UNIVERSIDADE DE LISBOA
INSTITUTO SUPERIOR TÉCNICO

THE IMPORTANCE OF CROSS-BORDER ANCILLARY SERVICES IN THE NEW RENEWABLE PARADIGM

Pedro Miguel Simões Frade

Supervisor: Doctor João José Esteves Santana

Co-Supervisor: Doctor João Paulo da Silva Catalão

Thesis approved in public session to obtain the PhD Degree in Sustainable Energy Systems

Jury final classification: Pass with Distinction

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Jury

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2020

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Resumo

As fontes de energia, que abasteceram o nosso planeta num passado recente, estão a sofrer uma tremenda modificação. As energias renováveis tornaram-se viáveis do ponto de vista tecnológico, economicamente atrativas e capazes de satisfazer as necessidades energéticas de países, empresas e pessoas. Simultaneamente, as alterações climáticas tornam-se cada vez mais impactantes, pelo que urge continuar a apostar no processo de transição energética, para fontes de energia sustentáveis.

Porém, a integração massiva de energias renováveis, introduz novos desafios ao sector elétrico. Manter o equilíbrio entre a geração e o consumo, sem colocar em causa a integridade do sistema elétrico, tornou-se mais desafiante. Para superar este desafio, os Operadores de Sistema, suportado pelos decisores políticos adotaram um conjunto de medidas, no sentido de manter a segurança do sistema elétrico, sem colocar em causa a competitividade proveniente de um ambiente de mercado.

No caso da União Europeia, a legislação consiste em mudanças significativas no desenho de mercado, bem como na implementação de regras iguais nos distintos mercados de energia elétrica, como os mercados de balanço. Neste sentido, os Serviços Sistema assumem um papel fundamental, no novo paradigma energético devido ao aumento de renováveis, conjugado com a integração de mercados. Esta dupla transição leva a uma maior utilização destes serviços, que, por seu lado, leva ao aumento de custos para os consumidores.

Este trabalho procura investigar e quantificar a importância da coordenação entre Operadores de Sistema, com o propósito de assegurar a segurança, fiabilidade e qualidade de serviço no abastecimento num ambiente de elevada penetração de geração renovável, bem como reduzir o custo de Serviços Sistema com uma adequada cooperação. Inicialmente, elaborou-se um estudo profundo, relativamente ao mecanismo bilateral já implementado, na reserva de regulação. Posteriormente avaliou-se a possibilidade da criação de um mercado multilateral e respetivo apuramento dos ganhos desta solução. A extensão dos mecanismos de partilha, à regulação secundária foi também tema de análise, terminando com uma avaliação do sobrecusto da geração eólica.

Palavras-chave: Serviços Sistema, Mercados de Eletricidade, Energias Renováveis, Operação do Sistema, Reserva de Balanço, Coordenação transfronteiriça

Abstract

The energy sources that have powered our planet in the recent past have been undergoing a period of significant change. Renewables have finally emerged as technologically feasible and economically attractive to satisfy the energy needs of countries, corporations and citizens. At the same time that climate change is becoming more critical and renewables are steadily increasing their capacity, the global transition to sustainable sources of energy will continue to accelerate.

However, the integration of variable renewable energy introduces new and specific challenges to the electrical sector. Maintaining the balance between supply and demand without putting in check the integrity of the electrical system is becoming more of a challenge. To overcome this challenge, System Operators around the world, supported by policy-makers, are adopting a range of measures to maintain the reliability of the electrical sector in this evolving landscape without compromising the competitiveness of the electrical markets.

In the particular case of the European Union, legislation consists in significant changes in some elements of the market design and in the implementation of equal rules in all energy markets where balancing markets are included. Ancillary services assume a fundamental role in the new energy paradigm with the increase of renewable generation as well as the integration of energy markets. This integration, allied to the increase of renewable generation, increases also the utilisation of ancillary services that improve the costs for end users.

This work studies the importance of the coordination between System Operators with the purpose of at the same time assuring the security, reliability and quality of the supply of electricity under a high share of renewable penetration, while also reducing the cost of ancillary services by providing appropriate cooperation. First, it was analyzed the cooperation in replacement reserve. In a second phase, it was studied the possibility of a cooperation in secondary reserve and the calculations of potential profits. Finally, an evaluation of wind balancing costs was made.

