an overview of the evaluation methods identified will be introduced, as well as the problem formulation. Then, the investigation of generation expansion in a single area or multi-area will be presented, concluding with the interconnection expansion approach.

As it has been introduced in section 4.1, the evaluation of Missing Capacity is divided by the area of study and the capacity source defined for its calculation. Once this classification is made, an evaluation method for solving the Missing Capacity problem should be selected. Two main evaluation methods have been identified, and in function of the case analysed the most suitable one should be implemented. However, the use of these methods is applied in more than one type of case. The evaluation methods identified for calculating the missing capacity are the following:

Integrated optimisation approach

The Missing Capacity problem is implemented as an optimisation problem of finding the optimal amount of generation or transmission capacity expansion that is required to reach the LOLE target in a specific region. The problem is formulated as stochastic optimisation, taking into account the random nature of several variables to find the optimal solution. The Missing Capacity problem is implemented in an electricity market modelling tool that performs the unit commitment and economic dispatch problem. This evaluation method represents the core of the Missing Capacity problem in the case of Single-area capacity expansion. The methodology identified for finding the missing capacity of a single-area by means of generation expansion is a process formed by different steps where the integrated optimisation is the core of the problem formulation, but also Monte Carlo simulations are implemented as a validation test. The integrated optimisation approach of the Missing Capacity problem can be implemented through two different techniques:

- Shortfall Constraint: implementation of the reliability target as a constraint in the problem formulation.
- Economic Optimisation: optimisation of the build cost of the new generators, in a way that the investment is profitable to the extent of the reliability target.

While the integrated optimisation approach is the core for solving the Single-area generation expansion case, it also represents the base of the processes to obtain the missing capacity in other cases, like the Multi-area approach or the Interconnection expansion approach.

Iterative approach

In this evaluation method, the missing capacity of a region is found by a direct increase of capacity in the area of study. An iterative process is followed by a manual increase of the number of units in the areas analysed and computing the LOLE after each iteration until the reliability standard is reached. This method is applied in the case of Multi-area generation expansion and Interconnection expansion approaches. Despite that the iterative approach is the core of the problem formulation in the mentioned cases, the starting point of the iteration is defined by the result obtained in the integrated optimisation approach.

In the following sections, the implementation of these evaluation methods in each of the cases identified will be applied. The approaches that will be presented are the following:

- Single-area generation expansion.
- Multi-area generation expansion.
- Single-area generation/interconnection expansion.

As the integrated optimisation approach represents the core of the Missing Capacity problem in a Single-area generation expansion, as well as the starting point for the iterative method, its problem formulation will be described before presenting in detail the different approaches.

4.4.1. Integrated optimisation approach: problem formulation

The Missing Capacity problem is an optimisation problem of finding the optimal amount of generation/ transmission required to reach the LOLE target in a specific region. In the framework of this project, the Missing Capacity investigation has been performed using the market modelling tool PLEXOS. In PLEXOS the capacity expansion problem that represents the calculation of Missing Capacity, is solved by finding the optimal combination of generation/transmission new build to reach the reliability target while minimizing the total costs of the system.

In order to solve a capacity expansion problem, it is required to use the PLEXOS Long Term Planning simulation phase. LT plan optimises the generation/transmission building decisions while minimizing the Net Present Value (NPV) of the total cost of the system over a long-term planning horizon [37]. This simulation engine solves simultaneously the capacity expansion and the unit commitment economic dispatch problem. The Missing Capacity problem is formulated in the simulator as a Mixed-Integer Linear Program (MILP).

Before introducing the problem formulation, the definition of all the parameters and variables introduced in the objective function and constraints, as well as the values that have been used equally in all the models of this research, can be observed in tables 4.3 and 4.4.

Table 4.3: Variables included in the Missing Capacity formulation.

Variable	Description
$GenBuild_{g,y}$	Number of units build of generator g in year y.
$GenLoad_{g,t}$	Dispatch level of generator g in period t.
ENS_t	Unserved energy in dispatch period t.

Table 4.4: Parameters included in the Missing Capacity formulation.

Parameter	Description	Units	Input value
DF	Discount factor applied to a year, DF_y, or to dispatch period DF_t.	-	0
L_t	Duration of dispatch period t.	Hours	
$BuildCost_g$	Overnight build cost of generator g.	$/kW	
$MaxUnitsBuilt_{g,y}$	Maximum number of units of generator g allowed to be built in year y.	-	100
$PMAX_g$	Maximum generating capacity of each unit of generator g.	MW	
$Units_g$	Number of installed units of generator g.	-	
$VoLL$	Value of Lost Load.	$/MWh	10000
$SRMC_g$	Short-run marginal cost of generator g: Heat Rate × Fuel Price + VO&Mcharge.	$/MWh	
$FOMcharge_g$	Fixed operations and maintenance charge of generator g.	$	
$Load_t$	Average power demand in dispatch period t.	MW	
$PeakLoad_y$	System peak demand in year y.	MW	
MF_t	Region Maintenance Factor in period t.	-	
MOR_g	Maintenance Rate of generator g.	%	
FOR_g	Forced Outage Rate of generator g.	%	
$WACC_{g,y}$	Weighted-average cost of capital of generator g in year y.	%	0

The core formulation of the capacity expansion problem is the following [37]:

$$\begin{aligned} \text{Minimize} \sum_{(y)}\sum_{(g)} DF_y \cdot (BuildCost_g \cdot GenBuild_{(g,y)}) \\ + \sum_{(y)} DF_y \cdot [FOMcharge_g \cdot 1000 \cdot PMAX_g (Units_g + \sum_{i \le y} GenBuild_{g,i})] \\ + \sum_{(t)} DF_{t \in y} \cdot L_t \cdot [VoLL \cdot ENS_t + \sum_{g} (SRMC_g \cdot GenLoad_{g,t})] \end{aligned} \tag{4.4}$$

subject to:

Equation (4.5) Energy Balance:

$$\sum_{(g)} GenLoad_{(g,y)} + ENS_t = Demand_t \ \forall t \tag{4.5}$$

Equation (4.6) Feasible Energy Dispatch accounting for outage rates:

$$GenLoad_{g,t} \le (1 - MOR_g \cdot MF_t - FOR_g) \cdot PMAX_g \cdot (Units_g + \sum_{(i \le y)} (GenBuild_i)) \ \forall g, t \tag{4.6}$$

In the LT Plan formulation is assumed that neither forced outages nor maintenance outages affect capacity, but both outages are subtracted from the available energy, without simulating the forced outage events. Therefore, Generator Forced Outage Rate (FOR) and Maintenance Rate (MOR) are subtracted from the energy contribution of generators.

Equation (4.7) Feasible Builds:

$$\sum_{i \le y} GenBuild_{g,i} \le MaxUnitsBuilt_{g,y} \tag{4.7}$$

Equation (4.8) Integrality:

$$GenBuild_{g,y} \text{ integer} \tag{4.8}$$

The Generator Build Cost property included in the core formulation, represents the per kW overnight cost of building a new unit, this is only suitable if the planning horizon is long enough to amortize the build cost, i.e. the Economic life of the plant is within the planning horizon. In order to account for the cost of the projects whose life surpass the end of the planning horizon, the build cost should be annualized [37]. The annualized cost represents the equivalent annual charge which is applied in the year of build and every following year during the economic life of the generator.
In the case of the models used for calculating the missing capacity, the Build Cost property has already been introduced as an annualized cost, setting the Economic Life to 1 year, which is equal to the duration of the

planning horizon. Therefore, the Build Cost parameter introduced in equation (4.4) represents the annualized generator build cost.

As it is seen in the objective function, the core formulation of the capacity expansion problem seeks to minimize the net present value of build cost plus fixed operations and maintenance costs plus production costs. As previously mentioned, LT Plan solves the capacity expansion problem that can be run in deterministic or stochastic mode. In stochastic mode, LT simulation finds the single optimal set of building decisions taking into account the variations introduced by the load and intermittent generation (stochastic variables), and without the simulation of the random outage events. In the study of Missing Capacity, stochastic optimisation has been implemented in several approaches. Hence, an introduction to the stochastic implementation in LT plan and the features of stochastic optimisation will be presented.

Stochastic programming allows to model optimisation problems that include uncertainty, and required decisions that have to be taken "ahead of time". Contrary to deterministic problems, stochastic optimisation accounts for the unknown parameters that can be present in reality. In this kind of optimisation problems, the probability distributions that define the random data are known or can be estimated, and the objective is to find a solution within the feasible region. It aims to provide a single solution to key decisions, like generation build decision, given the uncertainty of parameters such as hydro generation, wind, solar or demand [40].

LT Plan solves Stochastic Integer Problems (SIP), where some of the decision variables are integer, like it is the case of the number of generating units built. It applies the solution technique scenario-wise decomposition. In this formulation, the random variables take discrete scenarios e.g. the variables dependent on the climate years, like hydro inflows, with estimated probabilities. The user defines the non-anticipative variables e.g. generator build decision, that have to be optimised with respect to the uncertainty. The simulator formulates the production part of the capacity expansion problem as many times as the number of samples, S. Each of these production problems will have different values for the stochastic variables. Then, the non-anticipative variables (build decisions) are introduced in each scenario. Finally, non-anticipativity constraints are added, which force the non-anticipative variables to be equal across all S scenarios [41]. This method provides a final single solution for the expansion decisions.

The main difference with the Monte Carlo technique as implemented in PLEXOS is that Monte Carlo simulation provides the optimal decision for each scenario assuming perfect foresight of the uncertain variables, but cannot provide the optimal decision that is feasible for all possible scenarios [42].

SIP problems are often modelled as two-stages models. As explained, in these models the decision is taken in the first stage, then, random events occur affecting the outcome of that decision and after that, a recourse decision or second stage decision can be made to compensate the effects of the random events [42].

Figure 4.5: Two-stage stochastic model. Source: [42]

PLEXOS allows two or multi-stage optimisation using MIP.

As a drawback, stochastic programming is computationally hard to solve and grows in complexity and required computational power and time, with the size of the system and time resolution of the problem [42].

In order to solve the Missing Capacity problem, several parameters should be included in the capacity expansion formulation, either in the Shortfall Constraint or the Economic Optimisation method, as it is explained below.

Shortfall Constraint

To follow the integrated optimisation approach by introducing the reliability target as a constraint, the introduction of an additional equation to the capacity expansion problem is required, equation (4.9).

Equation (4.9) Reliability Constraints:
In order to determine the amount of capacity expansion that is required to reach a specific reliability threshold, in terms of LOLE, it is necessary to introduce an extra constraint in the capacity expansion problem. This constraint, Reliability Constraint, limits the annual hours of energy not served in a specific region or node to the amount equal to the LOLE target in that region. The general formulation of the constraint is as follows:

$$\sum_{t,r} ENS_{hour_{t,r}} \leq TLOLE_r \ \forall t \tag{4.9}$$

Where $ENS_{hour_{t,r}}$= decision variable representing each hour with/without ENS in dispatch period t in region r.
$TLOLE_r$= LOLE target in region r [h/year].

PLEXOS minimises ENS not LOLE, thus for limiting the total LOLE it is necessary to create a time series of all the hours with ENS in the year. The annual time series of $ENS_{hour_{t,r}}$ represents the existence of unserved energy in a region for a specific hour; being 0 an hour without unserved energy, and 1 an hour with unserved energy. It can be described by the following constraints:

$$ENS_{hour_{t,r}} = 1,\ ENS_{t,r} > 0 \ \forall t, r \tag{4.10}$$

$$ENS_{hour_{t,r}} = 0,\ ENS_{t,r} = 0 \ \forall t, r \tag{4.11}$$

$$ENS_{hour_{t,r}} \in \{0, 1\} \text{ Integer} \tag{4.12}$$

Where $ENS_{t,r}$= variable of unserved energy in dispatch period t in region r.

In order to introduce these constraints in PLEXOS, and create the time series of the $ENS_{hour_{t,r}}$, another mathematical formulation is required as the variable $ENS_{hour_{t,r}}$ is not directly defined in the tool, contrary to the ENS. For the implementation, a decision variable $ENS_{hour_{t,r}}$ that can take the value 0 or 1 is introduced. Then, to make this decision variable take a value of 1 when there is ENS and 0 otherwise, the big M method was applied:

$$ENS_{t,r} \geq ENS_{hour_{t,r}} \cdot M^{-1} \ \forall t, r \tag{4.13}$$

$$ENS_{t,r} \leq ENS_{hour_{t,r}} \cdot M \ \forall t, r \tag{4.14}$$

Being $\text{ENS}_{t,r}$: $0 \leq ENS_{t,r} \leq M$

M was defined as a large value higher than the peak load of the region studied, and also above the ENS values observed for that region.

The general formulation of the big M method allows the utilization of the Simplex method on optimisation problems with mixed constraints. It is based on the association of a “sufficiently large” constant to an artificial variable that is introduced in the objective function. This leads to the Simplex algorithm that seeks for the minimization of the objective function, to discard any solution with a positive artificial variable, forcing the value of this variable to be 0 [43]. In this case, the big M method has been applied to the constraints, instead of including the constant in the objective function. What is intended with this technique, commonly used in MIP, is to limit the value of a set of variables based on the value of a binary variable.

One of the limitations identified of using PLEXOS software was that the Reliability Constraint implemented limiting the LOLE of the region to a fixed value, was applied per sample. This means that instead of having a limitation of, for example, 3h/year LOLE, for the projected year, 2025, the constraint was applied at each simulated sample (climate year). The goal of the constraint was to impose a limitation in the loss of load expectation, for that, the average of unserved energy hours of all the samples should be 3h or less. This implementation would allow, for example, to have 6h, 2h and 1h of ENS distributed across three samples, resulting in a LOLE of 3h/year. In contrast, by constraining each sample to 3h of ENS, the missing capacity result is the capacity required to solve the scarcity under the most extreme conditions, in this case represented by the climate year 1985, as it is the one presenting highest unserved energy values.

To overcome this issue other set up options and problem formulations were investigated. Concerning the modelling tool, there is no possibility of implementing the user-defined constraints in a way that are applied to the target year, i.e. across all climate years, and not per sample. Therefore, a change in the problem formulation was studied.

The alternative implementation is explained in the following section.

Economic Optimisation

In response to the limitations introduced by the Reliability Constraint, another formulation of the Missing Capacity problem, excluding the implementation of such constraint was analysed.

The solution studied was the definition of a Build Cost for the new units, that could provide a price signal that limits by itself the amount of new capacity selected by the optimizer. The capacity expansion problem optimises the total system cost, therefore a build cost that represents the optimality of building just to reduce energy shortages to 3h of unserved energy a year would provide the Missing Capacity solution. To define this build cost value it is necessary to find a trade-off between the cost of a new unit and the Value of Lost Load (VoLL).

As it can be seen in equation (4.4), the problem optimises the total system costs considering the build cost, the energy not served and the VoLL, apart from other operational costs.

The VoLL is the consumers' willingness to pay to avoid disconnection [44], reflecting the cost of energy not served to consumers [9]. In case of an investment decision, like the capacity expansion decision, the VoLL represents the benefit of avoiding a curtailment [45].

The addition of a new generator with any amount of capacity will reduce curtailments and hence contribute a capacity benefit [45]. This benefit can be compared to the annual cost of the generator to evaluate if the generator is cost-effective. Therefore, the capacity benefit defines the value of energy that is no longer curtailed when a generator is added to the system, it represents the capacity benefit for consumers [45].

$$Capacity\ benefit = VoLL \cdot \Delta EENS \tag{4.15}$$

This Capacity Benefit is also introduced by the United Kingdom Department of Energy and Climate Change in the guidelines for the Reliability Standard Methodology, as the cost of blackouts to consumers [46]:

$$BC(k) = EENS(k) \cdot VoLL \tag{4.16}$$

Where BC is the cost of blackouts, that would represent the capacity benefit of equation (4.15) when a resource is added in the system.
k is the total system capacity.

From equation (4.16) the incremental cost of blackouts becomes:

$$\frac{dBC}{dk} = \frac{dEEU}{dk} \cdot VoLL \tag{4.17}$$

With the addition of a new generator, thus increasing the total system capacity, the expected energy not served would be reduced for each curtailment event by the generator rated capacity, which represents the increment of the total system capacity, Δk.

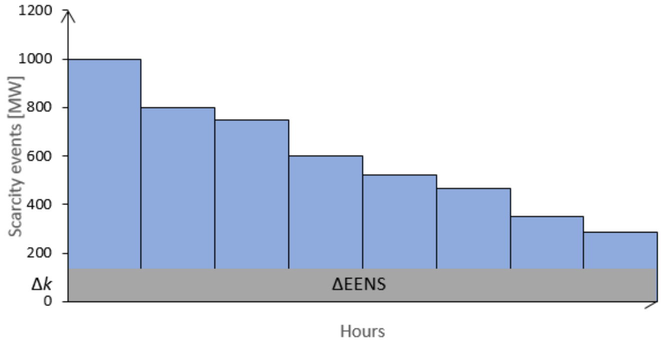

Figure 4.6: Addition of a new generator and the change in expected unserved energy. Source: [45]

Therefore, from the graph it can be derived that the incremental change in EENS is equal to the product of the total expected hours of unserved energy, what is the same as LOLE, and the capacity of the new unit [45]:

$$\begin{aligned} \Delta EENS &= LOLE \cdot \Delta k \\ \frac{dEENS}{dk} &= LOLE \end{aligned} \tag{4.18}$$

Substituting equation (4.16), where $\frac{dBC}{dk}$ is the cost of new entry into the market, CONE:

$$\begin{aligned} CONE &= \frac{dEENS}{dk} \cdot VoLL \\ CONE &= LOLE \cdot VoLL \end{aligned} \tag{4.19}$$

Equation (4.19) defines the optimal relation between the expected hours of unserved energy, the cost of new entry and the value consumers will pay for avoiding lost load.

In the case of the model used for the study of Missing Capacity, the CONE is represented by the Build Cost of a new unit.

With the introduction of equation (4.19) the value of the Build Cost is determined as follows:

$$\begin{aligned} CONE &= Capacity\ Benefit \\ Build\ Cost &= Capacity\ Benefit \\ 1\text{MW} \cdot Build\ Cost &= VoLL \cdot 1\text{MW} \cdot LOLE \\ BuildCost &= VoLL \cdot LOLE \end{aligned} \tag{4.20}$$

The obtained Build Cost should, therefore, result in the target LOLE established in the region, which is called $TLOLE$.

These two techniques of the integrated optimisation approach, have been implemented in the evaluation of missing capacity in a Single-area generation expansion, and also represent the base for the iterative approach.

4.4.2. Missing Capacity methodology: Single-area generation expansion

As previously mentioned, this approach represents the required capacity to reach the reliability target in a specific region, by means of local generating capacity expansion. Given the scenario where a country is facing a reliability index, LOLE, higher than its national standard, the required amount of firm capacity to reduce the hours of LOLE to the level of the standard is the Missing Capacity of the country.
In this section, the process and the models followed for the calculation of the Missing Capacity will be introduced. First, the "Single Node Model - Shortfall constraint" approach will be explained followed by a variation of the approach based on the economic optimisation of the generator build cost. Both approaches are based on the evaluation method of integrated optimisation.