Keywords: Ancillary Services, Electricity Markets, Renewable Energy, System Operation, Balancing Reserve, Cross-border Coordination

Dedication

To my beloved sons Rafael and Simão

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Abbreviations

ACE	Area Control Error
AC	Alternate Current
aFRR	Automatic Frequency Restoration Reserve
AGC	Automatic Generation Control
AS	Ancillary Services
BALIT	Balancing Inter TSOs
BRP	Balance Responsible Party
BSP	Balancing Service Provider
CA	Control Area
CB	Control Block
CC	Coordination Center
DA	Day ahead
EEG	European Electrical Grid
ENTSO-E	European Network of Transmission System Operators
ES	Electrical System
EV	Electrical Variability
FiT	Feed in Tariff
FRR	Frequency Restoration Reserve
ISO	Independent System Operator
LFC	Load Frequency Control
MARI	Manually Activated Reserves Initiative
mFRR	Manual Frequency Restoration Reserve
MIBEL	*Mercado Ibérico de Energia*
NG	National Grid (Great Brittan TSO)
NTC	Net Transmission Capacity
PICASSO	Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation
REE	*Red Electrica de España* (Spanish TSO)
REN	*Rede Elétrica Nacional* (Portuguese TSO)
RR	Replacement Reserves
RSCs	Regional Security Coordinators

RTE	*Réseau de Transport d'Électricité* (French TSO)
SDR	Secondary Downward Reserve
SR	Secondary Reserve
SUR	Secondary Upward Reserve
SO	System Operator
TERRE	Trans-European Replacement Reserves Exchange
TSO	Transmission System Operator
TRN	Total Net Reserves
TTC	Total Transmission Capacity
UCTE	Union for the Co-ordination of Transmission of Electricity
VRE	Variable Renewable Energy

List of Variables & Symbols

Chapter 4

OCu	Energy over-cost of tertiary reserve upward.
Pu	Price of balancing reserve upward.
Ps	Spot Price.
Qu	Quantity upward of tertiary reserve..
OCd	Energy over-cost of tertiary reserve downward.
Pd	Price of balancing reserve downward.
Qd	Quantity downward of tertiary reserve.
Q	Quantity of tertiary reserve mobilized.
VBI	Value of Import balancing reserve.
Pi	Price of Import balancing reserve.
CPM	Cost of Potential Mobilization.
CM	Cost of Mobilization.
PBI	Price of Import Balancing Reserve.
PBE	Price of Export Balancing Reserve.
VBE	Value of Export balancing reserve.
CWM	Cost Without Mobilization.
$Quwb$	Quantity of balancing energy Upward Without cross-border trade mechanism.

$Qdwb$	Quantity of balancing energy Downward Without cross-border trade mechanism.
$Puwb$	Price of balancing energy Upward Without cross-border trade mechanism.
$Pdwb$	Price of balancing energy Downward Without cross-border trade mechanism.

Chapter 5

PsF	Price of Selling tertiary reserve by French TSO
PsS	Price of Selling tertiary reserve by Spanish TSO
PaF	Price of Assignation of tertiary reserve by French TSO
PaS	Price of Assignation of tertiary reserve by Spanish TSO
Qe_{total}	Quantity of potential exportation
QPe	Quantity of Potential exportation from Portugal
QFi	Quantity of Potential importation from France
APE	Additional Profits for Exporting
QPi	Quantity of Potential importation for Portugal
QFe	Quantity of Potential exportation from France
Qi_{total}	Quantity of potential importation
ASI	Additional Savings from Importation
AG	Additional Gains

Chapter 6

EV	Electrical Variability
Δ_{Prod}	Production Variation
Δ_{Con}	Consumption Variation
Δ_{Inter}	Interconnection variation
$Prod_{effective}$	Real production
$Prod_{market}$	Energy market output (from production side)
Δ_{Load_h}	Load Variation
$Load_{h(minute\ 0)}$	Load at beginning of the market period
$Load_{h(minute\ 59)}$	Load at the end of the market period
$Inter_h$	Value of the Interconnection at the time h
$Inter_{h-1}$	Value of the Interconnection in the previous period
$Inter_{h+1}$	Value of the Interconnection in the following period
$TISRE_h$	Total cost of Imported Secondary Reserve energy at time h
$ISRE_{PT_h}$	Imported Secondary Reserve energy from the Portuguese TSO at time h
$SMPD_{PT_h}$	Secondary Downward reserve price asked to the Portuguese TSO at time h
$ISRE_{SP_h}$	Imported Secondary Reserve energy from the Spanish TSO at time h
$SMPD_{SP_h}$	Secondary Downward reserve Price asked to the Spanish TSO at time h
$TESRE_h$	Total cost of Exported Secondary Reserve energy at time h
$ESRE_{PT_h}$	Exported Secondary Reserve energy from the Portuguese TSO at time h
$SMPU_{PT_h}$	Secondary Upward reserve price asked to the Portuguese TSO at time h

$ESRE_{SP_h}$	Exported Secondary Reserve energy from the Spanish TSO at time h
$SMPU_{SP_h}$	Secondary Upward reserve Price asked to the Spanish TSO at time h
$TSRG_h$	Total Secondary Reserve transacted between the Iberian TSOs at time h
$CIGCC_h$	Cost of the Iberian Grid Control Cooperation at time h
$MIGCC_{PT}$	Individual Grid Control Cooperation costs from Portuguese TSO
$MIGCC_{SP}$	Individual Grid Control Cooperation costs from Spanish TSO
$BCSDR_{PT_h}$	Bidding Costs of Secondary Downward Reserve for the Portuguese TSO
$BCSUR_{PT_h}$	Bidding Costs of Secondary Upward Reserve for the Portuguese TSO
$BCSDR_{SP_h}$	Bidding Costs of Secondary Downward Reserve for the Spanish TSO
$BCSUR_{SP_h}$	Bidding Costs of Secondary Upward Reserve for the Spanish TSO
BGC_{PT_h}	Bidding Costs Cooperation for the Portuguese TSO
BGC_{SP_h}	Bidding Costs Cooperation for the Spanish TSO
$BCGT_h$	Overall Bidding Costs Cooperation

Chapter 7

V_i	Hourly imbalance cost for agent i
D_i	Energy imbalance for the agent i
P	Hourly price for in day-ahead market
K_i	Weight of the imbalance agent in the whole imbalance system
R	Extra cost for balancing the whole system during that hour
$\underline{P}$	Market clearing prices of downward balancing reserve
$\overline{P}$	Market clearing prices of upward balancing reserve
$\underline{E}$	Total balancing downward energy
$\overline{E}$	Total balancing upward energy
TNR	Total net reserves
$WindImb_t$	Total wind imbalance
$OtherImb_t$	Aggregated imbalance of all other agents
$Load_t$	Load consumption in the period t
$Load_{t-1}$	Load consumption in the previous period
$Load_{t+1}$	Load consumption in the following period
$Trade_t$	Amount of energy traded in the period t
$Trade_{t-1}$	Amount of energy traded in the previous period
$Trade_{t+1}$	Amount of energy traded in the following period
$VW\ Avg$	Wind-generation value-weighted average
C_i	Balancing cost of the wind production

Introduction

1.1 Motivation

During the last years the change in the global energy systems are notorious. However, the pace and sometimes the direction are not well defined by some economies. Electricity produced from renewable sources now accounts for a quarter of global production and solar PV is in cheapest value ever. Instead of that, there are signs that near-term deployment of new solar capacity might be slowing down. The decease of coal has been commonly predicted and consumption fell for two years straight from 2015, but bounced back in 2017.

Energy efficiency is a recognized way of meeting several energy policy goals but is implementation appears to be beyond the desirable. It was expressed a general commitment by several nations to address the climate change, but after three flat years, the CO_2 emissions (in what concern to energy production) are on rise again until the end of 2019.

It is expected that the global energy production increases 60 %, which correspond to 15,000 TWh, until 2040. Fossil fuels remain the major source for electricity generation, however it is expected that falls at least 50% until 2040. Coal and renewables will switch positions in the generation energy mix. Actually, the share of coal is 40 % and it is expected to decline to a quarter of share in the next years. The share of Natural Gas remains steady in over 20 % and hydropower contributes with 15% of the total energy generation. The renewables all together surpass the 70% of all electricity produced. In terms of solar PV, it is expected the cost continues to fall more than 40% to 2040. Finally, the output for nuclear power plants remains around the 10% of the global power mix. China will become the country with the largest generation of nuclear energy [1].

In 2016, the power sector became the principal destination for global investment in energy supply for the first time. The same happened in 2017, with global investment in electricity generation, networks and storage reaching $750 billion, 5% more than investment in oil and gas. Such values show a long-term shift in the balance of investments flows towards electricity and clean energy technologies. The global power sector accounts for more than 60% of all capital flows into new energy supply and nearly 20 trillion USD in spent on clean technologies as a whole [2].