Single Node Model - Shortfall constraint

The focus on this approach is to obtain the missing capacity of the region by means of local generation expansion. The region selected for conducting the study has been Belgium (BE), in this specific study it presents 48.87h/year of LOLE (table 4.1), which is above the national target of 3h/year. Moreover, Belgium is a highly interconnected country, thus it also allows the analysis of how interconnections can affect adequacy.

For conducting the evaluation of missing capacity in a single area, the Integrated optimisation - Shortfall constraint method was applied. Moreover, a stochastic approach was selected, as introduced in section 4.4.1. Applying stochastic optimisation the optimum amount of generation required to reach a LOLE of 3h/year in Belgium for 2025, can be obtained, taking into account the uncertainty of the random variables, in this case, represented by 3 different climate years. The extra capacity required has to be optimal for different possible weather conditions projected for 2025, thus a different result for each simulation would not bring a meaningful solution. For this goal, the stochastic optimisation is presented as the optimal method, although given the high computational time and power required for conducting the stochastic analysis with 34 climate years, the research has been reduced to three. These climate years represent the most severe climatic conditions, and therefore, the highest capacity is required.

Methodology applied:

For obtaining the local generation capacity that is required above the already installed capacity in the country, and avoiding, at the same time, an increase in the unserved energy of the neighbours, a solution was found by isolating the node of study. To obtain the final solution, a process involving different models has to be conducted:

1. Simulation of the Base-Case European Model.
2. Single Node Model -Missing capacity problem.
3. Impact of capacity expansion in the MAF Base-Case Model.

The Missing Capacity problem is solved in the model representing the country of interest, the single node model. This means that the problem formulation is implemented in the mentioned model. The steps 1 and 3 serve as the preparation of input data into the Single Node Model, and the post validation of the capacity expansion result.

1. Simulation of the Base-Case European Model.

The Single Node Model aims to represent the specific country with the same conditions as when it is simulated in a European model. To this respect, the exchanges should be included in the one node model.

In order to account for the exchanges, as the Single Node Model cannot simulate the imports/exports with the rest of the areas, the exchanges are represented as fixed generation at the boundary node. The fixed generation is introduced into the Single Node Model as the hourly exchanges extracted from the Base-Case European model.

The Base-Case European Model is the representation of the European electricity market operations, hence the core optimisation is the unit commitment and economic dispatch problem. The objective of this model is to simulate the normal operations of the country of study, in this case Belgium, when is part of the European network, to then extract the hourly flows. With the incorporation of the hourly exchanges in the single node model, the base case conditions are reproduced avoiding the increment of imports to fulfil the reliability constraint. However, the exports are also limited in the model, for that reason a post validation in the MAF Base-Case Model can show the effect of the extra capacity in the rest of the perimeter.

Model Building – Base-Case European Model
The model has been built from the MAF 2018 model for the low-carbon 2025 scenario. The set up of the model was implemented as required for running stochastic simulations.

The input parameters included are explained in section 4.3, no additional parameters were defined, neither expansion candidates.

Simulation configuration
The simulation phase implemented in this model is the Long Term Plan. Although no capacity expansion problem is included in this step, as the objective is to use the flow results of this model as an input into the Single Node Model, the same conditions and features between models should be kept.

As the resolution of the results should be hourly, the chronology selected for the simulation is “Sampled chronology”. The chronology configuration controls how the load is modelled, either as Load Duration curves or the complete chronology. The sample type is set to days and 365 samples per year. The Sample chronology preserves the sample type data identically as the original, in this case days, but only a specific number of samples. By setting the number of samples to 365, the data is entirely reproduced, hence obtaining a full chronology.

Concerning the stochastic optimisation, it is set as scenario-wise decomposition (section 4.4.1). The stochastic variables simulated are the climate-dependent variables, the outages patterns are not included in this simulation. As it is explained in the problem formulation (4.6), the maintenance and forced outage rate are subtracted from the available energy, but random outage events are not modelled.

2. Single Node Model – Missing Capacity problem.

This model holds the core problem formulation, since it is applied in the different approaches. The Missing Capacity problem is implemented at this step. As a result, the required capacity to fulfil the 3h/year of LOLE in Belgium is obtained. As mentioned in the previous part, the exchanges are introduced as fixed generation at the node. Fixed generation is a PLEXOS property that allows to include extra generation embedded at the node. The total flows per hour obtained in the Base-Case European Model are introduced as time series input files. With this approach, the contribution of interconnection is aimed to be included to a certain extent.

Model Building – Single Node Model
As stated for step one, the model has been built from the MAF 2018 model for the low-carbon 2025 scenario. The set up of the model was implemented as required for running stochastic simulations.

As in this stage, the capacity expansion problem is implemented, several parameters should be added to the model. An expansion candidate has to be defined. The expansion candidate is the generator that can be built, it is defined by the maximum number of units allow to be built, the build cost, economic life and other elements that are presented in table 4.5.

Table 4.5: Defining parameters capacity expansion candidate: Missing Capacity generator.

Node	BE
Units	0
Max Capacity	100 MW
VO&M Charge	80 $/MWh
Build Cost	10100 $/kW
WACC	0%
Economic Life	1 year
Max Units Built	100

The Variable Operations and Maintenance (VO&M) charge selected, represents the highest short-run marginal cost (total variable cost) among all the generators of the node, Belgium. This is chosen in order to make the Missing Capacity generator behave as a peak unit. In this case 80$/kW is a cost 1$/kW higher than that of the most expensive generator in Belgium. The pricing method followed in the model is based on marginal cost. Therefore, defining the highest variable cost for the new units, makes the generator operates to avoid having unserved energy but not because is more cost-effective than other generators.

The build cost is a random value that represents a high cost. The goal of having a significantly high build cost is to force the optimisation to just build the minimum number of units required to cover all the hours with unserved energy, except for maximum 3h/year. The high build cost will result in the absolute minimum number of units that satisfies the problem constraints. With a lower build cost was observed that the number of units built were more than what was required for having 3h/year LOLE, thus being cost beneficial to build in excess than to have energy not served.

Apart from the expansion candidate, the Reliability Constraints (4.9), are defined in the model, allowing maximum 3h LOLE a year.

Simulation configuration
The Long Term Plan simulation is implemented. The Missing Capacity problem formulated in section 4.4.1 is solved in this model. The chronology configuration is defined as in the European Base-Case model, full chronology. For the stochastic optimisation, following the European Base-Case model, it is set to scenario-wise decomposition where the stochastic variables are represented by the climate-dependent variables. Each climate year represents a sample, equal probabilities were assigned to each sample.

3. Impact of capacity expansion in the MAF Base-Case Model.

As a validation process the results obtained in the previous step, the missing capacity, are introduced in the MAF 2018 model for low-carbon 2025 scenario. This is done in order to observe what is the influence on adequacy caused by this new installed capacity, in the neighbouring countries. Due to the previous simulation of a one node model, the cross-border exchanges between countries as a result of the additional capacity installed, are not reflected. This additional capacity can change the flows among the neighbouring countries, modifying their adequacy levels, Belgium that before was a net importer of electricity at times of system stress, can become a net exporter or increase its exports towards the rest of the countries, lowering the adequacy burden of the region. Moreover, in this model, the Monte Carlo method is conducted, implementing the forced outage patterns, thus the influence of these events on the capacity result can be also analysed.

Model Building – MAF Base-Case Model
The model employed in this stage is the MAF 2018 model with the input data of low-carbon 2025 scenario. As additional input, the missing capacity result of the previous step is included. This additional capacity is defined as a new generator at the node of study, Belgium. The behaviour of the power plant is modelled as a peak unit, as mentioned. Thus, the defining parameters of the Missing Capacity generator are the following:

Table 4.6: Defining parameters Missing Capacity generator (BE).

Node	BE
Units	*Missing Capacity result*
Max Capacity	100 MW
VO&M Charge	80 $/MWh

Simulation configuration
In this step, the simulation phases implemented are the Medium Term Schedule and Short Term Schedule. By means of the MT Schedule the mid/long term constraints and the storage (hydro) trajectories are simulated and transfer to the ST Schedule. The latter conducts a detailed, full chronology, unit commitment and economic dispatch. In the ST simulation phase the random forced outage events and the distributed maintenance events are simulated. Therefore, the Monte Carlo method is conducted in this simulation, implementing 20 outage patterns per sample, i.e. climate year.

In this case, the stochastic configuration is set to Sequential Monte Carlo. As a result, ST Schedule runs as many times as the number of samples, i.e. number of outage patterns times climate years.

Single Node Model - Economic optimisation

In the previous approach, Shortfall constraint, the Build Cost selected was a high value that would make the investment just profitable in order to fulfil the Reliability Constraint. Following the integrated optimization approach with the introduction of equation (4.20) the value of the Build Cost is determined as:

$$1\text{MW} \cdot Build\ Cost = VoLL \cdot 1\text{MW} \cdot LOLE \tag{4.21}$$

For the case of study VoLL=10000$/MWh, LOLE for Belgium=3h/year, thus:

$$1\text{MW} \cdot Build\ Cost = 3\text{h} \cdot 1\text{MW} \cdot 10000\$/\text{MWh} \tag{4.22}$$

Obtaining a Build Cost of 30000\$/MW, same as 30\$/kW.

With this approach the Reliability constraints are substituted by the correspondent build cost, constraining the loss of load expectation to 3h/year over all the samples. The implementation of this approach follows the same procedure as the Single Node Model - Shortfall constraint, namely steps 1, 2 and 3. Except for the addition of the Reliability Constraint in step 2, equation 4.9.

Methodology applied:

As mentioned in the previous paragraph the procedure conducted was the same as in the Single Node Model - Shortfall constraint approach:

1. Simulation of the Base-Case European Model.
2. Single Node Model -Missing capacity problem-Build Cost Variation.
3. Impact of capacity expansion in the MAF Base-Case Model.

The steps 1 and 3 are performed exactly in the same manner, hence the model building and simulation phases applied are explained in section 4.4.2. In step 2 some changes were implemented.

2. Single Node Model - Missing capacity problem-Build Cost Variation.

The variation introduced in this step is the substitution of the Reliability Constraint by the Build Cost obtained through the application of the equation (4.22). Before the direct implementation of the Build Cost, several test runs were conducted to verify that the behaviour of the model was aligned with the reasoning of the previous equations.

For these test runs the results of the base case of the Single Node Model were compared with the adequacy benefits achieved by the addition of 100MW of capacity. Table 4.7, presents both results:

Table 4.7: Belgium EENS and LOLE results of the Single Node Model 2025 before and after the addition of a new resource.

		ENS [GWh]			ENS hours [h]		
		Sample CY 1985	Sample CY 1986	Sample CY 2012	Sample CY 1985	Sample CY 1986	Sample CY 2012
Single Node Model	BE	320.82	161.93	146.63	120	50	51
Single Node Model after addition of 100MW		304.76	154.54	137.68	119	42	50

To compare the LOLE obtained in the simulations, after the addition of capacity, with the one expected from the theory, the equation (4.18) was applied using the values presented in table 4.7. The theoretical LOLE that should be achieved by the addition of 100MW into the system, was obtained:

Table 4.8: Theoretical LOLE resulted from the addition of a new resource.

	$\Delta EENS/\Delta k$
Sample CY 1985	160.59
Sample CY 1986	73.90
Sample CY 2012	89.49

Comparing these theoretical LOLE results with the hours of unserved energy of table 4.7, it can be observed that in the simulation the LOLE is further reduced. The unserved energy hours resulted in the model are between 35% and 80% less than what it is expected from the theory:

Table 4.9: Difference between the theoretical LOLE and the LOLE obtained by the addition of a new resource in the system.

	$\Delta EENS/\Delta k$	ENS hours [h]	Percentage of reduction
Sample CY 1985	160.59	119	35%
Sample CY 1986	73.90	42	76%
Sample CY 2012	89.49	50	79%

This variation of the results from what is expected from the theory can be explained due to the action of flexible resources such as hydro generation and the activation of demand side response. The generation of these resources can shift, making the new resource reduce the shortages by more than 100MW. Moreover, it should be noted that the distribution of EENS across time can be variable, hence it is not possible to have a direct relation between EENS and LOLE. For example, 50MW can solve all the EENS when there is 50MW/h and 50MW/h of unserved energy in two different hours, but in another case, there could be 100MW unserved energy in one hour. This, difference in distribution causes that the LOLE obtained can vary for the same capacity in different simulations.

To translate this divergence in results to the build cost, a build cost 80% higher than what was obtained in equation (4.22), 30$/kW, was established. Thus, a final build cost of 50$/kW was determined.

Model Building – Single Node Model-Build Cost Variation
As presented in section 4.4.2 the model has been built from the MAF 2018 model for the low-carbon 2025 scenario, making the required modification for running stochastic simulations.

The Missing Capacity problem is solved in this stage, being necessary to define an expansion candidate. In this case, the parameters that define the expansion candidate are the following:

Table 4.10: Defining parameters capacity expansion candidate: Missing Capacity generator-Build Cost.

Node	BE
Units	0
Max Capacity	100 MW
VO&M Charge	80 $/MWh
Build Cost	50 $/kW
WACC	0%
Economic Life	1 year
Max Units Built	100

In this implementation the Reliability Constraints are not included.

Simulation configuration
As explained in section 4.4.2, the Long Term Plan simulation phase with a full chronology is employed. The stochastic optimisation is as well set to scenario-wise decomposition.

Figure 4.7 represents the process conducted for the calculation of the Missing Capacity in the Single area approach, either through the shortfall constraint or the economic optimisation:

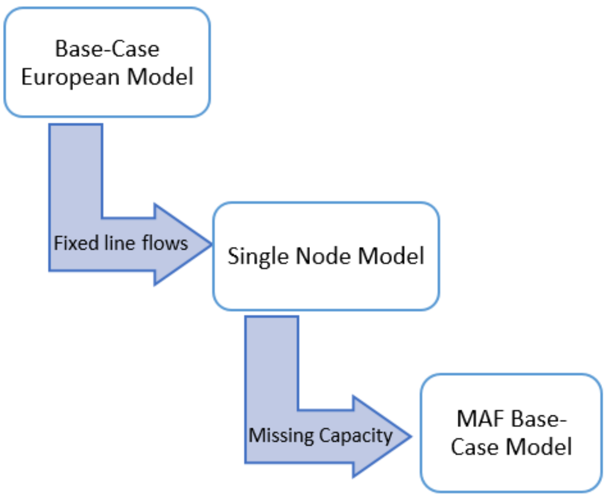

Figure 4.7: Single Node Model simulation process.

The simulation results obtained for the Single Node Model, in both of the approaches, are explained in chapter 5.

4.4.3. Missing Capacity methodology: Multi-area generation expansion

In this section, the Missing Capacity problem will be tackled from a multi-area perspective. First, the variations introduced in the Missing Capacity problem formulation will be introduced. Then, the models and the process followed for the evaluation of the missing capacity in a multi-area approach will be explained.

Problem formulation: iterative approach

The Missing Capacity multi-area problem represents the procurement of the required capacity to reach the reliability targets of two or more countries, by means of generation capacity expansion. Given the scenario where both countries are facing scarcity, with a reliability index, LOLE, higher than its national standard. This approach also accounts for the shared benefits of capacity expansion through the existing interconnectors.

The focus on this implementation has been put into the simulation of a two-area approach, so two neighbouring countries or market nodes.

To the general problem formulation, section 4.4.1, the difference implemented is that instead of just having a LOLE target for one country, in this case two reliability targets should be reached. Nevertheless, after the realisation of the limitations introduced by the implementation of the Reliability Constraints, the methodology selected follows an iterative approach. Therefore, the capacity expansion problem is not directly implemented. Instead, a direct increment of capacity in the areas studied is directly made by manually increasing the number of generating units. The increase is repeated computing the LOLE at each iteration until the reliability target is achieved.

It should also be defined, as it is introduced in the literature, a supporting policy between regions. In the case of study, the simulation of the electricity market is conducted, solving the UCED problem, thus a sharing policy is modelled. Under this policy, areas share shortages in proportion to their demands and the availability of interconnection capacity.

Two-area Model

The objective of this approach is to obtain the missing capacity of an area integrated by two countries. The capacity required to reach the reliability targets is represented by generation capacity expansion, either in one country or shared among both. The regions selected to conduct the study have been Belgium and the Netherlands. Both present LOLE values above their national standards (see table 4.1):

- Belgium presents a LOLE of 48.87h/year. Belgium national reliability standard: 3h/year LOLE.
- The Netherlands presents a LOLE of 8.08h/year. The Netherlands national reliability standard: 4h/year LOLE.

Moreover, both countries are interconnected and their power systems are similar in size.

In this approach the integrated optimisation approach is not applied, but an iterative approach is conducted as presented below.

Methodology applied:

To obtain the additional generation capacity that is required to reach the reliability target of two neighbouring countries, two iterative processes are conducted. This method makes use of the existing interconnections to share the benefits of capacity expansion. In that respect, two approaches aim to be tested:

A. Adequacy benefits for both regions by installing extra capacity in one node.

B. Adequacy benefits for both regions by installing extra capacity in both nodes.

These approaches aim to test if a generation source can contribute to the adequacy of one country not being necessary placed within its borders.

For obtaining the result of missing capacity, the following process has to be conducted:

1. Compute the Missing Capacity result from the Single Node Model-Shortfall constraint.
2. Follow an iterative process by increasing the capacity obtained in 1. until the targets of both countries are reached.
   (a) In the case of A, the iterative process is conducted in one node.
   (b) In the case of B, the result obtained in 1. is shared among the regions and by iterating, the capacity in both counties is increased.

The step one constitutes the process conducted for the approach presented previously (section 4.4.2), the Single Node Model. Once the Missing Capacity required for one node is obtained, that results becomes the starting point of the Two-area Model.

2. Follow an iterative process by increasing the capacity obtained in the Single Node Model until the targets of both countries are reached.

Model Building
For this method, the MAF 2018 model for low-carbon 2025 scenario is used. As an addition to the model, the result of the Missing Capacity problem is included. This means that extra capacity is included in one node, Belgium.

For conducting the iterative process, the capacity in that node is increased and the LOLE result for the two areas is computed. The target is to reach a LOLE of 3h/year in Belgium and 4h/year in The Netherlands.

In approach B, where the capacity expansion is shared, the base result obtained for the Single Node Model is shared among the regions. Once there are new generation units in both nodes, the increment of capacity starts in an iterative manner. At each iteration, the LOLE results are computed until the targets are achieved.

The new generators included in the model, represent peak units in both nodes, highest VO&M charge among national generators. Hence, the defining parameters of both power plants are as follows:

Table 4.11: Defining parameters Missing Capacity generators (BE & NL).