These signals point out to today's energy transitions as complex, uneven, multi-speed processes in a system that is under pressure to meet rising demand for energy services**.** Several critical goals are mandatory to achieve a reliable, affordable and sustainable energy future. One of them is the co-operation and regional integration with the purpose to improve outcomes, were this work is inserted. An adequate cooperation is one of the keys for the success for an adequate energy transition. To exist a deep and effective energy union strategy it is necessary the existence of solidarity between all involved actors. In the particular case of Europe, the main goal is to provide a secure, sustainable and competitive energy system to the users.

Until a recent past, the dimension of balancing reserves, their procurement and activation are mainly dealt with at a national level. After the intraday and XBID markets close, TSOs estimate their reserve needs to be able to face their national risk independently, procure the required reserves nationally, and finally activate the reserves they have secured when their system faces imbalances. A number of ongoing projects and initiatives and also pilot projects are already exploiting the benefits emerging from a deeper cooperation between TSOs. This thesis proposes some solutions and estimate savings that can be generated by introduce sharing mechanisms in the Iberian and Southwest Europe zone [3].

1.2 Power System Operation and Balancing Mechanisms

Electricity has a special characteristic that changes the paradigm of the trading process, compared with other commodities: it should be allocated at the same instant as it is produced because it cannot be stored in a national dimension scale. With this condition, the provision of electricity requires effective balance management.

The total production needs always to be equal to the total consumption in order to keep the frequency stable at the pre-defined value. This is called load-frequency control (LFC). If an electrical system (ES) is without control, the power stability and quality will be lost and will ultimately provoke a blackout. The TSO is the entity that is responsible for the power transmission and the system operation within a power system, which includes balance management. Other of TSO responsibilities is voltage control and ensuring the black-start functionality [4].

The real-time balancing energy market is a single-buyer market with a System Operator on the acquisition side. The balancing market is not only a real-time market. There exists also energy scheduling and imbalance settlement processes. The integration of balancing markets is seen as a logical follow-up step after the success of the day-ahead and intraday market integration [5].

This work will focus on the cross-border cooperation in the Iberian sphere and in the sub-region of Southwest Europe that also includes France.

1.3 The Challenge of Electrical Flexibility

Flexibility can be defined as the capacity to incorporate cumulative levels of uncertainty while keeping adequate levels of performance at a reduced costs for the defined period of time. The flexibility of a system can be observed from either a system planning or a system operation perspective. Operational flexibility is the capability of the system to adapt its operations to mutable conditions (the predictable and unpredictable) from either the generation or demand side, from timescales of seconds to hours within reasonable financial costs [6].

Energy systems have always needed a certain degree of flexibility: the electricity supply needs to balance demand at all times; on the other hand, demand has always changed hourly, daily, weekly and seasonally. From the traditional perspective in power systems, flexibility has come from thermal generation and hydropower capacity together with a combination of pumped storage hydropower, interconnections and demand-side response from large industrial and commercial consumers.

This situation, however, is changing rapidly. From the supply side, the growth of non-dispatchable resources such as wind and solar increases the need for flexibility in power systems. On the demand side, digitalisation is opening the possibility of increasing the flexibility. Steep reductions in battery storage costs are unlocking new flexibility options, while smart grids have the potential to become the backbone of modern and reliable electric systems.

New market players as demand aggregators and virtual power plants and are emerging. Because of that, distributed resources are becoming increasingly available to network operators as alternatives to traditional forms of flexibility. As the need for flexibility increases, the challenges of providing it become more complex and dependent on regulatory and market design.

The modification in the net load from one timescale to the following is a robust indicator of the need for overall flexibility – this is also known as the hourly ramping requirement of the system. The more frequent large ramps become, the higher the ramping requirement for the power system becomes, and the greater the need to source more flexibility from existing assets or invest in new sources of flexibility. Intrinsically associated are considerable increases in variable renewable energy.

However, power plants remain the main pillar of system flexibility. VRE increases the variability of net demand, and power plants are able to provide a range of essential flexibility services based on their ability to adjust output. The flexibility of existing power plants can be improved by retrofitting, while replacement with new, more flexible plants is mandatory. Changes in policy and regulatory frameworks as well as economic incentives are the key to unlock the full potential of existing power plant flexibility and to ensure adequate investment in new flexible power plants.

1.4 Research Scope

The general objective of this work is study, propose and investigate, from an economical perspective, solutions for the potential of cross-border balancing in the Southwest of Europe, in order to facilitate the current increase of variable generation with the aim of efficiently performing power balancing and securing electricity supply at the lowest possible costs. This work can be divided into three research topics of investigation:

- Elaborate a deep analysis of the cross-border balancing mechanisms between the Iberian countries, defining the concepts and methodology for calculating the profits obtained with the acquisition and provision of balancing reserve. In a second stage the importance of creating a multilateral market for balancing reserve is investigated and the potential increasing profits of this cooperation for periphery TSOs like the Portuguese one are studied;
- Investigate the possibility of extending the balancing cooperation to the automatic frequency restoration reserve in an Iberian perspective. Estimate the potential savings for an adequate coordination between TSOs;
- Evaluate the balancing costs in an Electrical System of a high share of renewables and the framework of the Portuguese balancing cost mechanism compared with other control areas.

1.4.1 Research Question

The central research question of this investigation is:

Can cross-border ancillary services contribute to a significant reduction of the costs of balancing mechanisms in a scenario of increasing renewables penetration?

The central research question will be answered with the following additional research questions:

- (Q1) What is the economic impact of the cross-border replacement reserve mechanism between Portugal and Spain?
- (Q2) Could the profits of cross-border replacement reserves (RR) in a multilateral cooperation be improved significantly compared with a bilateral one?
- (Q3) Is it possible to extend the cross-border replacement reserve to the secondary reserve regulation, with considerable cost reductions?
- (Q4) Can the variable renewable generators introduce relevant balancing costs for the Portuguese Electrical System?

1.4.2 Methodology and Approach

The methodology and the approach are elaborated according to the research questions:

- In the first research question (Q1), the concepts of the virtual scenarios will be defined: the cost of potential mobilisation (CPM) and cost without mobilisation (CWM). CPM and CWM are scenarios of replacement reserve mobilisation that did not occur. These situations would have occurred if the cross-border balance reserve regulation offers had not been activated.
  To identify the energy and the respective price of the CPM (import) or CWM (export) has not occurred, it is necessary to compare the energy activation (bought or sold) with data information from the TSOs. The different types of each scenario were also categorised, and how each impacts with the tertiary mobilisation;
- In the second research question (Q2), the economic constraints observed in a bilateral replacement reserve exchange were analysed, compared with offers submitted in a multilateral market. A cross-comparative evaluation between different bilateral combinations of TSOs' offers is elaborated. Energy and prices are compared for offers of tertiary reserve available in the first step, and in the second step for the effective tertiary transactions. After the bilateral comparison between all TSOs, the most competitive combinations are identified in terms of the direction, quantity and price. When a TSO is unable to transact energy with another TSO, a constraint is identified and the loss of economic value is calculated;
- In the third research question (Q3), the main goal is to evaluate the possibility of extending the replacement reserve cooperation between Iberian countries to a secondary reserve (SR) cooperation. The TSO with more SR energy needs in its own control area supplies to the control area with lower SR energy. In this sense, a reduction in SR energy needs may occur in each TSO, and consequently the need for SR energy is mitigated by considering the remaining demand. It as also developed an adequate methodology to provide a fair split up the savings made through the prevented use of SR energy between the TSOs;
- In the last research question (Q4), the goal is to measure wind balancing costs, using real market data, in a setting of high wind penetration. It was necessary to understand the factors in the economic and technical details that influence the wind balancing costs. The cost of balancing reserves is allocated to imbalanced agents. However, in addition to imbalances, there may be other causes for the use of reserves. Since imbalances can be either positive or negative, we focus on net reserves. To consider all potential drivers simultaneously, an hourly regression of the Total Net Reserves (TRN) was performed.

1.5 Relevance of the Work, Contributions and Associated Publications

Balance management is imperative to guarantee the security of supply, and a balancing market is necessary to certify an effective and efficient procedure in a liberalised electricity reality, which makes the cross-border balancing market a relevant topic to ensure system reliability at the same time as reducing the balancing costs. The research is conducted with the objective of maximising the efficiency of the total system, which consists on promoting adequate mechanisms of balancing cooperation. The methodology applied as focus of generating efficiency and value for the different electrical systems, without putting in strain the security of supply

The applied importance of the research lies in the design, formulation and categorisation of a process as well as the estimation of the potential profit of a comprehensive cooperation that can be used by involved actors regarding the harmonisation and integration of the balancing market.

The scientific importance of this work consists in the definition of the concepts and methodologies of cross-border balancing markets and the formulation of market design variables and performance criteria.