Node	BE	NL
Units	*Iterative increment of units*	
Max Capacity	100 MW	100 MW
VO&M Charge	80 \$/MWh	94 \$/MWh

Simulation Configuration
This step required the simulation of the Medium Term Schedule and Short Term Schedule. A detailed full chronology of unit commitment and economic dispatch is performed. Moreover, the Monte Carlo method is applied, with 20 outage patterns per sample.
The methodology followed for obtaining the Missing Capacity in a Multi-area approach can be seen in figure 4.8

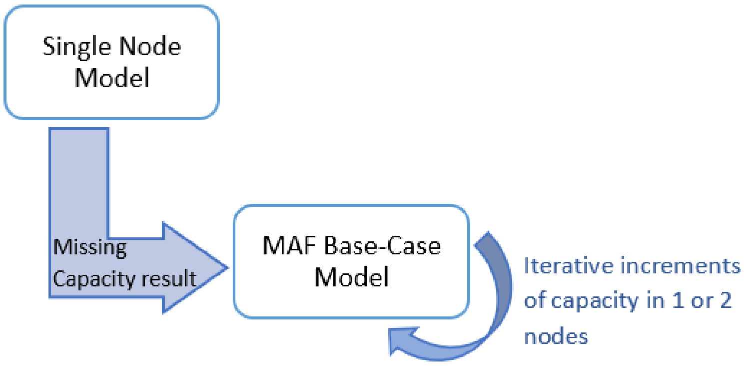

Figure 4.8: Two-area Model simulation process.

The results obtained in the two area approach can be seen in the chapter 5.

4.4.4. Missing Capacity methodology: Interconnection expansion

The Missing Capacity problem can be solved through generation capacity expansion or interconnection capacity expansion. After introducing the generation expansion option, this section will investigate the transmission expansion method. In this approach, the assessment is focused on the adequacy of a single-area and the effect of the cross-border expansion on the adequacy level.

First, the problem formulation will be introduced, based on the general Missing Capacity problem formulation. Then, the methodology applied will be explained, followed by its modelling implementation.

Problem Formulation: iterative approach.

The Missing Capacity- interconnection expansion problem represents the required capacity to reach the reliability target in a specific region, by a combination of generation capacity and interconnection capacity expansion.

The goal of this assessment is to evaluate if the required adequacy level of a country can be reached not only by an increment of the installed capacity of the region, but also by the increase of cross-border capacity between countries. The aim is to compute a sensitivity of generation capacity that could be replaced by transmission expansion. For this assessment, the focus is on a single-area and the sensitivity is computed per each interconnection.

The approach followed to evaluate the missing capacity through interconnection expansion, is based on an iterative process, rather than a direct integrated optimisation. The final solution to this approach accounts for both capacity and transmission expansion. The starting point of the iterative process is the solution of the Single Node Model. Once having the extra capacity required to reach the reliability target, the capacity is reduced by a fixed number of units to then conduct the sensitivity study of transmission expansion. The iterative process is performed by increasing the capacity of each interconnector separately, and computing the LOLE level at every iteration. The objective is to increase the cross-border capacity until the adequacy level reached by the addition of the missing capacity units, before the reduction, is achieved.

To summarize, the problem is based on a single area and generation/transmission capacity expansion options, the final goal of the problem being a sensitivity result of generation capacity that could be replaced by interconnection expansion.

Interconnection expansion Model

The goal of this approach is to obtain a sensitivity result of generation capacity that can be substituted by interconnection capacity, to reach the required reliability target. The final combination of generation and interconnection expansion represents the missing capacity of the area. The study has been conducted in Belgium and the sensitivity results are computed per interconnection. Before conducting the Missing Capacity

interconnection expansion study, possible expansion candidates should be identified. By analysing the use of interconnectors in the area of study the candidates that can result more suitable for conducting the study can be selected. Therefore, after identifying the expansion candidates the Missing Capacity analysis is conducted in each of those interconnectors.
To obtain the mentioned results, an iterative process has to be conducted as presented below.

Methodology applied:

To compute the sensitivity of interconnection capacity expansion, the following process should be conducted:

1. Compute the Missing Capacity result from the Single Node Model in the MAF Base-Case Model: Base-LOLE.

2. Reduction of the Missing Capacity units by a fixed amount.

3. Follow an iterative process by increasing the import capacity of each interconnection independently, until the Base-LOLE is reached.

1. Compute the Missing Capacity result from the Single Node Model: Base-LOLE.

The step one constitutes the process applied for the approach of the Single Node Model (section 4.4.2). The final step of such approach is to compute the Missing Capacity result into the MAF 2018 model for low-carbon 2025 scenario. The LOLE result obtained for Belgium in that stage represents the Base-LOLE. This Base-LOLE is the target value that is aimed to be reached through the interconnection expansion.

2. Reduction of the Missing Capacity units by a fixed amount.

To start the iterative process first a reduction on the installed capacity of the area should be made. To that end, the Missing Capacity units are reduced by a fixed amount in the MAF 2018 model for low-carbon 2025 scenario. In this case, the selected amount was 5 units, 500MW.

3. Follow an iterative process by increasing the import capacity of each interconnection independently, until the Base-LOLE is reached.

In this step, the iterative process is conducted with the objective of reaching the Base-LOLE value through interconnection expansion. This sensitivity analysis aims to reach the amount of interconnection capacity that can replace the 500MW of generation capacity and reach the same LOLE target. The final output will be a ratio between MW of interconnection capacity and MW of generation capacity, which quantifies the adequacy contribution of interconnection in comparison to the contribution of generation. The sensitivity is analysed per interconnection, i.e. the iterative process is first conducted in one interconnector, the results are analysed, and then, starting from the base situation the process is repeated on a different line.

Model Building
The implementation of this approach is made on the MAF 2018 model for low-carbon 2025 scenario. As an additional input, the Missing Capacity units are included in Belgium, after the correspondent reduction.

For conducting the iterative process, one interconnector is selected, and by blocks of a standard amount, like 100MW or 500MW, the import capacity of the line is increased. At each iteration the LOLE result for Belgium is computed. The objective is to reach the Base-LOLE value, which would represent the end of the iterative process.

The Missing Capacity generators are modeled as peak units. The defining parameters of the generators are the following:

Table 4.12: Defining parameters Missing Capacity generator (BE) - Interconnection expansion.

Node	BE
Units	*Missing Capacity Single Node Model result* - 5
Max Capacity	100 MW
VO&M Charge	80 $/MWh

Simulation Configuration
The simulation of the Medium Term Schedule and Short Term Schedule is implemented. A detailed full chronology of unit commitment and economic dispatch is performed. Moreover, the Monte Carlo method is applied, with 20 outage patterns per sample.
The process conducted for the evaluation of Missing Capacity considering interconnection expansion can be seen in figure 4.9

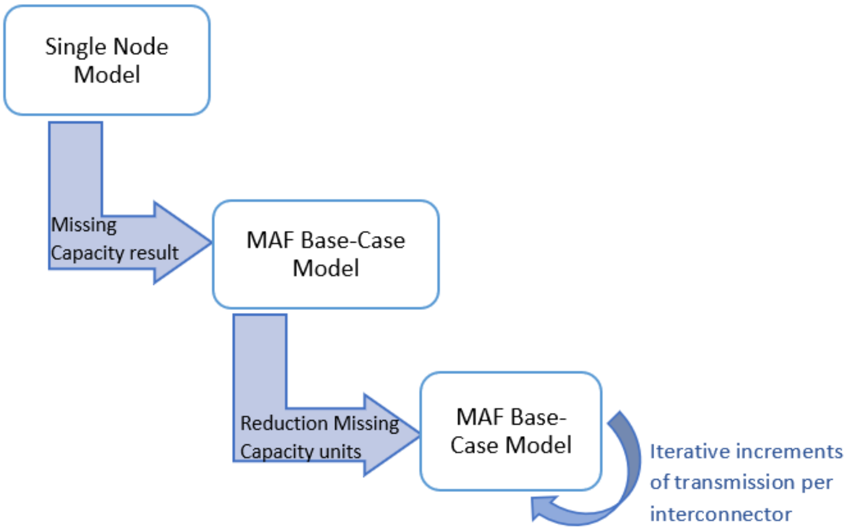

Figure 4.9: Two-area Model simulation process.

The simulation results obtained for the transmission expansion approach are presented in chapter 6, where also a previous study of the expansion candidates is conducted.

4.5. Summary

Chapter 4 introduces the concept of Missing Capacity and analyses the methodology for its assessment with the objective of answering the third sub-question: *Which are the different approaches to ensure the required level of system adequacy?*

Missing Capacity is introduced as a possible adequacy indicator that quantifies the required capacity to reach a defined reliability target in a specific region. It defines the capacity needed to achieve the required adequacy level in a future scenario. For the Missing Capacity evaluation, two main methods can be applied, an integrated optimisation approach or an iterative process. The evaluation is defined by the area considered, single area or multi-area, and the source of the required capacity, generation or transmission expansion.
In this chapter, the methodology identified for calculating the missing capacity in function of the object of study, area and capacity source, has been analysed. First, in a single area approach, two methods have been introduced. Both are solved through the integrated optimisation evaluation method, which is implemented on a linear programming optimisation model that performs the UCED problem as well as a capacity expansion problem, applying stochastic optimisation. On one hand, in the Single Node Model - Shortfall constraint the Missing Capacity problem is implemented by introducing the reliability target as a constraint in the model. On the other hand, by the Economic optimisation of the new generators Build Cost, the missing capacity is obtained without the need of introducing a constraint in the model. In both approaches the validation of results is performed conducting Monte Carlo simulations.
The calculation of missing capacity in a multi-area approach is introduced by the Two-area model. This method accounts for the contribution of interconnectors in sharing the benefits of the capacity expansion. In this approach, an iterative process is followed bringing two possible results: the achievement of the required reliability level in two areas by generation expansion in one node, or by sharing the extra capacity among the two nodes. Both solutions evidence the possible contribution of interconnectors to adequacy.
Finally, the methodology for the evaluation of missing capacity in a single-area by means of generation and in-

terconnection expansion is analysed. In this approach, the generation expansion result is computed for then conduct a sensitivity analysis of the cross-border capacity that can substitute generation capacity, achieving the same reliability target.
The following table presents an overview of the studies performed and their main features.

Table 4.13: Comparison of studies performed.

	Evaluation method	Reliability target area	Capacity Source	Methodology	Simulation phases & Outages	Horizon & Climate Years
Single Node Model – Shortfall constraint	Integrated optimisation approach-Shortfall constraint	Single-area	Generation capacity expansion	1. Simulation of the Base-Case European Model. 2. Single Node Model - Missing capacity problem. 3. Impact of capacity expansion in the MAF Base-Case Model.	1. LT plan – no outages. 2. LT plan – no outages. 3. MT+ST Schedule– 20 outage patterns.	2025. CY: 1985, 1986, 2012.
Single Node Model – Economic optimisation	Integrated optimisation approach–Economic optimisation	Single-area	Generation capacity expansion	1. Simulation of the Base-Case European Model. 2. Single Node Model - Missing capacity problem- Build Cost Variation. 3. Impact of capacity expansion in the MAF Base-Case Model.	1. LT plan – no outages. 2. LT plan – no outages. 3. MT+ST Schedule– 20 outage patterns.	2025. CY: 1985, 1986, 2012.
Two-area Model	Iterative approach	Multi-area	Generation capacity expansion	1. Compute Missing Capacity result from Single Node Model. 2. Iterative increments of capacity in one or two nodes.	1. LT plan & MT+ST Schedule– 20 outage patterns. 2. MT+ST Schedule– 20 outage patterns.	2025. CY: 1985, 1986, 2012.
Interconnection expansion Model	Iterative approach	Single-area	Generation and transmission capacity expansion	1. Compute Missing Capacity result from Single Node Model: Base LOLE. 2. Reduction of the Missing Capacity units. 3. Iterative increment of transmission capacity per interconnector.	1. LT plan & MT+ST Schedule– 20 outage patterns. 2. MT+ST Schedule– 20 outage patterns. 3. MT+ST Schedule– 20 outage patterns.	2025. CY: 1985, 1986, 2012.

5

Simulation Results: generation expansion

Following the methodology presented in the previous section, the content of this chapter will introduce the results derived from each approach. The simulation results obtained at each step will be presented, analysing the effect and implications behind the outcomes. In this chapter the Missing Capacity results obtained from the generation expansion approaches will be shown, tackling the interconnector expansion results in chapter 6.
As in chapter 4, first the results obtained for the Single-area approach will be presented, to conclude with the Two-area results.

5.1. Single-area generation expansion

The methodology identified for calculating the missing capacity in a single-area is based on the integrated optimisation approach. Two possible implementations of the mentioned approach were analysed. The first is based on the calculation of the missing capacity by the introduction of a reliability constraint, and the second by the optimisation of the new generators build cost. Both techniques solve the missing capacity problem of a single area by generation expansion. The simulation of the approaches was based on the Single Node Model. In the coming sections, the results of the Single Node Model for each of the techniques will be presented.

5.1.1. Single Node Model - Shortfall constraint

The methodology for the evaluation of missing capacity in the Single Node Model - Shortfall constraint is the following:

1. Simulation of the Base-Case European Model.
2. Single Node Model -Missing capacity problem.
3. Impact of capacity expansion in the MAF Base-Case Model.

The results obtained at every stage of the process are presented below.

After conducting the step 1 - "Simulation of the Base-Case European Model", the LOLE and EENS values for Belgium were obtained. In the second stage, Single Node Model – Missing Capacity problem, first, a test run was performed to prove that similar values to the Base-Case European Model were achieved. Both results can be observed in table 5.1

Table 5.1: Belgium EENS and LOLE results of the Base-Case European Model and Single-Node Model 2025.

		ENS [GWh]			ENS hours [h]			EENS [GWh]	LOLE [h/year]
		Sample CY 1985	Sample CY 1986	Sample CY 2012	Sample CY 1985	Sample CY 1986	Sample CY 2012		
Base-Case European Model 2025	BE	320.82	161.93	146.63	113	38	48	209.80	66.33
Single-Node Model 2025		320.82	161.93	146.63	120	50	51	209.80	73.67

It can be observed comparing both results, table 5.1, that the LOLE values diverge, not being exactly the same. Despite the difference in LOLE, the amount and total distribution among samples of ENS is preserved verbatim. The alteration in LOLE is explained by differences between the two models in the hydro generation production and the activation of Demand Side Response. Both resources operate at different moments in each model, inducing variations in the distribution of shortfalls, that result in different LOLE values. In spite of that, as the energy not served is kept the same, the reproduction of Belgium by a one node model can serve the purpose of the study. It should be noted that the core cost minimization problem optimises the total ENS of the system, not the LOLE.

After the validation of the test run, the Missing Capacity problem can be simulated. For the implementation of the problem, the expansion candidate is defined, as presented in table 4.5, and the Reliability Constraints for Belgium are as well established. The capacity required to reach a LOLE of 3h/year in Belgium, the Missing Capacity result, is the following:

Table 5.2: Result Missing Capacity in Belgium.

	ENS [GWh]			ENS hours [h]			Generation Capacity Built [MW]	EENS [GWh]	LOLE [h/year]
	Sample CY 1985	Sample CY 1986	Sample CY 2012	Sample CY 1985	Sample CY 1986	Sample CY 2012			
BE	6.86	0.00	0.00	3	0	0	4900	2.29	1

As it can be observed the result is 49 units, 4.9GW, are required in Belgium to comply with the reliability target of 3h/year LOLE under the scenario of low-carbon 2025. Note that as introduced in section 4.4.1, this approach constrains the results to 3h/year of unserved energy per sample, thus the capacity obtained reduces the LOLE below the target.

Once the missing capacity is obtained, the effect that the new capacity can have in terms of adequacy in the neighbouring countries is analysed by adding the calculated number of units, Missing Capacity units, to the MAF Base-Case model. By running this model also a more accurate result of the adequacy level achieved with this capacity can be analysed due to the use of the Short Term simulation, as well as the effect of the random outages.

Table 5.3 presents the EENS and LOLE values achieved by adding into the MAF Base-Case model 49 units of 100MW in Belgium, and the comparison with the results obtained in the low-carbon 2025 scenario without the additional units.

Table 5.3: Comparison EENS and LOLE results for low-carbon scenario 2025 before and after addition of Missing Capacity units.

Zone Code	Low-carbon 2025 scenario		Low-carbon 2025 after addition of Missing Capacity units	
	EENS [GWh]	**LOLE [h/year]**	**EENS [GWh]**	**LOLE [h/year]**
AL	0.01	0.03	0.00	0.00
AT	0.00	0.00	0.00	0.00
BA	0.00	0.00	0.00	0.00
BE	133.44	48.87	1.88	2.88
BG	0.17	0.43	0.10	0.25
CH	0.00	0.00	0.00	0.00

Zone Code	Low-carbon 2025 scenario		Low-carbon 2025 after addition of Missing Capacity units	
	EENS [GWh]	LOLE [h/year]	EENS [GWh]	LOLE [h/year]
CY	152.43	1244.78	152.43	1244.78
CZ	13.71	16.90	7.40	9.05
DE	9.63	4.18	4.60	2.28
DEkf	0.00	0.00	0.00	0.00
DKe	2.35	8.28	1.59	5.10
DKkf	0.00	0.00	0.00	0.00
DKw	1.01	3.67	0.68	2.43
EE	1.04	2.95	0.73	1.88
ES	0.00	0.00	0.00	0.00
FI	1.45	5.15	1.07	3.98
FR	262.86	45.67	168.16	31.87
FR15	1.87	30.47	1.61	28.75
GB	47.56	17.13	32.58	11.92
GR	0.06	0.20	0.06	0.20
GR03	2.61	55.83	2.50	55.50
HR	0.00	0.00	0.00	0.00
HU	0.00	0.03	0.00	0.00
IE	34.35	96.12	31.14	89.78
IS00	0.00	0.00	0.00	0.00
ITcn	13.92	24.93	9.54	18.20
ITCO	0.00	0.00	0.00	0.00
ITcs	0.22	0.47	0.25	0.52
ITn	59.07	24.43	37.08	17.33
ITs	0.00	0.00	0.00	0.00
ITsar	0.47	2.60	0.35	2.05
ITsic	0.12	0.62	0.10	0.53
LT	0.93	2.63	0.65	1.55
LUb	1.91	66.67	0.55	20.08
LUf	8.92	65.37	6.34	46.50
LUg	33.95	38.32	17.02	20.63
LUv	0.00	0.00	0.00	0.00
LV	0.08	0.32	0.11	0.27
ME	0.00	0.00	0.00	0.00
MK	0.06	0.38	0.02	0.13
MT	0.70	15.40	0.70	15.37
NI	6.74	42.65	5.68	35.62

Zone Code	Low-carbon 2025 scenario		Low-carbon 2025 after addition of Missing Capacity units	
	EENS [GWh]	LOLE [h/year]	EENS [GWh]	LOLE [h/year]
NL	7.65	8.08	5.05	4.87
NOm	0.00	0.00	0.00	0.00
NOn	0.00	0.00	0.00	0.00
NOs	0.00	0.00	0.00	0.00
PL	12.01	12.87	7.84	9.07
PT	0.00	0.00	0.00	0.00
RO	0.00	0.00	0.00	0.00
RS	0.00	0.00	0.00	0.00
SE1	0.00	0.00	0.00	0.00
SE2	0.00	0.00	0.00	0.00
SE3	0.00	0.00	0.00	0.00
SE4	0.96	1.28	0.66	1.00
SI	0.01	0.07	0.02	0.07
SK	1.64	2.50	1.41	2.13
TN00	0.20	1.03	0.20	1.02
TR	0.00	0.00	0.00	0.00

As it can be seen in the previous results, by the addition of the 4.9GW the LOLE of Belgium is reduced slightly below 3h/year. Therefore, after the validation in this model, applying the Monte Carlo method, the capacity result obtained in the Single Node Model constitutes an accurate solution to the Missing Capacity problem. Comparing these results with the base results from the low-carbon scenario 2025, it can be observed that the adequacy of the neighbouring countries also experiments an improvement.