The following list of journal papers that categorizes the publications made is somewhat ordered in the reverse order of the structure of this thesis. Thus, paper [J4] seeks to answer the first research question; paper [J3] seeks to answer the next question raised. Starting with the analysis of secondary regulation, [J2] seeks to answer the third research question. Finally, the last research question raised is answered by [J1] and partially by [J5].

1.5.1 List of Published Articles

[J1] **P.M.S. Frade**, J.P. Pereira, J.J.E. Santana, J.P.S. Catalão, "Wind balancing costs in a power system with high wind penetration – evidence from Portugal", ***Energy Policy*** (ELSEVIER), Vol. 132, pp. 702-713, September 2019. https://doi.org/10.1016/j.enpol.2019.06.006

[J2] **P.M.S. Frade**, G.J. Osório, J.J.E. Santana, J.P.S. Catalão, "Regional coordination in ancillary services: an innovative study for secondary control in the Iberian electrical system", ***International Journal of Electrical Power & Energy Systems*** (ELSEVIER), Vol. 109, pp. 513-525, July 2019. https://doi.org/10.1016/j.ijepes.2019.02.027

[J3] **P.M.S. Frade**, M. Shafie-khah, J.J.E. Santana, J.P.S. Catalão, "Cooperation in ancillary services: Portuguese strategic perspective on replacement reserves", ***Energy Strategy Reviews*** (ELSEVIER), Vol. 23, pp. 142-151, January 2019. https://doi.org/10.1016/j.esr.2018.12.011

[J4] **P.M.S. Frade**, J.J.E. Santana, M. Shafie-khah, J.P.S. Catalão, "Impact of tertiary reserve sharing in Portugal", ***Utilities Policy*** (ELSEVIER), Vol. 55, pp. 167-177, December 2018. https://doi.org/10.1016/j.jup.2018.10.008

[J5] **P.M.S. Frade**, J.V.G.A. Vieira-Costa, G.J. Osório, J.J.E. Santana, J.P.S. Catalão, "Influence of wind power on intraday electricity spot market: a comparative study based on real data", ***Energies*** (MDPI), Vol. 11, No. 11, pp. 1-19, November 2018. https://doi.org/10.3390/en11112974

1.5.2 Publications in International Conference Proceedings

[C1] **P.M.S. Frade**, J.P. Pereira, J.J.E. Santana, J.P.S. Catalão, "Balancing reserves in a power system with high wind penetration – evidence from Portugal", in: Proceedings of the 15th International Conference on the European Energy Market — EEM 2018 (technically co-sponsored by **IEEE**), Lodz, Poland, 27-29 June, 2018. https://doi.org/10.1109/EEM.2018.8469910

1.6 Thesis Outline

This dissertation is divided into three structural parts: Background and literature study, Research and Closure, described below.

In the **Background and literature study**, an overview is given of the electricity sector, in particular with the new trends and the importance of adapting to a new renewable and integrated reality. This part is composed of two distinct chapters: the first one, Chapter 2, is dedicated to the new challenges of the System Operator in the new electrical sector paradigm.

Also, Chapter 2 will describe the role of System Operators in the importance of increasing the cooperation with peers. An overview is given of the European Network of Transmission System Operators (ENTSO-E) sphere. The different mechanisms of the load-frequency control reserves and the respective complementarity are described.

The second part, Chapter 3, is dedicated to the integration of renewables and the respective impact on electricity markets, costs and prices. With its focus on the detailed description of the importance of the integration of renewables and its impact in the electrical sector, Chapter 3 will also describe the importance of the policies on renewables for the implementation of renewable energy, with a focus on the European and Portuguese realities and their adaptation to a mature renewable reality. In this chapter a description will also be given of the electricity markets reality and the corresponding impact of the integration of renewables on electricity prices.

In the **Research, Investigation and Results** section, the core investigation and innovation of this work is developed. This part is divided into four chapters. Chapter 4 is dedicated to a detailed analysis of the cross-border mechanism implemented in Iberia as well as the definition and categorisation of concepts that allow the calculation of the profits (savings) with the cross-border transactions for the Portuguese TSO.

Chapter 5 investigates the importance of a comprehensive cooperation as concerns the RR, including the economic constraints of the existing bilateral replacing reserve markets along with the identification of the periods and quantities of economic losses in the absence of a multilateral market.

Chapter 6 investigates the possibility of extending the cross-border replacement reserve market to other mechanisms of load-frequency control, specifically the secondary reserve. Iberia geographically can be defined as a sub-region of Europe. The potential synergies will be identified and the economic losses in the event of a lack of cooperation will be calculated.

Chapter 7 presents the study of the balancing costs of a system with a high share of renewables. A detailed study from the Portuguese case scenario is presented. The Portuguese balancing market and the respective imbalance system are studied. The main drivers of balancing reserve mobilisation are defined and identified and finally the wind balancing costs in the Portuguese ES are calculated.

The **Closure** is a single chapter (Chapter 8) which presents the conclusions and remarks of this work and suggests a pathway for future investigation in this research domain.

Background and Literature Study

Chapter 2

New Challenges for the System Operator

For several decades, electricity systems were centralised and vertical structures. However, worldwide, electricity systems have been changing during the last few years. At the end of the 20th century, a considerable number of European ESs have moved to operate under an economic perspective and in an unbundling model.

Although transmission and distribution network operation are still monopolies, competition appeared in the production and retailing/commercial sectors. Producers and retailers are nowadays trading energy through bilateral contracts and/or participating in the wholesale electricity markets, making bids for the day-ahead, the intraday and hourly (continuous market) time span. In terms of ancillary services (AS), there has already existed a market for producers for some years now, and more recently this possibility has been extended for the consumers.

Simultaneously, due to the technological evolution as well as the investments made in the renewables sector, the penetration of electricity generation coming from renewable sources has been increasing significantly in the last decades. In the near future, it is expected that the share of renewables will continue to increase, namely in the form of microgeneration located throughout the electricity distribution networks [1].

Undoubtedly, these variable and dispersed generation sources will bring new challenges to power systems operation and management. An example of these challenges is the provision of AS – namely reserve services – for the integration of renewables. In fact, renewables are bringing more uncertainty and variability to the system due to the unexpected changes in power output, which requires an additional amount of balancing of reserve resources available for the SO [7].

The current chapter presents an overview and a state-of-the-art about the new challenges for the SOs, specifying the importance of the coordination of AS in a paradigm of high renewables integration and in a market environment.

Sub chapter 1 presents an explanatory definition of a System Operator, the importance of this entity, and the new reality of the SO in a regional context. This is the specific case of ENTSO-E.

Sub chapter 2 presents an overview of the balancing systems and ancillary services and the importance of a new and adequate design in the new renewable context.

Sub chapter 3 focuses on the analysis of the importance of ample transmission and cross-border mechanisms for and adequate coordination between System Operators (SO). A review of the cross-border trade in energy will be elaborated. An overview of the importance of a European strategic reserve in energy transition is given.

2.1 System Operation and Transmission

The European Internal Energy Market aims to promote trade and competition in electricity generation across the European Union (EU), with investment signals for new generation capacity and interconnection coming from zonal electricity prices reflecting scarcity value. The efforts to harmonise the balancing capacity between different TSOs and the possible sharing of their balancing mechanism may help the ESs, as in the Iberian case, to cope with the European requirements and be more competitive and active when compared to the overall European transmission system, in the near future, fulfilling the latest European directives for the energy sector and the environmental targets [8]. In [9] the option was investigated of one integrated pan-European AS market, quantifying the potential benefit of such an option and outlining a possible approach to it, highlighting its positive properties as well as the risks and challenges.

Given the challenges to electricity market design in a multi-regional context, in [10] is analysed how different design aspects, namely cross-border congestion management and capacity mechanisms, affect welfare and generation adequacy in Europe [11]. The collaboration between TSOs starts through the cross-border very high-voltage lines, where the electricity interchanges may help to reduce the imbalances arising in the demand and consumption equilibrium, or to increase the integration of renewable production, or even to aid in the enhancement of electrical security and reliability [12].

With the actual energy transition, gas power plants will develop a fundamental role in the stability of the systems, functioning as backup mechanisms. The variable nature of wind generation requires the introduction of technologies that can provide flexibility to the generation portfolios, and therefore, compensate for the intermittency of wind generation [13].

TSOs that belong to their own countries within the EU and other external TSOs whose electrical grid is connected to EU networks, and all their technical and market issues, are represented by the organisation called ENTSO-E, which comprises 41 members.

It is the responsibility of ENTSO-E to create network codes for providing and managing effective and transparent access to the transmission networks across borders, and to ensure coordinated and sufficiently forward-looking planning and sound technical evolution of the transmission system in the community, including the creation of interconnection capacities. The load-frequency control reserves, operational security, and electricity balancing are the more relevant network codes for ENTSO-E's operation [14], [15], [16].