In figure 5.1, the countries which adequacy levels experienced a larger improve after the capacity increase in Belgium can be identified.

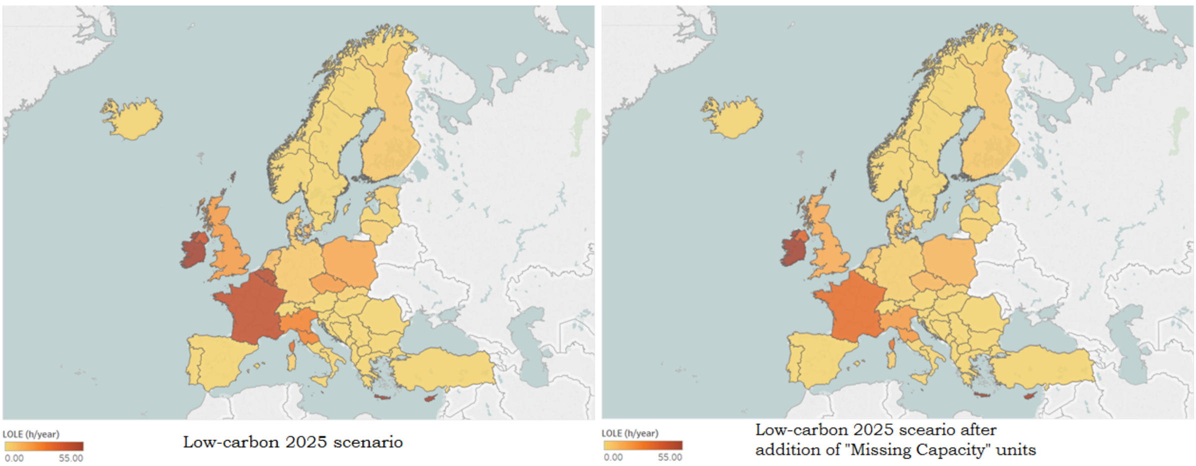

Figure 5.1: Comparison LOLE results for low-carbon 2025 scenario before and after the addition of Missing Capacity units.

It can be noted that the direct interconnected neighbours: France, the Netherlands, the United Kingdom, Germany and Luxembourg; experience a reduction on their LOLE values of 29% to 70%, Luxembourg being the country most benefited by the capacity increment. It also should be noticed the benefits of this capacity expansion to more peripheral regions like Portugal or Finland. This is due to the highly interconnected system, and also the change in the direction of exports that before were directed to the area that on the second case profits from extra capacity.

5.1.2. Single Node Model - Economic optimisation

The process defined for evaluating the missing capacity of a single-area through the economic optimisation of the generators build cost, is as follows:

1. Simulation of the Base-Case European Model.
2. Single Node Model - Missing capacity problem-Build Cost Variation.
3. Impact of capacity expansion in the MAF Base-Case Model.

Step 1 has been presented in the previous section 5.1, the main objective of this stage is to obtain the flow values for their implementation in the single node model.
The results obtained from the implementation of steps 2 and 3 of the procedure are explained below.

As introduced in section 4.4.2, the optimal value obtained for the generator build cost, was 50$/kW, with this cost the LOLE is directly reduced to approximately 3h/year without the necessity to introduce an explicit constraint. After running the simulation of the Missing Capacity problem with the build cost variation in place, the results of table 5.4 were obtained.

Table 5.4: Result Missing Capacity in Belgium. Single Node Model-Build Cost Variation.

	ENS [GWh]			ENS hours [h]			Generation Capacity Built [MW]	EENS [GWh]	LOLE [h/year]
	Sample CY 1985	Sample CY 1986	Sample CY 2012	Sample CY 1985	Sample CY 1986	Sample CY 2012			
BE	8.78	0.13	0.00	9	1	0	4700	2.97	3.33

The results of the Missing Capacity problem introducing the variation of build cost and not implementing the constraints that limit the LOLE in the country to 3h/year, present a capacity expansion that does not reach exactly the target of 3h/year of unserved energy. However, it can be determined that this estimation of the build cost, can provide a very close value of the missing capacity, which then can be validated in the MAF Base-Case model. Therefore, through this implementation is stated that 47 units, 4.7GW is the missing capacity in Belgium.

Through the implementation of the Missing Capacity outcome in the MAF Base-Case model, the influence of the outage patterns can be considered and the subsequent adjustments to the result can be made if needed.

Table 5.5 presents the EENS and LOLE results obtained in the MAF Base-Case model after the addition of 47 units of 100MW in Belgium.

Table 5.5: EENS and LOLE results for Belgium low-carbon scenario 2025 after addition of Missing Capacity units in the MAF Base-Case model.

	ENS [GWh]			ENS hours [h]			Missing Capacity units [GW]	EENS [GWh]	LOLE [h/year]
	Sample CY 1985	Sample CY 1986	Sample CY 2012	Sample CY 1985	Sample CY 1986	Sample CY 2012			
BE	6.41	1.03	0.10	8.25	2.40	0.20	4.7	2.51	3.62

It can be observed in the LOLE result that the target of 3h/year of unserved energy is surpassed. Despite that, the result of 3.62h/year LOLE is a reasonable result, through this implementation the optimisation is conducted as a minimization of total system cost, having a trade-off between the cost of lost load (VoLL) and the cost of a new unit, without direct constraint on the LOLE hours. Therefore, the LOLE resulted from the economic optimisation is expected not to be exactly 3h/year but an approximation. In response, an iterative process increasing the capacity by blocks of 100MW (one Missing Capacity unit) is conducted. The final result of the capacity required in Belgium to reach its reliability target of 3h/year LOLE, the Missing Capacity is shown in the table below, together with the LOLE and EENS values achieved.

Table 5.6: EENS and LOLE results for Belgium low-carbon scenario 2025 after adjustment of Missing Capacity units.

	Missing Capacity units [GW]	EENS [GWh]	LOLE [h/year]
BE	4.8	2.12	2.83

As it can be observed, the final result is 48 units, 4.8GW are required in Belgium to reach the adequacy target of 3h/year LOLE, under the low-carbon 2025 scenario.

Comparing the result of the Economic optimisation of build cost with the one obtained in the Single Node Model - Shortfall constraint, an original difference of two units was obtained, 47 respect to 49. After conducting the iterative process the difference is reduced to one unit. It should be clarified that in the Shortfall constraint approach the final result with 49 units was slightly below the target and no iterative process was conducted to bring the result closer to a LOLE of 3h/year. If an iterative process would have been performed in the Single Node Model - Shortfall constraint result, the same Missing Capacity solution would have been reached, 48 units. However, it should be mentioned the low responsiveness of the LOLE. While with 4.9GW installed the LOLE obtained is 2.88h/year, it goes to 2.83h/year with the installation of 4.8GW. Thus, showing a slight decrease of LOLE by the reduction of 100MW, which may seem contradictory. Despite that, the difference in EENS is more pronounced, showing that EENS is an index more responsive to the changes in capacity installed. The EENS achieved with 4.9GW installed is 1.88GWh, while with 4.8GW is 2.12GWh. This difference in the behaviour of LOLE and EENS metric is also presented in [47] which shows the difference of the adequacy contribution of storage when it is accounted through EENS or LOLE.

The Economic optimisation of build cost serves as a method to indirectly implement a constraint in the hours of unserved energy, allowing to respect the expectation nature of the LOLE metric. This approach accomplishes to lower the impact on results that the sample with the most extreme climate conditions can generate. Moreover, by avoiding the direct implementation of a constraint in the model, other interference in the dispatch of units can be avoided. Nevertheless, it should be noted that the founded build cost value of 50$/kW did not constitute a solution when simulating the problem in a pan-European model instead of a one node model. In the case of a pan-European model, this build cost seems to reduce the LOLE to less than 3h/year. As a result, the number of units built was more than what is required to achieve the target of 3h/year LOLE in Belgium, obtaining 0h/year of LOLE in Belgium and improving considerably the adequacy levels of the neighbouring countries. The non-responsiveness of such build cost can be due to the influence of other countries in the imports/exports and the action of their flexible resources.

5.2. Multi-area generation expansion

The Multi-area generation expansion method is based on the Two-area model. The missing capacity of two countries is evaluated, in this case, the countries studied are Belgium and the Netherlands. In this method, two approaches for evaluating the missing capacity considering a perimeter of two areas are analysed:

A. Adequacy benefits for both regions by installing extra capacity in one node.

B. Adequacy benefits for both regions by installing extra capacity in both nodes.

For obtaining the result of missing capacity, the following process is conducted:

1. Compute the Missing Capacity result from the Single Node Model-Shortfall constraint.
2. Follow an iterative process by increasing the capacity obtained in 1. until the targets of both countries are reached.
   (a) In the case of A, the iterative process is conducted in one node.
   (b) In the case of B, the result obtained in 1. is shared among the regions and by iterating, the capacity in both counties is increased.

The results obtained are divided among the two approaches: capacity expansion in one node, or capacity expansion in both nodes.

A. Adequacy benefits for both regions by installing extra capacity in one node.

In this method, the iterative approach was conducted in Belgium, as it is the node suffering more shortfalls, higher LOLE. The starting point of the iteration was the resulted 49 units, 4.9GW of capacity required in Belgium, which resulted in the following LOLE and EENS values for both countries.

Table 5.7: Belgium and Netherlands EENS and LOLE results of the Single Node Model.

	EENS [GWh]	LOLE [h/year]
BE	1.88	2.88
NL	5.05	4.87

As it is observed the LOLE value of the Netherlands is slightly above its target. After several iteration by blocks of 100MW, what it is the same to 1 extra unit, the final solution was reached at 53 units.

Table 5.8: EENS and LOLE results Two-area Model extra capacity in one node.

Zone Code	Missing Capacity units [GW]	EENS [GWh]	LOLE [h/year]
BE	5.3	0.70	1.22
NL	0	4.78	4.02

As shown by the results, the installation of 53 units in Belgium provides adequacy benefits to the Netherlands. By the addition of 5.3GW in Belgium, not only the reliability target of the country is fulfilled, but also the adequacy standard of the Netherlands is reached. It should be noted that the application of an iterative approach hinders the achievement of a fixed value, as the values obtained oscillate around the objective. As it is seen in this result for the Netherlands, a value slightly above the target of 4h/year is reached, but successive iterations bring the value below 4h/year, thus the exact solution for the granularity of the unit additions used, is tough to be reached.

This solution can lead to the conclusion that a generation resource can contribute to the adequacy status of the country where it is installed, and its interconnected neighbours. With this result the contribution of interconnectors to adequacy can be proved, indicating that the exclusion of interconnections in the national adequacy plannings can lead to a devaluation of the adequacy level of the country. It should be noted that the contribution of interconnections is to the extent of available interconnection capacity.

However, with this result can be observed that Belgium would profit from a situation of extra capacity, with a LOLE of 1.22h/year, below its standard. Hence, it is worth to analyse if there is a solution where both regions can share capacity and reach their target more efficiently.

B. Adequacy benefits for both regions by installing extra capacity in both nodes.

The results obtained in the Single Node Model, table 5.7, constitute the starting point of this method. First, the 49 units were distributed across both regions, and then the iterative process was conducted.

The first result obtained was by the distribution of 25 units in Belgium (2.5GW) and 24 units in The Netherlands (2.4GW). The following values resulted:

Table 5.9: First distribution of Missing Capacity units among two areas.

Zone Code	Missing Capacity units [GW]	EENS [GWh]	LOLE [h/year]
BE	2.5	9.33	7.53
NL	2.4	0.25	0.48

As it is observed, the amount of extra capacity in Belgium is not enough for reaching the LOLE target. Therefore, an iterative process increasing the units in Belgium while reducing the units in the Netherlands was performed. The selection of this approach was driven by the goal of finding an optimal solution that does not require the increase of capacity rather an optimal distribution of resources. Seeking to find the solution where one country can assist the other by sharing their capacity instead of having a capacity surplus in the overall region. The final result of the iterative process was the following:

Table 5.10: EENS and LOLE results Two-area Model extra capacity in two nodes.

Zone Code	Missing Capacity units [GW]	EENS [GWh]	LOLE [h/year]
BE	4.7	2.13	2.77
NL	0.2	4.34	3.97

The results show that to fulfil the target of 3h/year LOLE for Belgium and 4h/year LOLE in the Netherlands, 4.7GW are required in Belgium and 0.2GW in the Netherlands.

Comparing both results, table 5.8 and 5.10, it can be observed that option B reduces the capacity surplus of Belgium presented in option A and achieves as well an adequate reliability level. The reliability standards of both countries are reached in the two approaches. However, in option B the capacity installed is 400MW less. Both results show the possibility of achieving the required level of security of supply in an interconnected region by means of exogenous capacity. In option A, the Netherlands is able to reach its reliability target thanks to the capacity installed in Belgium, and in option B both countries can reach its reliability targets by sharing the extra capacity required. In both cases the solution accounts for the contribution of interconnectors to adequacy. Without considering interconnectors the capacity required in both countries would be higher resulting in capacity surplus in the area.
Option B is presented as a more efficient solution as it requires less extra capacity. Comparing this result with the one obtained in the Single Node Model, it can be seen that 4.9GW in Belgium fulfil the adequacy standard of the country, but leave the Netherlands above its standard, 4.87h/year LOLE. Contrary, by splitting the units among the two regions, and making use of the cross-border capacity, both adequacy targets are reached.

5.3. Summary

Chapter 5 presents the simulation results obtained after the implementation of the different methodologies identified for the assessment of Missing Capacity in a single or multi-area approach, through generation expansion.
The analysis of a single-area has been conducted through two different approaches, both of them bringing similar results. By the implementation of the Reliability constraint, the optimizer enforces the LOLE per sample to maximum reach the target value, generating a capacity result that is dictated by the capacity required under the most adverse climatic conditions. Contrary, the Economic optimisation of the new generator build cost, provides a solution that achieves the reliability target in expectation. Hence, it does not provide a result based on the sample with the extreme weather conditions.
The multi-area approach investigates the missing capacity solution in a perimeter of two areas. The results obtained show that the required adequacy levels in both countries can be achieved either by sharing the capacity across the area, or by the allocation of the extra capacity in one of the countries. This analysis makes use of the existing interconnectors to share the benefits of capacity expansion. From the results, it can be depicted that sharing the additional capacity across both countries achieves a more efficient solution requiring less units to accomplish the reliability standard of the two countries.
In all the approaches analysed, the results show the influence and effect that the adequacy situation of one country can have in the whole region. Europe being a highly interconnected area, the capacity addition or shortage in one country can indirectly affect the resource adequacy of its direct and indirect neighbours.

6 The role of interconnectors in system adequacy

As introduced in section 4.1, there are two possible sources of capacity expansion: generation and transmission. Having presented the method and results of the missing capacity evaluation by generation expansion, this chapter will focus on the contribution of interconnectors to adequacy, and the transmission expansion approach.

First, a sensitivity analysis based on the use of interconnectors during times of scarcity will be presented, with the objective of finding possible expansion candidates. Then, the interconnection expansion will be conducted and the methodology presented in section 4.4.4 will be applied to the interconnectors previously identified. The results and conclusions of this approach will be presented.

This chapter will tackle the fourth sub-question: *What is the role of interconnectors in contributing to system adequacy?*

6.1. Sensitivity analysis: contribution of interconnectors in times of scarcity

The contribution of interconnectors to security of supply is still not accounted in all European countries. Countries like Austria, Bulgaria, the Czech Republic, Latvia, Norway, and Spain do not consider interconnectors in their national adequacy studies [48]. Contrary, countries like Sweden, Slovakia or Greece, have recently introduced ways to account and model the interconnections in their adequacy studies. As a result of this consideration, the relevance of the adequacy results of these countries has improved. Therefore, it is worth to analyse the possible contribution of interconnectors to system reliability, and how is the use of the interconnectors in times of scarcity.

To that end, this section describes a sensitivity study on the action of interconnectors during shortfalls. The assessment is based on the simulation of the MAF 2018 model for the low carbon 2025 scenario, applying the climate year 1985 and 20 outages patterns. The focus of this study is on Belgium and its interconnected neighbours, thus Central Europe.

The results obtained from the model are the hourly values of the Available Capacity Reserves[6], the Net Interchange[7], the ENS, and the Flows per interconnector.

The expected interconnection values for 2025 in Belgium, represented by the Net Transfer Capacities are the following:

[6] Available Capacity Reserves= Available Capacity + Curtailable Load - Peak Load - Net Capacity Interchange.
[7] Region Net Interchange= Export-Imports

Table 6.1: NTC values for interconnectors of Belgium in 2025. Source:[49]

Border	NTC [MW]
BE-DE	1000
BE-FR	2800
BE-GB	1000
BE-LUB	380
BE-LUG	300
BE-NL	3400
DE-BE	1000
FR-BE	4300
GB-BE	1000
LUB-BE	0
LUG-BE	180
NL-BE	3400

Consequently, the interconnectors studied will be the ones between Belgium and Germany, France, the United Kingdom, the Netherlands, and Luxembourg.

First, an overview of the situation of Belgium when facing scarcity will be presented. To continue, an analysis per interconnector will be performed to find possible expansion candidates for the Missing Capacity study.

6.1.1. Analysis of Belgium during scarcity events

In times of scarcity in Belgium, unserved energy events, the average of imports from all the interconnected neighbours accounts for 28% of the import capacity of Belgium. This, in principle, lower percentage of imports can be explained by the occurrence of simultaneous scarcity events in some of the neighbouring Member States. This is the case of France, which in 71% of the cases when Belgium is facing scarcity, France is also presenting positive ENS values. The market node Luxembourg G experiences simultaneous scarcity with Belgium in 60% of the cases and Luxembourg B in 100% of the cases. The simultaneous scarcity of Luxembourg B is due to the fact that this market node is just characterized by demand, not having generation, and the only existent interconnection is with Belgium. Thus, LUB supply completely relies on Belgium. These two countries are the ones that present the highest alignment between their unserved energy events and those of Belgium. Table 6.2 present the percentage of cases when Belgium is facing ENS, and at the same time, one of its interconnected neighbours does it too.

Table 6.2: Percentage of occurrence of simultaneous scarcity events between Belgium and its interconnected neighbours.

Simultaneous scarcity of BE with...	
FR	71.12%
DE	3.88%
GB	26.84%
LUB	99.95%
LUG	60.01%
NL	6.57%

The high rate of simultaneous scarcity cases with France has a significant impact on the lower imports accounted in Belgium. The net transfer capacity FR-BE is the highest of Belgium neighbours, but the imports from France just occur in 7.47% of the cases when Belgium presents ENS. During those import moments, the average imported capacity is 1500.14 MW, being far less than the maximum of 4300MW. This can be explained due to unavailability of generating margin in France to supply Belgium.

Contrary, countries like the Netherlands or Germany export to Belgium in 52% and 79% of cases when the country is facing scarcity, having low values of simultaneous scarcity events.

Table 6.3 presents the percentage of cases when Belgium is facing shortfalls and it is importing from the neighbouring countries.

Table 6.3: Percentage of hours where Belgium has unserved energy and it is importing energy from its neighbours.

From	BE Importing
FR	7.47%
DE	52.14%
GB	42.33%
LUG	31.42%
NL	78.69%

Focusing on the use of each interconnector when Belgium experiences unserved energy, it can be seen in table 6.4 the percentage of the cases when the interconnector is conducting the full capacity (NTC). As it is mentioned before, the low usage of the line BE-FR and BE-LUG is due to the high percentage of simultaneous scarcity events and the low availability of generation margins. In the case of Germany and the United Kingdom, the use of these interconnectors is quite high, being almost saturated during importing moments. Therefore, this suggests that a subsequent study of the adequacy benefits that could bring an increment in the cross-border capacity between BE-DE and BE-GB could bring meaningful results.

Table 6.4: Percentage cases the interconnector is being used at its maximum capacity when BE is importing.

Line	Full use of interconnector when importing
BE-FR	7.33%
BE-DE	94.56%
BE-GB	74.71%
BE-LUG	0.95%
BE-NL	42.28%

This first overview of the situation of Belgium when it presents unserved energy, leads to the conclusion that high alignment in scarcity events, climate correlation, between regions can result in lower use of the interconnection capacity. This lower use is either in terms of the times the interconnector is being used or the capacity that is carried through the line. Contrary, the regions that present lower simultaneity in their scarcity periods, show higher potential of transmission capacity. This is reflected in the use of the interconnections between those areas, which are highly used during scarcity and with values closer to the line NTC. Overall, the interconnection between the Netherlands, Germany and the United Kingdom present a larger contribution to the system adequacy of Belgium, than those of France and Luxembourg. Thus, additional cross-zonal capacity between France or Luxembourg and Belgium, is unlikely to yield significant adequacy benefits.

Following this conclusion, a detailed analysis of the use of the transmission lines BE-DE, BE-GB and BE-NL will be introduced.

6.1.2. Interconnector BE-DE

Belgium and Germany do not present a high rate of simultaneous scarcity, just in 3.88% of the cases when Belgium is affected by unserved energy, so does Germany. Although, during the scarcity periods of Germany, Belgium is usually under shortage as well, in 83.87% of the cases. These values suggest that the use of the transmission capacity would be more profited by Belgium than Germany.

In order to have more insights about the adequacy contribution of interconnectors in each country, as well as the usage of the specific transmission line to evaluate its potential as expansion candidate, the average amount of imports in several situations is computed. In each case, the study is conducted between two interconnected countries in the following situations:

1. Average total imports during local ENS: total average of imports, considering all interconnectors, when one of the two studied countries presents ENS and the other does not.

2. Average total imports during simultaneous ENS between Belgium and Germany: total average of imports of Belgium or Germany, considering all interconnectors, when there is simultaneous scarcity between the studied countries, i.e. ENS in Belgium and Germany at the same time.

3. Average total imports during ENS: total average imports, considering all interconnectors, when the country of study, Belgium or Germany, presents unserved energy, independently of the situation in the neighbouring countries.

4. Average imports from the interconnector BE-DE, during ENS: average imports from the transmission line of study when each of the countries has ENS, independently of the situation in the neighbouring countries.

Case 1 and 3 will give an estimation of the contribution of interconnectors to the national security of supply. Case 4 will provide insight on the usage of the particular line, and additionally by comparing cases 1 and 2 the impact of the interconnector to the national adequacy can be observed.

The results of these cases are represented in figure 6.1 and 6.2, based on the data shown in table 6.5 and 6.6.

Table 6.5: Average imports Belgium & Germany under several cases.

		Belgium [MW]	**Germany [MW]**
	Average total imports local ENS	2886.49	10947.10
	Average total imports during simultaneous ENS	687.55	10343.34
Total imports during ENS	Average imports	2801.08	10440.72
	Percentage of NTC	28.35%	27.69%
Imports from the line BE-DE during ENS	Average imports	974.57	0.00
	Percentage of NTC	97.46%	0.00%

Table 6.6: Belgium & Germany import capacities.

	Belgium [MW]	**Germany [MW]**
Total import capacity	9880	37700
Import capacity line BE-DE (NTC)	1000	1000

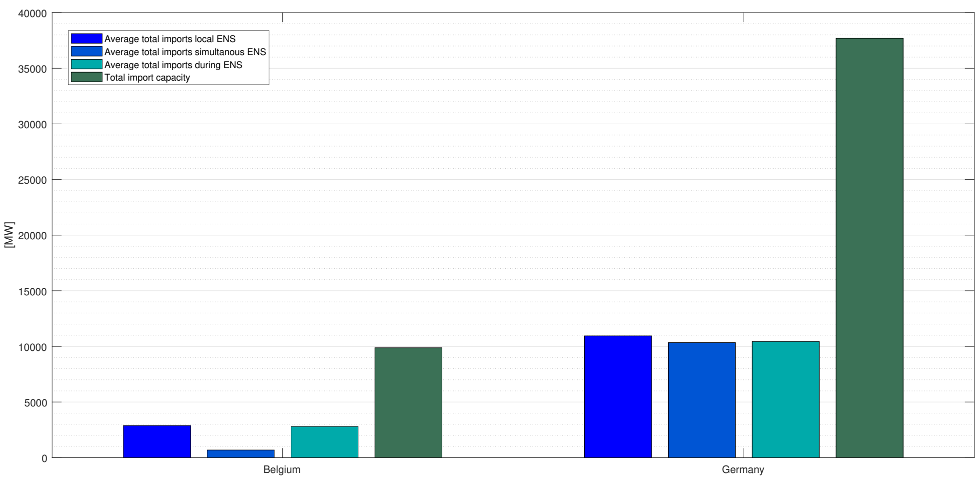

Figure 6.1: Average imports Belgium & Germany under several cases.

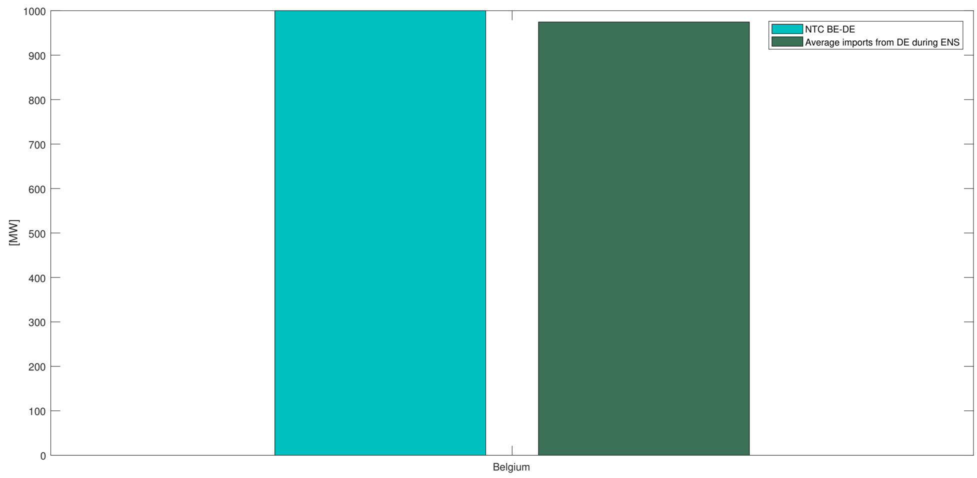

Figure 6.2: Average imports interconnector BE-DE.

From figure 6.1, it can be observed that there is a slight difference between the average imports during times of ENS or local ENS, for both countries. This is due to the low simultaneous scarcity between countries, which allows Belgium to import from Germany in most of the cases when it is experiencing unserved energy. In the case of Germany, this low difference is due to the fact that it is never importing from Belgium, thus the level of imports does not change depending on the scarcity situation of Belgium. It can be stated that the contribution of interconnectors to adequacy is similar in the two countries, accounting both around 28% average usage of their total import capacity during ENS events.

The contribution of German exports to Belgium has a significant impact on the average imports of Belgium, as it can be depicted from the graph. During simultaneous scarcity the average imports of Belgium drop by 75%. This effect together with the average usage of the line, 97.46% of the NTC, presents the high contribution of this particular interconnector to the adequacy of Belgium. The average imports of the line being close to the total NTC, shows that the interconnector can be frequently congested. Therefore, the increment of cross-border capacity between those countries could bring additional adequacy benefits for Belgium, representing a possible expansion candidate.

6.1.3. Interconnector BE-GB

Belgium experiences simultaneous scarcity with the United Kingdom in 26.84% of the moments when it is facing ENS. However, in around 42% of the scarcity events, Belgium imports from the United Kingdom, and it does it using the full capacity of the interconnector in the majority of cases, 75%. From these factors, the transmission line BE-GB could represent a potential expansion candidate, and its analysis could bring insights to the adequacy benefits that it could bring.

Following the same analysis as for Germany, the results of the average imports under the four different situations are presented in the tables below.

Table 6.7: Average imports Belgium & United Kingdom under several cases.

		Belgium [MW]	**United Kingdom[MW]**
	Average total imports local ENS	3132.23	3836.90
	Average total imports during simultaneous ENS	1898.55	3190.48
Total imports during ENS	Average imports	2801.08	3236.18
	Percentage of NTC	28.35%	30.02%
Imports from the line BE-GB during ENS	Average imports	858.60	135.96
	Percentage of NTC	85.86%	13.60%

Table 6.8: Belgium & United Kingdom import capacities.

	Belgium [MW]	**United Kingdom[MW]**
Total import capacity	9880	10780
Import capacity line BE-GB (NTC)	1000	1000

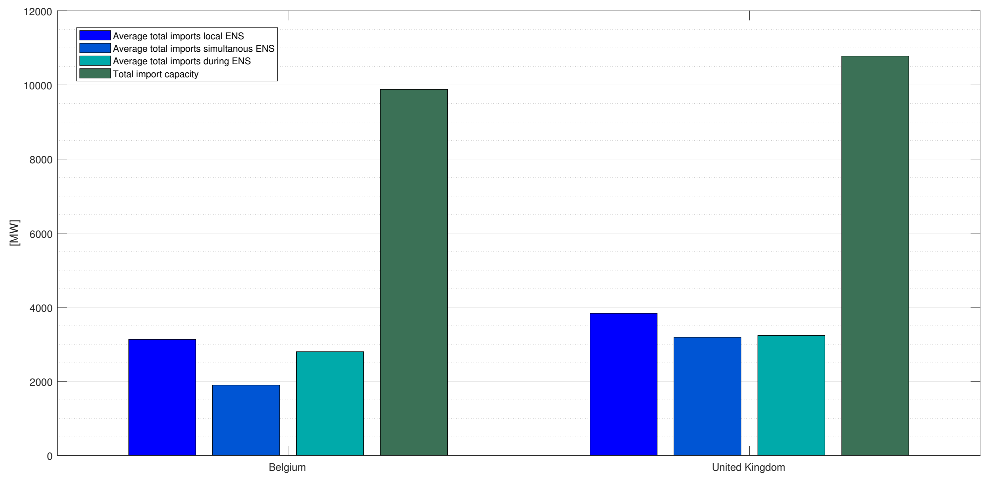

Figure 6.3: Average imports Belgium & United Kingdom under several cases.

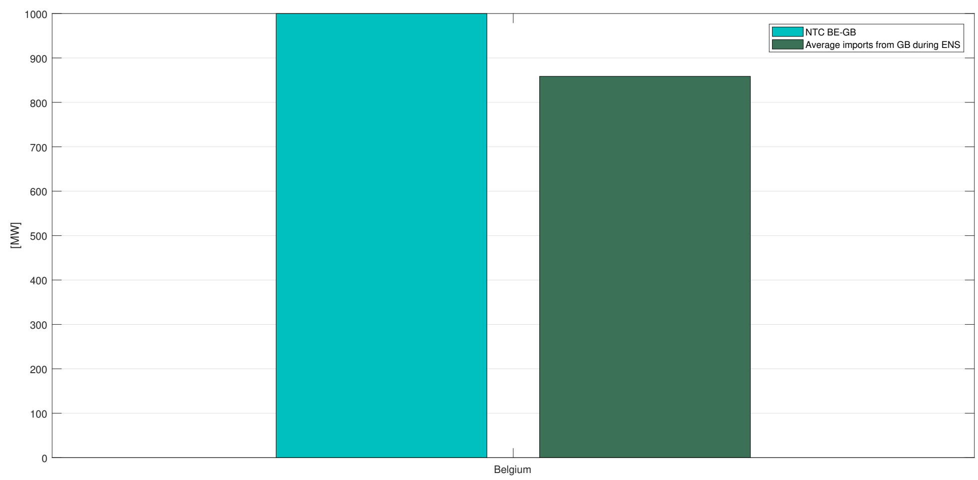

Figure 6.4: Average imports interconnector BE-GB.

In this case, as well as for the previous assessment of Germany, the difference between the average imports during ENS and local ENS does not notably differ. The reason is the no so frequent moments of simultaneous scarcity, which allows having imports from the United Kingdom in a significant percentage of the moments with ENS in Belgium. It can be stated that in both cases the use of interconnectors is not significantly high, accounting for 28% of the total import capacity of Belgium, and 30% for the United Kingdom.

Focusing on the contribution of this specific interconnector, BE-GB, it can be observed that the average usage of the interconnector in the direction GB-BE is close to its full capacity, 85.86% of NTC. As for the contribution of the interconnector to the security of supply of the United Kingdom, it is significantly lower, accounting the average imports for 13.6% of the NTC. Analysing the average imports during simultaneous scarcity, the previous remarks are confirmed, the use of the interconnector is higher in the direction of Belgium, experiencing a larger drop of imports in comparison to the United Kingdom.

Overall, the interconnector BE-GB is efficiently used in the direction GB-BE, so that it is possible, in principle, to obtain adequacy benefits with the increment of the cross-border capacity.

6.1.4. Interconnector BE-NL

Belgium presents a low rate of simultaneous scarcity events with the Netherlands, 6.57% of the cases. Contrary in most of the moments when the Netherlands faces scarcity, Belgium experiences the same situation. This is due to the lower LOLE values for the Netherlands in comparison to the ones of Belgium, under this study case.

The use of the interconnector BE-NL during unserved energy events in Belgium is significant, being used in around 79% of the scarcity events. However, the use of its entire capacity is quite below the maximum, 42.28% of its NTC. This result, despite the low simultaneity of scarcity events, can be explained due to the non-availability of capacity in the Netherlands.

To have a more detail analysis, the previous four cases are studied, bringing the following results:

Table 6.9: Average imports Belgium & Netherlands under several cases.

<table>
<tr><th></th><th></th><th>Belgium [MW]</th><th>The Netherlands [MW]</th></tr>
<tr><td></td><td>Average total imports local ENS</td><td>2950.26</td><td>1148.26</td></tr>
<tr><td></td><td>Average total imports during simultaneous ENS</td><td>680.89</td><td>919.38</td></tr>
<tr><td rowspan="2">Total imports during ENS</td><td>Average imports</td><td>2801.08</td><td>953.34</td></tr>
<tr><td>Percentage of NTC</td><td>28.35%</td><td>8.83%</td></tr>
<tr><td rowspan="2">Imports from the line BE-NL during ENS</td><td>Average imports</td><td>2290.81</td><td>220.81</td></tr>
<tr><td>Percentage of NTC</td><td>67.38%</td><td>6.49%</td></tr>
</table>

Table 6.10: Belgium & Netherlands import capacities.

	Belgium [MW]	The Netherlands [MW]
Total import capacity	9880	10800
Import capacity line BE-NL (NTC)	3400	3400

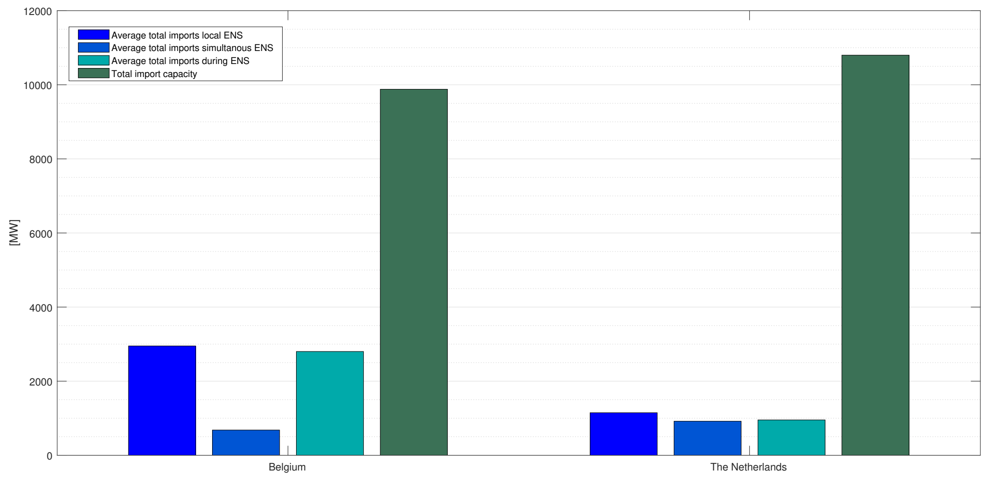

Figure 6.5: Average imports Belgium & Netherlands under several cases.

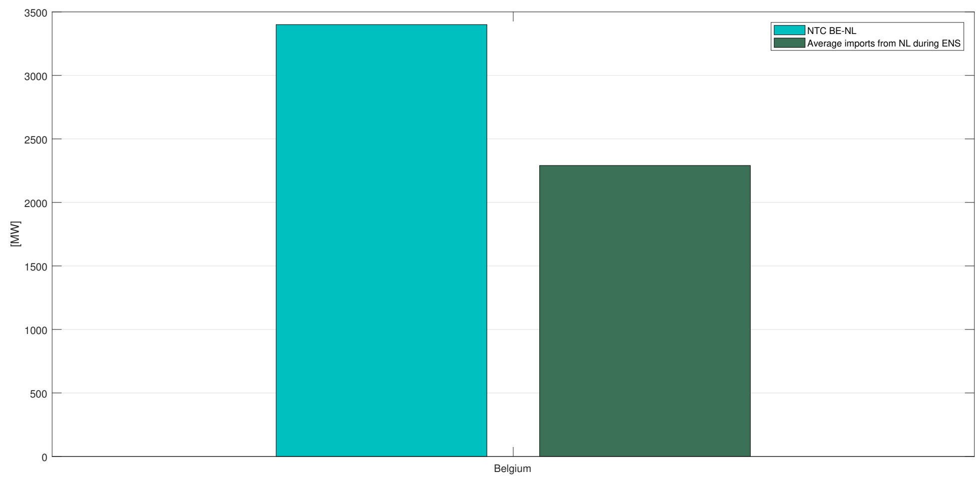

Figure 6.6: Average imports interconnector BE-NL.

As explained in the previous cases, the difference between the average total imports during ENS and local ENS is not significant. In this case, there is a difference in the contribution of interconnectors to each country. On one hand, in Belgium, as already presented, average imports account for 28% of the import capacity of the country. On the other hand, for the Netherlands imports only account for 9% of its total import capacity. Hence, the contribution of interconnectors to the adequacy of the Netherlands is not substantial.

Regarding the interconnector BE-NL, it is frequently used during scarcity periods in Belgium, but as stated before the capacity used during the imports is far from its maximum capacity. 67% of the import capacity of Belgium, from the Netherlands, is used in scarcity moments, while for the Netherlands the value drops to 6% of the NTC. Therefore, the contribution of the interconnector to security of supply is higher in the case of Belgium.

Analysing the results of the three interconnectors, the cross-border areas of BE-DE and BE-GB represent potential expansion candidates. While the use of the line BE-NL is significant, it is not used to full capacity. The high capacity transmitted in the lines BE-DE and BE-GB shows the possibility of having congested lines, thus an increment of transmission capacity could bring additional adequacy benefits. Contrary, the results of the Netherlands present the non-availability of resources in the country in order to share capacity with Belgium, hence an increase in cross-border capacity does not seem to bring additional adequacy benefits.

6.2. Simulation Results: interconnection expansion

This section will present the results obtained by the interconnection expansion. First, following the findings of the previous section, an increase in the transmission capacity of the interconnector will be conducted. Second, a combination of interconnection and capacity expansion will be presented through the evaluation of Missing Capacity.

6.2.1. Interconnection expansion

Following the study of the contribution of interconnectors in times of scarcity, the interconnection expansion is analysed on the previously identified expansion candidate, line BE-DE. This interconnector was selected since Germany presents the lowest simultaneity with the scarcity events of Belgium.
The objective of this study is to analyse if the increment of cross-border capacity brings adequacy benefits for the studied country and compare it with the adequacy level reached by the generation expansion approach. The assessment is focused on the adequacy effects on a single-area, in this case, Belgium. The methodology applied to compute the interconnection expansion is as follows:

1. Iterative process by increments of 500MW of the interconnector capacity.

For the simulations, the MAF Base-Case Model with no additional generation capacity in Belgium was used. The analysis of the contribution of interconnectors in times of scarcity that led to the identification of the expansion candidates was based on the climate year 1985. Hence, to base the interconnection expansion on the same data, and due to timeframe of this thesis and the computational time required for conducting such an iterative process, the evaluation of interconnection expansion is performed for the target year 2025 build upon the climate year 1985 and 20 outage patterns.

In the model building phase, the definition of the expansion line is required. The original line BE-DE was preserved and an additional line in which to conduct the iterative process was created. The defining data of each line can be seen in table 6.11.

Table 6.11: Defining parameters lines BE-DE & transmission expansion BE-DE.

Line	**BE-DE**	**Expansion candidate BE-DE**
Max Flow	1000 MW	0 MW
Min Flow	-1000 MW	*Iterative capacity increment* MW
Wheeling Charge	0.01 $/MWh	
Wheeling Charge Back	0.01 $/MWh	
Forced Outage Rate	2%	–
Mean Time to Repair	168h	–

It should be noted that the increment in interconnection is done unidirectional, in the direction towards Belgium, thus increasing the import capacity. As it is indicated in table 6.11, only the parameter "Min Flow", that represents the flow in the counter-direction, is increased.

The addition of cross-border capacity brought the following results:

Table 6.12: Belgium & Germany results iterative increment interconnector BE-DE without Missing Capacity units.

		BE				DE			
Interconnector Capacity [MW]	Increment interconnection [MW]	LOLE [h/year]	EENS [GWh]	ΔLOLE	ΔEENS	LOLE [h/year]	EENS [GWh]	ΔLOLE	ΔEENS
1000	0	98.70	244.32			4.45	7.88		
1500	500	88.50	224.42	-10.33%	-8.14%	8.10	17.40	82.02%	120.83%
2000	1000	81.70	211.11	-7.68%	-5.93%	8.00	16.72	-1.23%	-3.87%
2500	1500	77.55	207.44	-5.08%	-1.74%	8.15	16.46	1.88%	-1.59%
3000	2000	73.95	201.31	-4.64%	-2.95%	8.50	17.56	4.29%	6.67%
3500	2500	70.25	198.08	-5.00%	-1.61%	7.45	16.50	-12.35%	-6.03%
4000	3000	68.50	198.63	-2.49%	0.28%	7.75	16.12	4.03%	-2.30%
4500	3500	68.35	201.06	-0.22%	1.23%	7.45	17.65	-3.87%	9.52%
5000	4000	66.65	198.19	-2.49%	-1.43%	7.80	19.37	4.70%	9.74%

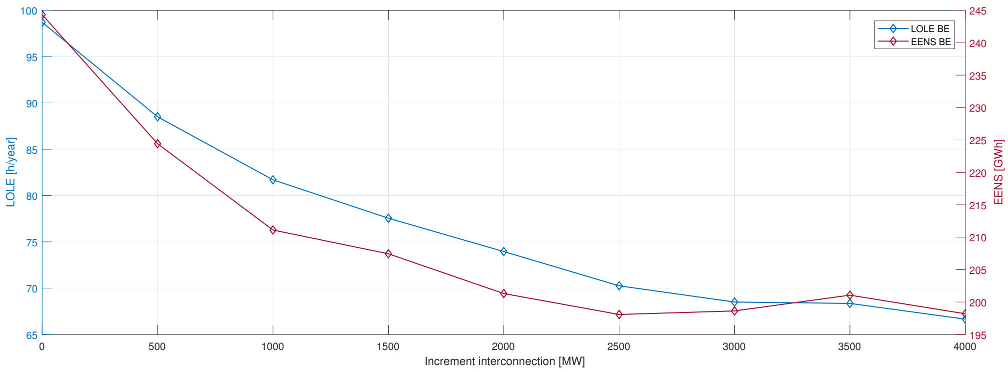

Figure 6.7: Belgium LOLE & EENS results iterative increment interconnection BE-DE without Missing Capacity units.

Analysing the results it can be stated that, in this case, the increase of the interconnection capacity between BE-DE in the direction towards Belgium brings adequacy benefits to Belgium. The LOLE of Belgium is reduced by 32.47% by the addition of 4000MW of cross-border capacity, the reduction is 18.88% in terms of EENS. Therefore, in this case the contribution of interconnections to adequacy is notable. These results reflect the dependence of the interconnection contribution on the correlation of the scarcity events among countries, and the difference in their adequacy levels. Additionally, it can be observed that the adequacy contribution is reduced as capacity increases, approaching to a steady LOLE and EENS curve. This indicates that probably further transmission increment would not bring considerable reliability benefits. By studying the use of the interconnection through its congested[8] hours, figure 6.8, the previous observation is sustained. The hours congested follow a decreasing trend as the interconnector is increased, thus it can imply that with further increment not higher use of the interconnector will be incurred.
It should also be noted that the adequacy benefit in Belgium comes with a substantial detriment of the reliability levels of Germany, as it is presented in table 6.12.

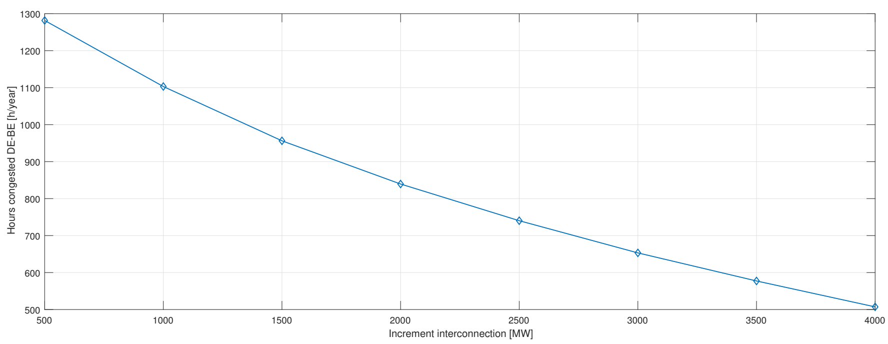

Figure 6.8: Congested hours interconnection BE-DE in DE-BE direction without Missing Capacity units.

Comparing this LOLE and EENS results with the ones obtained in the generation capacity expansion by the addition of 4.9GW. It can be seen that the adequacy benefits brought by the transmission capacity are less significant than those of the generation capacity. By the increase of 4GW transmission capacity, a LOLE of 66.65h/year is achieved, while with 4.9GW of generation capacity 4.86h/year LOLE is achieved. Therefore from that comparison it is derived that the same level of adequacy is far from being achieved by interconnection expansion. Moreover, as previously mentioned the steadiness that the LOLE and EENS curves reach by the increment of line capacity, might indicate that additional increments would not bring a major reduction on the reliability indicators.

6.2.2. Missing Capacity evaluation: interconnection expansion

The methodology applied for computing the sensitivity of interconnection capacity expansion, as introduced in section 4.4.4, follows the process:

1. Compute the Missing Capacity result from the Single Node Model in the MAF Base-Case Model: Base-LOLE.
2. Reduction of the Missing Capacity units by a fixed amount.
3. Follow an iterative process by increasing the import capacity of each interconnection independently, until the Base-LOLE is reached.

The aim of this method is to compute a sensitivity of generation capacity that could be replaced by transmission expansion reaching the same adequacy result. For this assessment, the focus is on a single-area and the sensitivity is computed per each interconnector.

For the simulations the MAF Base-Case Model was used, for the target year 2025 based on the climate year 1985 and with 20 outage patterns. In the model building phase, apart from the definition of the Missing Capacity generator, required in steps 1 and 2, the definition of the expansion lines is needed.
In the case of study, the interconnectors identified as possible expansion candidates, as previously explained, have been the interconnectors BE-DE and BE-GB. Following the same procedure as in 6.2.1, to conduct the iterative process the original lines were preserved, and two additional lines, one at each interconnector, were added with increasing capacities by 500MW blocks. As in the previous case, the increment is applied on the import capacity of Belgium. The data defining each line can be observed in the following tables:

Table 6.13: Defining parameters lines BE-DE & BE-GB.

Line	**BE-DE**	**BE-GB**
Max Flow	1000 MW	
Min Flow	-1000 MW	
Wheeling Charge	0.01 $/MWh	
Wheeling Charge Back	0.01 $/MWh	
Forced Outage Rate	2%	
Mean Time to Repair	168h	

Table 6.14: Defining parameters transmission expansion candidates.

Line	**BE-DE**	**BE-GB**
Max Flow	0 MW	
Min Flow	*Iterative capacity increment* MW	
Wheeling Charge	0.01 $/MWh	
Wheeling Charge Back	0.01 $/MWh	
Forced Outage Rate	0%	

[8]Hours congested: number of hours the line is at its maximum or minimum flow.

From the computation of step one, the Missing Capacity result obtained in the Single Node Model - Shortfall constraint, an addition of 4.9GW, 49 units, was made into the MAF 2018 model. Table 6.15 presents the Base-LOLE achieved for the sample of the climate year 1985.

Table 6.15: Base-LOLE result in Belgium.

	EENS [GWh]	LOLE [h/year]	Missing Capacity units
BE	4.86	6.95	49

After the reduction of 5 units, 500MW, the Missing Capacity result, the LOLE value obtained in Belgium was the following:

Table 6.16: LOLE Belgium, Germany & the United Kingdom after reduction of Missing Capacity units.

	EENS [GWh]	LOLE [h/year]	Missing Capacity units
BE	9.65	9.90	44
DE	4.48	2.5	–
GB	49.95	21.35	–

Once made the reduction of the Missing Capacity units, the iterative process to reach the Base-LOLE was conducted at each interconnector, bringing the results presented below.

Interconnector BE-DE

Table 6.17: Belgium results iterative increment interconnector BE-DE.

BE	Cross-border Capacity [MW]	Increment interconnection [MW]	LOLE [h/year]	EENS [GWh]	EENS/Annual demand [%]
44 Missing Capacity units	1000	0	9.90	9.65	0.011%
	1500	500	12.10	11.60	0.014%
	2000	1000	11.25	10.94	0.013%
	2500	1500	11.30	9.76	0.011%
	3000	2000	11.20	10.56	0.012%
	3500	2500	11.40	10.64	0.012%
	4000	3000	12.45	11.39	0.013%
	4500	3500	11.10	10.76	0.013%
	5000	4000	11.65	10.17	0.012%

Interconnector BE-GB

Table 6.18: Belgium results iterative increment interconnector BE-GB.

BE	Cross-border Capacity [MW]	Increment interconnection [MW]	LOLE [h/year]	EENS [GWh]	EENS/Annual demand [%]
44 Missing Capacity units	1000	0	9.90	9.65	0.011%
	1500	500	11.80	11.84	0.014%
	2000	1000	11.70	11.28	0.013%
	2500	1500	10.95	9.82	0.011%
	3000	2000	11.40	10.42	0.012%
	3500	2500	10.70	9.23	0.011%
	4000	3000	11.65	10.73	0.013%
	4500	3500	12.50	11.45	0.013%
	5000	4000	12.45	11.18	0.013%

In both cases similar behaviour can be observed, as it is depicted in figure 6.9 and 6.10.

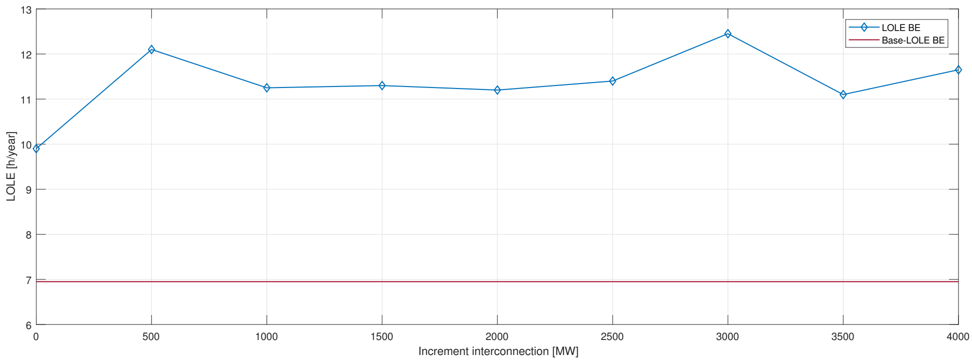

Figure 6.9: Belgium LOLE results iterative increment interconnection BE-DE.

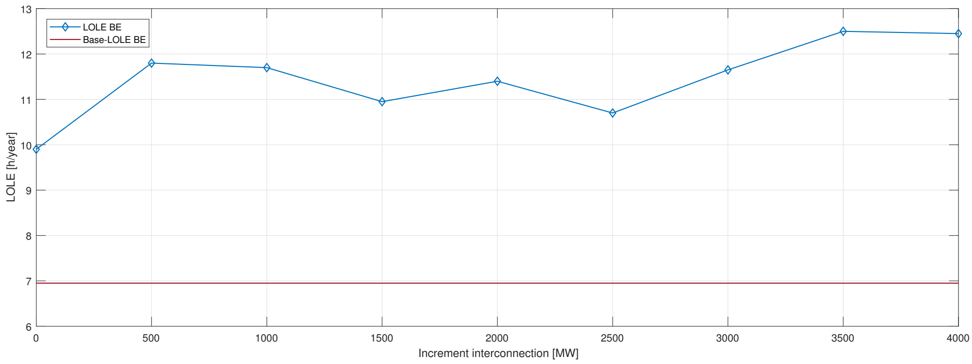

Figure 6.10: Belgium LOLE results iterative increment interconnection BE-GB.

Analysing the LOLE trend in both interconnectors it can be observed that an increase in the cross-border capacity across countries does not seem to provide additional adequacy benefits. In the case of the interconnection BE-DE, the LOLE results oscillate between 9.90h/year with no capacity increment, and 12.45h/year with a transmission capacity increase of 3000MW, not showing a clear trend. In the case of the interconnection BE-GB, a similar pattern is observed, with values ranging from 9.90h/year till 12.50h/year LOLE. In both cases, the LOLE values differ maximum 2.55h/year for BE-DE and 2.6h/year for BE-GB. These results lead to the idea that the adequacy levels are kept almost constant by the addition of cross-border capacity, without clear reliability improvements that could bring the values close to the Base-LOLE. To provide a final conclusion on the adequacy effects of the interconnection expansion, the EENS results should be analysed. As it has been already noticed, LOLE results are not always responsive to changes in system capacity.

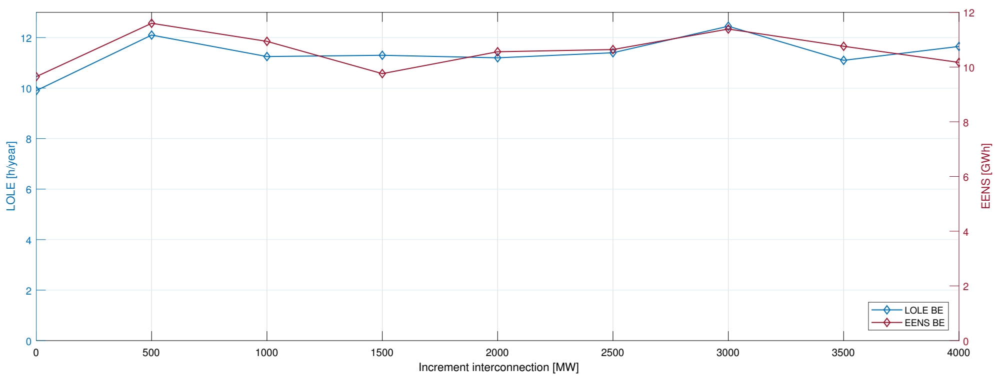

Figure 6.11: Belgium LOLE & EENS results iterative increment interconnection BE-DE.

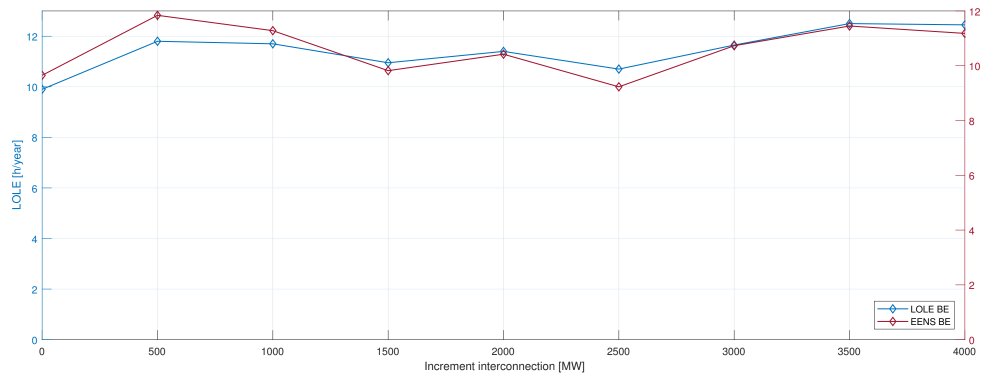

Figure 6.12: Belgium LOLE & EENS results iterative increment interconnection BE-GB.

As it can be derived from figure 6.11, the unserved energy not always follows the same progress as the LOLE. However, by analysing the EENS results, no different conclusions can be derived. The ENS progress by the rise of transmission capacity does not follow a clear trend, with values differing maximum 1.95 GWh in the case of BE-DE and 2.19 GWh for BE-GB. Hence, from these results it can be stated that increments in the transmission capacity among Belgium and Germany or Belgium and the United Kingdom do not seem to bring adequacy benefits for Belgium. Thus, further increase in the cross-border capacity would not bring the LOLE values close to the Base-LOLE, not being possible to compute the sensitivity analysis of generation capacity that can be replaced by interconnection capacity. The fluctuating behaviour presented in both figures, 6.11 and 6.12, can be due to the change in generation patterns and especially to the dispatch of hydro when increasing the interconnection, which might vary the distribution of EENS and LOLE. Furthermore, the number of outage patterns used in the simulations could be not sufficient to have an acceptable confidence interval, making the LOLE and EENS results oscillate in this way.

The steadiness of the adequacy levels observed during the addition of cross-border capacity, without a clear decrease of the LOLE values, can be explained by several reasons. First, both Germany and the United Kingdom might not have available capacity to exchange with Belgium in the moments when it has scarcity. The unavailable capacity can be present either in the moments when the United Kingdom or Germany suffer unserved energy or when they do not present ENS but there is not enough capacity to export towards Belgium. Second, derived from the first reason, if there is no available capacity in the neighbours and they present unserved energy which impedes the exchanges with Belgium, that implies that simultaneous scarcity is arising between the countries. However, in the study of section 6.1, Germany and the United Kingdom were presented as suitable candidates for expansion, since, among other features, they showed low simultaneity in their scarcity events with Belgium. These remarks bring the conclusions that with the addition of generation capacity in Belgium, the generation and exchanges among countries have changed, possibly leading to a different distribution of the scarcity events, and by consequence change in the simultaneous scarcity between countries. Finally, it should be noted that this iterative process is conducted in a pan-European model with a cost minimization objective function, where the ENS is included, that entails the whole system. Thus, the optimisation objective is the total system cost minimisation. This could result in cases where the effect of adequacy could leak to other parts of the system, not being directly reflected in the countries analysed.

In order to see how the interconnection is being used while increasing the transmission capacity, and if the availability of resources could be affecting the observed adequacy behaviour, the congested status of the interconnection can be analysed. Figure 6.13 and 6.14 depict the hours that the interconnection between Belgium and Germany or the United Kingdom is congested in the direction towards Belgium, i.e. when Belgium is importing.

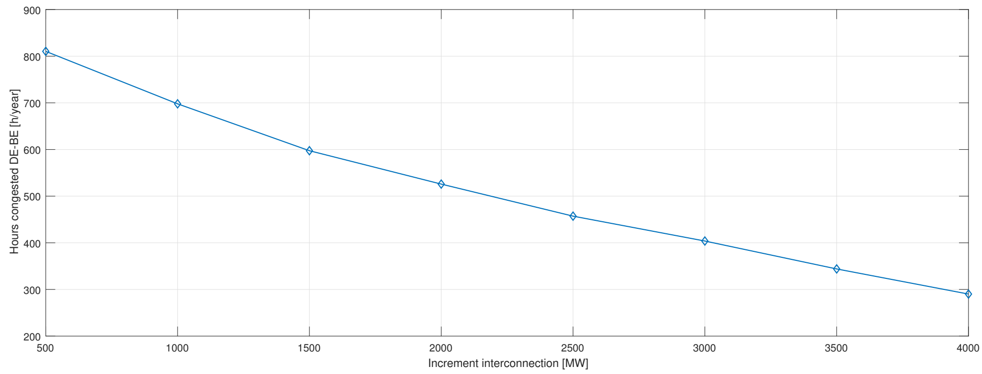

Figure 6.13: Congested hours interconnection BE-DE in DE-BE direction.

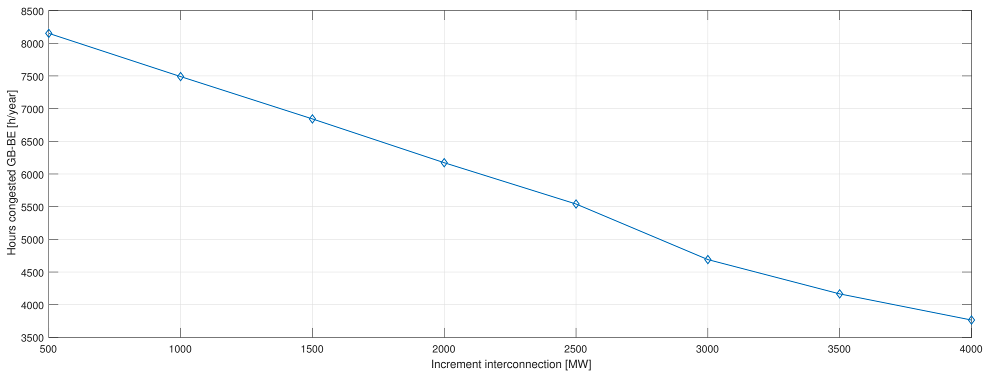

Figure 6.14: Congested hours interconnection BE-GB in GB-BE direction.

As reflected in the previous figure, the congested hours in both interconnections decrease with the increment of cross-border capacity. This tendency reflects that although the absolute usage of the interconnector increases by increasing their capacity, the relative use may decrease, thus possibly there is not enough available capacity neither in Germany nor the United Kingdom to be transferred to Belgium, being then unfruitful to add transmission capacity.

After the observation of the previous results, and following the second reason mentioned above, it is worth to analyse the simultaneous scarcity situation after the addition of the Missing Capacity units. Table 6.19 compares the simultaneous scarcity between countries before and after the addition of generation capacity.

Table 6.19: Effect of additional generation capacity on the occurrence of simultaneous scarcity events.

	Simultaneous scarcity of BE with...	
	Before addition of Missing Capacity units	After addition of Missing Capacity units
DE	3.88%	35.14%
GB	26.84%	75.68%

It can be derived from the previous table that the percentage of occurrence of simultaneous scarcity events between Belgium and Germany or the United Kingdom, notably increases by the addition of generation capacity in Belgium, in this case 4.4 GW were added. These results entail that Germany and the United Kingdom are not able to assist Belgium in many of the moments when it is experiencing scarcity, and hence the increase of interconnection does not bring adequacy benefits for the country, explaining the obtained results.

6.3. Summary

Chapter 6 investigates the contribution of interconnectors to system adequacy. First, by the sensitivity analysis of the contribution of interconnectors in times of scarcity and then by conducting the evaluation of missing capacity through transmission expansion. The goal of this chapter is to answer the fourth sub-question: *What is the role of interconnectors in contributing to system adequacy?*

The sensitivity analysis of the contribution of interconnectors in times of scarcity brings meaningful insights on how the interconnectors of Belgium are used. It has been observed that high alignment in scarcity events, climate correlation, between regions can result in lower use of the interconnection capacity. In contrast, countries with low simultaneity in their unserved energy events show higher potential of cross-border capacity. The study conducted in Belgium presents the interconnectors between the Netherlands, Germany and the United Kingdom, as the major contributors to the system adequacy of Belgium. While France and Luxembourg, with high simultaneity in their scarcity events, show a lower contribution to Belgium's security of supply. Following these findings, the interconnection expansion was investigated from two different perspectives. First, an iterative process by increasing the transmission capacity of the line BE-DE was performed. This process resulted in higher adequacy levels for Belgium, lower LOLE and EENS, by the increment of the cross-border capacity with Germany. Second, the evaluation of Missing Capacity through interconnection expansion was conducted in the expansion candidates identified: BE-DE and BE-GB. This methodology aimed to compute a sensitivity of the generation capacity that could be replaced by transmission expansion achieving the same adequacy result, in this case the target LOLE of 3h/year. The results obtained after conducting the Missing Capacity evaluation do not show that an increase in the cross-border capacity between Belgium and Germany or the United Kingdom would yield additional adequacy benefits. These results, at first contradictory to the previous findings, can be explained by several reasons. The introduction of the additional capacity in Belgium, Missing Capacity units, changes the generation and exchanges across countries, affecting the simultaneity of scarcity events. This change induces an increase in the simultaneity of unserved energy events between Belgium and Germany or the United Kingdom, which leads to a lower assistance capacity of Germany and the United Kingdom.
Comparing both implementations not only the effects of the simultaneous scarcity can be observed, but also the difference in the adequacy levels across countries, which is more marked in the first approach. In the case of the presence of the Missing Capacity units the adequacy difference, i.e. LOLE and EENS, between Germany and Belgium was not so sharp and the opposite without the additional capacity. Therefore, this difference can also affect the extent to which a country is able to assist the other in their scarcity situations.

The results of this analysis although they do not bring a sensitivity of generation capacity that could be replaced by transmission capacity, they reflect the contribution of interconnectors to system adequacy. It has been proved that the contribution is highly dependent on the correlation of the scarcity events across countries, as well as the difference in their adequacy levels.

7

Conclusions & Recommendations

The following chapter presents the conclusions of the research project and recommendations for further investigation. The conclusions are drawn as the answers to the research questions presented in chapter 1 and specified in each chapter. Section 7.1 will present the conclusions, starting with the answers to the research sub-questions which will lead to the answer of the main research question. To finalise, section 7.2 will suggest directions for future research.

7.1. Conclusions

The conclusions of the study will be presented following the order introduce with the research sub-questions, to finalise with the answer of the main research question.

Sub-question 1: ***What is system adequacy and how is it regulated in EU countries?***

In order to answer how to reach reliability targets in the European power system, is necessary to first define what are the reliability targets and how are they applied in the European power system. To this purpose chapter 2 serves as the answer to this sub-question.
The increment of uncertainties in the power system and electricity market increases the focus on resource adequacy. To ensure a reliable system either investments on power system developments, or the implementation of capacity mechanisms are being considered. To take these decisions, information on the reliability level of the power system and the required level to achieve are necessary. To that end, resource adequacy assessments are employed, and in the case of European countries, the consideration of the interconnected nature of the systems should be considered. System's adequacy is a dimension of the system's reliability. Adequacy is placed in the long term as the ability of the system to meet the load in a long horizon, considering planned and unplanned outages, and the development of the power system. When tackling European studies generation adequacy is assessed, leaving transmission adequacy to the national studies. To evaluate the maturity of the system with respect to an adequacy standard, the adequacy metrics are applied. Loss of Load Expectation and Expected Energy Not Served are presented as the most widely used indices, the LOLE being the most common in the planning area. However, the purpose of the assessment should be considered when selecting the adequacy index, as each metric provides different information that can better serve the study purpose. At European level, the lack of harmonisation and implementation of reliability standards is manifested. However, recent European regulation, (EC) NO 5070/19, increases the requirements to Member States in terms of adequacy assessments. The Regulation states that the national adequacy evaluations should be based on the European resource adequacy assessment. The European Commission also requests the implementation of a reliability target when a MS is considering the adoption of a capacity market. Moreover, the effect of this mechanism on the neighbouring countries should be assessed prior implementation, and the cross-border participation has to be allowed.

Sub-question 2: ***How to assess system adequacy in an interconnected power system?***

To evaluate the adequacy of a power system different methods can be applied as presented in chapter 3. Two main approaches are identified in the literature: deterministic and probabilistic methods. While deterministic methods are mainly applied in the operations area and dispatch level, probabilistic techniques are preferred for the planning phase, thus the resource adequacy evaluation. Probabilistic methods account for the stochastic nature of power systems and can be applied to obtain the probabilistic reliability indices. There are two probabilistic approaches: analytical or simulation/Monte Carlo method. The analytical method represents the system by a mathematical model that includes a load and generation model for then calculate the risk indices. In the case of the simulation or Monte Carlo method, it models the actual process and random behaviour of the power system by stochastic simulations using random numbers. The Monte Carlo method can be applied in a sequential or non-sequential approach. Both analytical and simulation methods evaluate different system areas as generating system adequacy or composite system adequacy. The latter comprises the interconnected systems.
While the analytical method is used by the American institution PJM, Monte Carlo technique is preferred by AEMO and European bodies. In the European assessments, the Monte Carlo method is applied by replicating the Unit Commitment and Economic dispatch problem over several simulations considering different climate scenarios and outages. As an outcome of the adequacy studies, the reliability metrics are obtained, mainly in terms of EENS and LOLE.
Overall, it can be stated that for assessing system adequacy of an interconnected power system, probabilistic methods are applied, and in particular Monte Carlo simulation is presented as the approach that can accurately reflect the power system and all its components and possible states, being widely used by the industry.

Sub-question 3: ***Which are the different approaches to ensure the required level of system adequacy?***

To answer this question the concept of Missing Capacity has been introduced. Missing Capacity is presented as a possible adequacy indicator that quantifies the required capacity to reach a predefined reliability target in a specific region. It defines the capacity needed to achieve the required adequacy level in a future scenario. Through the evaluation of the missing capacity several approaches are analysed that entails the different options to ensure the required level of system adequacy. Within the options for assessing the missing capacity, a distinction is made among the areas in which the capacity expansion is considered: single or multi-area approach. Once identified the area of study the evaluation can be applied investigating different capacity sources: generation and/or transmission capacity expansion. For conducting the Missing Capacity evaluation two main methods have been identified: the integrated optimisation approach and the iterative approach.
To determine the approaches to ensure the required level of system adequacy in a single area three methods have been analysed. First, focusing on generation expansion, the Missing Capacity problem can be solved by means of the integrated optimisation approach introducing a Shortfall constraint, or by an Economic optimisation of the build cost. The Shortfall constraint approach induces a limitation to the solution, as the reliability target is applied per simulation sample instead to the target year. Despite that, in both approaches has been noticed the influence that the additional capacity can cause in the adequacy levels of the neighbouring countries. The regional effects of the capacity expansion are apparent in reduced LOLE and EENS in the European countries after generation increment in one node. This behaviour manifests the importance of considering the interconnection contribution in the national adequacy assessments, and the benefits that harmonization of reliability standards could bring, facilitating regional adequacy assessments. Second, the single area approach can be solved by means of generation and transmission capacity expansion. Starting from the result obtained in the previous method, an iterative approach can be performed, increasing the capacity of each interconnector. This method presents a sensitivity study on the generation capacity that can be substituted by interconnection capacity achieving the same adequacy level.
In order to ensure the required level of system adequacy when considering a multi-area, one method has been studied, focused on two interconnected areas. Through this implementation, the contribution of interconnectors in sharing the benefits of capacity expansion is accounted. The evaluation technique applied is based on an iterative approach which brings two possible results: the achievement of the required reliability level in two areas by generation expansion in one node, or by sharing the extra capacity among the two nodes. Both solutions achieve the required reliability target and evidence the possible contribution of interconnectors to adequacy in sharing the benefits of capacity expansion. From the results obtained, it can be depicted that sharing the additional capacity across both countries achieves a more efficient solution requiring less installed capacity to accomplish the reliability standard of the two countries.
In all the approaches analysed, the results show the influence and effect that the adequacy situation of one

country can have in the whole region. Europe being a highly interconnected area, the capacity addition or shortage in one country can indirectly affect the resources adequacy of its direct and indirect neighbours.

Sub-question 4: ***What is the role of interconnectors in contributing to system adequacy?***

The effect of interconnectors on system adequacy has been observed in the course of this thesis and reflected in the results of several of the Missing Capacity approaches. Chapter 6 is focused on the role of interconnectors in security of supply, however, its effect has been already noticed while investigating the capacity expansion options, chapter 5. The Multi-area generation expansion reflects the effect that interconnectors can have on the adequacy levels of two areas, as the capacity benefits are shared through the interconnectors, leading to a more efficient allocation of capacity across regions. It shows that no consideration of interconnectors can lead to surplus capacity in a zone. Moreover, the adequacy effects have spread to peripheral countries, showing reduced LOLE. Hence, the interconnectors contribution to adequacy in highly interconnected areas, like Europe, is notable.
Referring to a more detailed analysis of the contribution of interconnectors to the system adequacy of a specific country, chapter 6 presents the main findings. The interconnectors contribution to a system's adequacy cannot be evaluated in a generic manner, a study of each line should be conducted instead, since differences among countries, i.e. system size, adequacy level, and weather correlation, highly affect the interconnector use. One of the main findings of this study is that the reliability role of interconnectors is highly dependent on the simultaneity of the scarcity periods across countries. The existence of climate or demand correlations among countries is detrimental to the use of interconnectors, not bringing additional benefits the increase of the transmission capacity. However, low levels of simultaneous scarcity show a marked contribution of cross-border capacity to national adequacy levels. Additionally, not only the simultaneity of unserved energy events affects the interconnectors utilization, but it has also been observed that larger differences in adequacy levels bring higher assistance capacity among countries. A remark should be made in how the change in capacity installed in a country strongly affects the adequacy situation of the neighbours, and also the distribution of ENS events, being possible to experience a reduction on their export availability. Therefore, regional adequacy studies are convenient when considering the increment of installed capacity, as this can affect the neighbours and the exchange patterns. Overall, the effect of cross-border capacity in system adequacy is remarkable but highly dependent on the particular condition of the target country and its neighbours.

Research question: ***How to reach reliability targets in the interconnected European power system?***

Through the investigation of the previous sub-questions, the answer to the main research question is reached. Having analysed the reliability targets and regulation in Europe, it can be stated that for determining the reliability situation at European level, a generation adequacy assessment should be conducted. This sort of assessments provide the adequacy metrics that can then be compared with the reliability targets in place, to determine the adequacy situation of each country. For conducting the adequacy assessment probabilistic methods are preferred, and in particular, Monte Carlo simulation is presented as the approach that can accurately reflect the power system and all its components and possible states. Concerning the reliability targets, there is a lack of implementation and harmonization of standards across European countries. However, recent regulation in the field of electricity markets stresses the importance of the establishment of a reliability standard when considering the implementation of capacity mechanisms. Regarding the metric used, LOLE is presented as the standard commonly adopted.
Having a reliability target in place the capacity required to reach the target can be calculated through the Missing Capacity evaluation. Missing Capacity is presented as a possible adequacy indicator that quantifies the required capacity to reach a defined reliability target in a specific region. Different methods to reach the reliability target have been proposed. They can be classified based on the area of study and the capacity source. When considering a single-area, two options for achieving the required adequacy level have been investigated: generation capacity expansion or generation and interconnection capacity expansion. The first can be calculated following an integrated optimisation approach which brings the optimal amount of capacity to be added in one node to reach the required reliability target. In the second, the integrated optimisation approach is followed by an iterative process, however, no satisfactory results were obtained. Despite these results, the contribution of interconnectors to a country's system adequacy has been proved under country specific conditions, like low simultaneous scarcity.
In the case of studying a multi-area, it has been investigated the achievement of the reliability target in two-areas by generation capacity expansion. Two solutions were reached: the achievement of the reliability target by generation expansion in one node, or the allocation of capacity among the two nodes, sharing the benefits

of the capacity expansion through the interconnectors.
To conclude, the research conducted in this master thesis presents different methods to calculate the capacity needed to reach the required reliability target under several scenarios.

Further remarks

The research conducted in this thesis has reflected how is the behaviour of different adequacy metrics to capacity changes in the system. In the case of study, the adequacy metrics LOLE and EENS have been applied. LOLE has been the metric selected to express the reliability target, as it is the one commonly used across Europe. However, some drawbacks on the utilization of this metric for this sort of adequacy studies haven been observed:

- Low responsiveness of LOLE: LOLE metric does not indicate the severity of the shortage, being possible to have same number of hours for events of different dimensions. In this thesis, the lack of responsiveness of LOLE to additions of capacity has been experienced in both the generation capacity expansion and the interconnection expansion. In the first, a slight decrease of LOLE was experienced by the reduction of 100MW installed capacity, while the EENS suffered an increase. In the second case, the LOLE and EENS trend also differ when increasing the interconnection capacity across countries. In conclusion, LOLE itself might not provide enough information to optimal define the capacity needs and support economic decisions. For those purposes, additional metrics should be used.
- Difficult implementation of LOLE target in market modelling tools: For the formulation of the Missing Capacity problem, and in a general to define the capacity needs by using market modelling tools, the LOLE metric has not been presented as the most suitable. The electricity market modelling tools employed in the adequacy assessments solve the UCED problem where the ENS is included. The cost minimisation problem directly includes the ENS but not the loss of load. Therefore if the LOLE target is used, a relation between both metrics is needed when implementing this kind of capacity optimisation problems. However, the definition of the EENS and LOLE relation is not straightforward and requires further investigation. Concerning this, the European Commission has required that when considering a capacity mechanism a reliability standard shall be established and be expressed as EENS and LOLE.

7.2. Recommendations

Regarding the aspects that can be improved for future research in the area, several suggestions can be made. The recommendations can be divided into the actions to improve in the current research work, and the directions for future research.

7.2.1. Research improvements

In the extent of this research project several limitations were found, to which future actions and improvements can be made:

Integrated optimisation - Shortfall constraint approach: As it was mentioned in section 4.4.1 this approach introduces a limitation on the results. Having a reliability target like the LOLE, which reflects the hours expected of unserved energy, the shortfall constraint provides the capacity needed to reach LOLE target per sample, not in expectation. Thus, the result answers the most extreme scenario. The formulation of a stochastic problem with a user-defined constraint applied to the target year is not possible to implement in the tool utilized for conducting this research project. Therefore, to overcome this limitation by using the same tool, other approaches need to be analysed. In this study alternative methods were presented, i.e. economic optimization and iterative approach, however an in depth analysis of other possible implementation in PLEXOS could be conducted. The variety of options and power systems' features present in PLEXOS is broad, thus there could be odds of defining the problem by means of other parameters.

Climate years & Outages patterns: Due to the timeframe of the thesis and the research objective of finding a methodology, the number of simulations applied was limited. When performing adequacy studies by the application of Monte Carlo methods, the number of simulations conducted should be large enough to reach the convergence criteria. In this study case, the samples are determined by the climate years, which entails the different weather and load data, and the number of outages patterns. For this research project, when applying Monte Carlo simulations, 3 climate years and 20 outages patterns were used. Although the selection of climate years was based on samples suitable for evaluating the missing capacity, for an adequacy assessment the number of climate years should be broader, increasing the different scenarios that the power system can experience. Similar, for the number of outage patterns, the number should be large enough to reach the convergence criteria. Nonetheless, the increased accuracy comes with an increase in computational time. In this regard, the complexity of the integrated optimization approach, presented in this project, could not be suitable for a large amount of samples.

Stochastic optimisation: In relation to the previous point, when selecting a set of scenarios for conducting stochastic optimisation, different probabilities can be assigned to each scenario. In the case of this study, the scenarios are represented by the climate years, and equiprobable probabilities of occurrence were assigned. However, if the number of scenarios to be included cannot be increased, a way to improve the accuracy of results respect to reality is by assigning probabilities of occurrence to the scenarios. Through cluster analysis techniques the climate data can be sorted in clusters depicting the most representative climate years.

Tool & model limitations: The tool utilized to perform this research project was the electricity market modelling tool PLEXOS. The main limitation experienced, related to the tool was, as mentioned, the shortfall constraint implementation. Related to the model itself, when using the MAF 2018 model, the limitations where present in the implementation phase and analysis of results. The MAF model is a detailed representation of the power system, and for the objective of the study this level of detail has hindered the implementation and analysis. For example, in the case of the interconnectors study, a simplified model might serve the objective of observing the sensitivity of transmission increment in the system. Overall, the use of simplified models could facilitate the study implementation and serve the research objectives.

Use & definition of Missing Capacity: From the current investigation, if an application of Missing Capacity wants to be made, based on the results, the recommended method to evaluate the missing capacity would be the Multi-area generation expansion approach. A regional evaluation of missing capacity allocates the capacity more efficiently and makes use of the existing interconnections. As a continuation of this research, the number of areas in the study can be increased. As to the evaluation method refers, the integrated optimisation approach can serve as a starting point for the investigation, but due to the dimension of the problem, and if more samples, i.e. climate years and outage patterns, want to be included, then the iterative approach seems to be the most suitable. Further investigation in techniques to automate the iterative process can bring very useful tools. As for the selection of climate years, as it is not possible to conduct the current evaluation with a high number of years, for a real practice it is recommended to apply a clustering method and select the most representative years. With this, the most realistic results within the constraints of the evaluation method will be obtained.

7.2.2. Future research

Concerning directions for further research, several suggestions are presented:

MAF methodology: As this thesis has been developed based on the MAF 2018 model, the methodology and assumptions applied in the MAF 2018 also affect this research. Hence, some of the limitations can be tackled in future research:

- Energy-only market is considered in the MAF model. Neither the capacity nor the balancing market are considered in the model, which could change the missing capacity results. Further investigation on the topic can be conducted.
- Internal grid limitations within a bidding zone are not considered in the model. The implementation of other approaches requires further analysis.

Economic optimisation: The Economic optimisation approach presented within the Integrated optimisation method, applies the equations derived in [46] for obtaining a generator build cost that is equivalent to the cost of new entry in [46]. Further investigation is needed on how to determine the CONE or a build cost that can provide a price signal to limit the addition of capacity to a reliability target. As presented in the results the build cost determined is not optimal when modelling the pan-European system. Therefore, further investigation in the Economic optimisation approach can be conducted.

Reliability target: The reliability target adopted in this study has been the LOLE. Although there is not a harmonisation on the reliability standards across European countries, LOLE is commonly the metric preferred. However, as it has been seen in this study, LOLE lacks responsiveness to capacity changes in the system. Therefore, it is not presented as the most suitable metric to conduct adequacy studies like the Missing Capacity. Additionally, the market modelling tools used by the industry in the adequacy assessments, perform a cost minimisation including the ENS in the objective function. Since the ENS is directly implemented in the objective function, a trade-off between the addition of capacity and the EENS could be easier to implement and provide more responsive results than with and LOLE target. Nevertheless, in the scope of a real application, the selection of the reliability target metric is subject to the reliability standards and metrics adopted by the countries. Further research on the selection of a reliability target and metric could bring useful insights.

Study scope: In terms of the areas analysed, the research can be continued by investigating the missing capacity considering different areas of study. Currently the multi-area approach was focused on two-areas, but the analysis of missing capacity in a wider region can bring interesting adequacy results that comprise the contribution of interconnectors.

Bibliography

[1] ENTSO-E. *Mid-term Adequacy Forecast. 2018 Edition.* Oct. 2018. URL: https://www.entsoe.eu/outlooks/midterm/.

[2] P. Kundur et al. "Definition and classification of power system stability IEEE/CIGRE joint task force on stability terms and definitions". In: *IEEE Transactions on Power Systems* 19.3 (Aug. 2004), pp. 1387–1401. ISSN: 0885-8950. DOI: 10.1109/TPWRS.2004.825981.

[3] Pei Zhang, S. T. Lee, and D. Sobajic. "Moving toward probabilistic reliability assessment methods". In: *2004 International Conference on Probabilistic Methods Applied to Power Systems.* Sept. 2004, pp. 906–913.

[4] H. Aghaie. "The impact of intermittent renewables on the resource adequacy in electricity markets". In: *2016 IEEE Electrical Power and Energy Conference (EPEC).* Oct. 2016, pp. 1–5. DOI: 10.1109/EPEC.2016.7771743.

[5] H. Chao and G. Simaan. "Resource adequacy assessment considering transmission and generation via market simulations". In: *2009 IEEE Power Energy Society General Meeting.* July 2009, pp. 1–13. DOI: 10.1109/PES.2009.5275426.

[6] European Environment Agency. *Renewable energy in Europe 2018 - recent growth and knock-on effects.* Dec. 2018. URL: https://www.eea.europa.eu/publications/renewable-energy-in-europe-2018#tab-data-references.

[7] David Newbery and Michael Grubb. "Security of Supply, the Role of Interconnectors and Option Values: insights from the GB Capacity Auction". In: *Economics of Energy Environmental Policy* 4.2 (Apr. 2015). DOI: 10.5547/2160-5890.4.2.dnew. URL: https://www.researchgate.net/publication/282199299_Security_of_Supply_the_Role_of_Interconnectors_and_Option_Values_insights_from_the_GB_Capacity_Auction.

[8] CIGRE. *Power System Reliability Analysis.* CIGRE WG 03 of SC 38 (Power system analysis and techniques), 1987.

[9] European Commission. *Identification of Appropriate Generation and System Adequacy Standards for the Internal Electricity Market.* Mar. 2016. URL: https://ec.europa.eu/energy/en/studies/identification-appropriate-generation-and-system-adequacy-standards-internal-electricity.

[10] Roy Billinton and Wenyuan Li. *Reliability assessment of electric power systems using monte carlo methods.* Springer Science Business Media, LLC, 1994. DOI: 10.1007/978-1-4899-1346-3.

[11] ENTSO-E. *Mid-term Adequacy Forecast 2018. Appendix 1: Methodology and Detailed Results.* 2018. URL: https://www.entsoe.eu/outlooks/midterm/.

[12] ACER/CEER. *Annual Report on the Results of Monitoring the Internal Electricity and Gas Markets in 2015. Key Insights and Recommendations.* Nov. 2016. URL: https://acer.europa.eu/Official_documents/Acts_of_the_Agency/Publication/ACER%20Market%20Monitoring%20Report%202015%20-%20KEY%20INSIGHTS%20AND%20RECOMMENDATIONS.pdf.

[13] Council of the European Union. *Council Regulation (EC) No. 5070/19 on the internal market for electricity.* Jan. 2019. URL: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1554051780327&uri=CONSIL:ST_5070_2019_INIT.

[14] Wenyuan Li. "Framework of probabilistic power system planning". In: *CSEE Journal of Power and Energy Systems* 1.1 (Mar. 2015), pp. 1–8. DOI: 10.17775/cseejpes.2015.00001. URL: https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=7086150.

[15] Jean-Christophe Alais et al. *METIS Studies. Study S04. Generation and System Adequacy Analysis.* Jan. 2016. URL: https://ec.europa.eu/energy/en/studies/common-approach-generation-and-system-adequacy.

[16] Wind Europe. *Assessing resource adequacy in an integrated EU power system*. June 2016. URL: https://windeurope.org/policy/position-papers/system-adequacy/.

[17] B. Bagen et al. "Probabilistic resource adequacy assessment of large interconnected systems". In: *2010 IEEE 11th International Conference on Probabilistic Methods Applied to Power Systems* (2010). DOI: 10.1109/pmaps.2010.5528519. URL: https://ieeexplore.ieee.org/document/5528519.

[18] André Månsson, Bengt Johansson, and Lars J. Nilsson. "Assessing energy security: An overview of commonly used methodologies". In: *Energy* 73 (2014), pp. 1–14. ISSN: 0360-5442. DOI: https://doi.org/10.1016/j.energy.2014.06.073. URL: http://www.sciencedirect.com/science/article/pii/S0360544214007725.

[19] R. N. Allan and R. Billinton. *Reliability Evaluation of Power Systems*. Second edition. Plenum, 1996.

[20] J. R. Haro and E. Inga. "State of Art, Reliability Assessment in the Transmission System based on Monte Carlo Method". In: *IEEE Latin America Transactions* 14.1 (Jan. 2016), pp. 398–403. ISSN: 1548-0992. DOI: 10.1109/TLA.2016.7430107.

[21] A. R. A. El Wafa, I. Helal, and G. Haggag. "Monte Carlo simulation in generating capacity adequacy assessment (state sampling technique)". In: *2006 Eleventh International Middle East Power Systems Conference*. Vol. 2. Dec. 2006, pp. 541–546.

[22] North American Electric Reliability Corporation. *Probabilistic Adequacy and Measures*. Apr. 2018. URL: https://www.nerc.com/comm/PC/Documents/2.d_Probabilistic_Adequacy_and_Measures_Report_Final.pdf.

[23] G. S. Vassell and N. Tibberts. "Analysis of Generating-Capacity Reserve Requirements for Interconnected Power Systems". In: *IEEE Transactions on Power Apparatus and Systems* PAS-91.2 (Mar. 1972), pp. 638–649. ISSN: 0018-9510. DOI: 10.1109/TPAS.1972.293250.

[24] C. K. Pang and A. J. Wood. "Multi-area generation system reliability calculations". In: *IEEE Transactions on Power Apparatus and Systems* 94.2 (Mar. 1975), pp. 508–517. ISSN: 0018-9510. DOI: 10.1109/T-PAS.1975.31878.

[25] W. Li. "Framework of probabilistic power system planning". In: *CSEE Journal of Power and Energy Systems* 1.1 (Mar. 2015), pp. 1–8. ISSN: 2096-0042. DOI: 10.17775/CSEEJPES.2015.00001.

[26] Simon H. Tindemans, Matthew Woolf, and Goran Strbac. "Capacity Value of Interconnection Between Two Systems". In: *CoRR* abs/1811.03131 (2018). arXiv: 1811.03131. URL: http://arxiv.org/abs/1811.03131.

[27] Australian Energy Market Operator. *About AEMO*. Sept. 2013. URL: https://www.aemo.com.au/About-AEMO.

[28] Australian Energy Market Operator. *Energy Adequacy Assessment Projection*. Nov. 2018. URL: https://www.aemo.com.au/-/media/Files/Electricity/NEM/Planning_and_Forecasting/EAAP/2018/EAAP---November-2018.pdf.

[29] Australian Energy Market Operator. *Reliability Standard Implementation Guidelines*. Oct. 2016. URL: https://www.aemo.com.au/-/media/Files/Stakeholder_Consultation/Consultations/Electricity_Consultations/2016/EAAP/Reliability-Standard-Implementation-Guidelines.pdf.

[30] PJM Interconnection. *About PJM*. 2019. URL: https://www.pjm.com/about-pjm/who-we-are.aspx.

[31] L.L.C. PJM Interconnection. *PJM Generation Adequacy Analysis: Technical Methods*. Oct. 2003. URL: https://www.pjm.com/~/media/etools/oasis/references/whitepaper-sections-12.ashx.

[32] PJM Interconnection. *PJM Manual 20: PJM Resource Adequacy Analysis*. Mar. 2019. URL: https://www.pjm.com/~/media/documents/manuals/m20.ashx.

[33] Pentalateral Energy Forum Support Group 2. *Generation Adequacy Assessment*. Jan. 2018. URL: http://www.elia.be/en/about-elia/newsroom/news/2018/20180131_Second-regional-generation-adequacy-assessment-report-published.

[34] ELIA. *Adequacy study for Belgium: the need for strategic reserve for winter 2019-20*. Nov. 2018. URL: http://www.elia.be/en/about-elia/newsroom/news/2018/20181129-Adequacy-study-winter-2019-20.

[35] ENTSO-E. *Who Is ENTSO-E?* 2019. URL: https://www.entsoe.eu/about/inside-entsoe/objectives/.

[36] Energy Exemplar. *PLEXOS*. 2019. URL: https://energyexemplar.com/products/plexos-simulation-software/.

[37] Energy Exemplar. *PLEXOS Wiki*. 2019. URL: https://wiki.energyexemplar.com/.

[38] Zofia Lukszo. *Basic Concepts of Optimization for Energy Systems*. Sept. 2017.

[39] ENTSO-E. *Mid-term Adequacy Forecast 2017 Edition*. 2017. URL: https://www.entsoe.eu/outlooks/midterm/.

[40] Stochastic Programming Society. *What is stochastic programming?* 2019. URL: https://www.stoprog.org/what-stochastic-programming.

[41] Shabbir Ahmed. "Two-Stage Stochastic Integer Programming: A Brief Introduction". In: *Wiley Encyclopedia of Operations Research and Management Science* (Jan. 2011). DOI: 10.1002/9780470400531.eorms0092.

[42] Energy Exemplar. *Stochastic Unit Commitment in PLEXOS*. May 2018. URL: https://energyexemplar.com/news/stochastic-unit-commitment-explained/.

[43] Shun-Chen Niu. *Initialization: The Big-M Formulation*. 2019. URL: https://www.utdallas.edu/~scniu/OPRE-6201/documents/LP07-Big-M-Formulation.pdf.

[44] David Newbery. "Missing money and missing markets: Reliability, capacity auctions and interconnectors". In: *Energy Policy* 94 (Oct. 2015), pp. 401–410. DOI: 10.1016/j.enpol.2015.10.028. URL: https://www.sciencedirect.com/science/article/pii/S0301421515301555.

[45] Thomas Karier et al. "The economics of electricity adequacy". In: *The Electricity Journal* 31.4 (2018), pp. 51–55. DOI: 10.1016/j.tej.2018.05.003. URL: https://www.sciencedirect.com/science/article/pii/S104061901830099X.

[46] Department of Energy Climate Change. *Annex C: Reliability Standard Methodology*. July 2013. URL: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/223653/emr_consultation_annex_c.pdf.

[47] Chris Dent, Amy Wilson, and Stan Zachary. "Valuation of storage for capacity markets". In: *Duration-Limited Storage De-Rating Factor Assessment - Final Report* (Dec. 2017). URL: https://www.emrdeliverybody.com/Lists/Latest%20News/Attachments/150/Duration%20Limited%20Storage%20De-Rating%20Factor%20Assessment%20-%20Final.pdf.

[48] ACER/CEER. *Annual Report on the Results of Monitoring the Internal Electricity and Gas Markets in 2016. Electricity Wholesale Markets Volume*. Oct. 2017. URL: https://acer.europa.eu/Official_documents/Acts_of_the_Agency/Publication/ACER%20Market%20Monitoring%20Report%202016%20-%20ELECTRICITY.pdf.

[49] ENTSO-E. *Download the MAF Data (23/11/2018)*. Nov. 2018. URL: https://www.entsoe.eu/outlooks/midterm/.