2.2 Ancillary Services and the Importance of Load-Frequency Control

With the goal of ensuring security, reliability and quality of services in the delivery of electricity, it is necessary for the real-time operation, the Independent System Operator (ISO) or TSO utilise complementary services that can be acquired in markets developed for the effect [17]. The electricity service is provided for the utilities in alternate current (AC) with stable values of frequency and voltage [14].

Worldwide technical and economic aspects, considering several types of AS, such as voltage control, frequency regulation, and system restoration (from Australia to the Nordic countries), were presented in [18]. To ensure this stability, it is necessary to monitor permanently these values for adequate operation of the system. In Europe, the mechanisms that allow the stability of the system to be maintained are called Ancillary Services. In [19] a detailed technical description and an overview of AS in Spain were elaborated, these being very similar to the Portuguese reality. The AS can be divided into three types:

Frequency regulation – It consists in the mobilisation/demobilisation of active power supplied/ consumed by the producer/consumer to cope with possible imbalances between electricity generation and consumption;

Voltage control – It consists in the generation/consumption of reactive power with the goal of maintaining adequate levels of voltage.

Black start – It is the possibility that a power plant could start operating when disconnected from the public grid in an autonomous start. This is a fundamental service in the case of blackouts or major incidents.

The AS cannot be provided by the normal mechanisms of the spot market because they are associated with the quality and security of the delivery of electricity, which is a public good. All consumers receive electricity at the same frequency. The entity that is responsible for providing the AS is the SO, which acts as a monopsony. In this work the focus will be on frequency regulation. The other types of AS will not be developed [20].

The increasing utilisation of renewable energy sources in electricity generation is increasing the need for AS in the power system [21]. It is important to identify the relevant design variables and performance criteria that play a role in the design and analysis of the European balancing market. Frequency regulation is intrinsically connected to the balance between generation and consumption. It is still not possible today to store electrical energy at a national level at competitive market prices. However, the disruption of storage will be a game changer [22].

The generation and load that are connected to and synchronous with the UCTE grid must be controlled and monitored for secure and efficient operation. The control actions of the reserves are organised in a hierarchical structure with control areas, control blocks and synchronous areas, with two coordination centres. Figure 2.1 presents an overview of this hierarchical control structure.

As observed in Figure 2.1, a synchronous area is built by one or more Load-Frequency Control Blocks (LFC Blocks). Each LFC Block is operated by one or more TSOs, responsible for operating a given area, the LFC Area. Each LFC Block is composed of one or more LFC Areas and each area is operated by a single TSO. The main TSO is responsible for ensuring the operational security per LFC Block. TSOs maintain a certain level of operational electrical security transmission and the inherent components to the grid, to keep a continuous balance between consumption and generation within the predefined limits and following the (N-1) criterion. (N-1) means that any TSO should ensure that can lose any element of its internal grid without generating a cascade effect that could originate a black start situation.

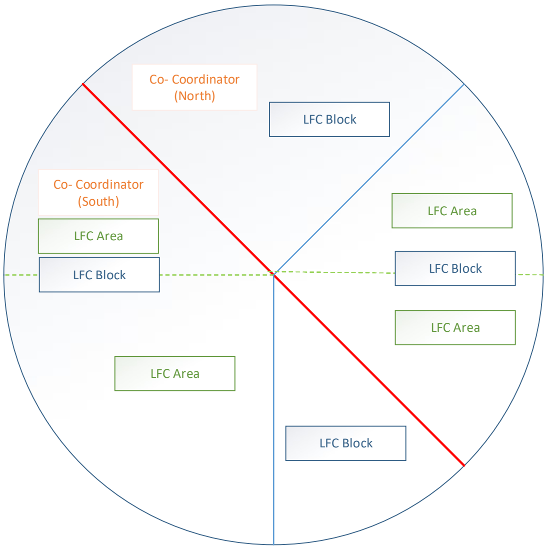

Figure2.1: Hierarchical control structure of UCTE Synchronous area composed by control areas, control blocks and co-coordination centers, control blocks and control areas.

The control actions are performed in successive steps, with different characteristics and qualities, and all are interdependent [23]. The primary control starts in a few seconds and is a joint action of all generators involved. The secondary control reserve replaces the primary control (over minutes) and is activated by the responsible TSOs. The tertiary control partially complements and replaces the secondary control reserve by re-scheduling generation. Similar to the secondary control, the tertiary control is only activated by the responsible parties/TSOs. Finally, the time control has the purpose of correcting the global time deviations of the synchronous time in the long-term as a joint action of all TSOs [24]. This is briefly shown in Figure 2.2, and described in detail next.

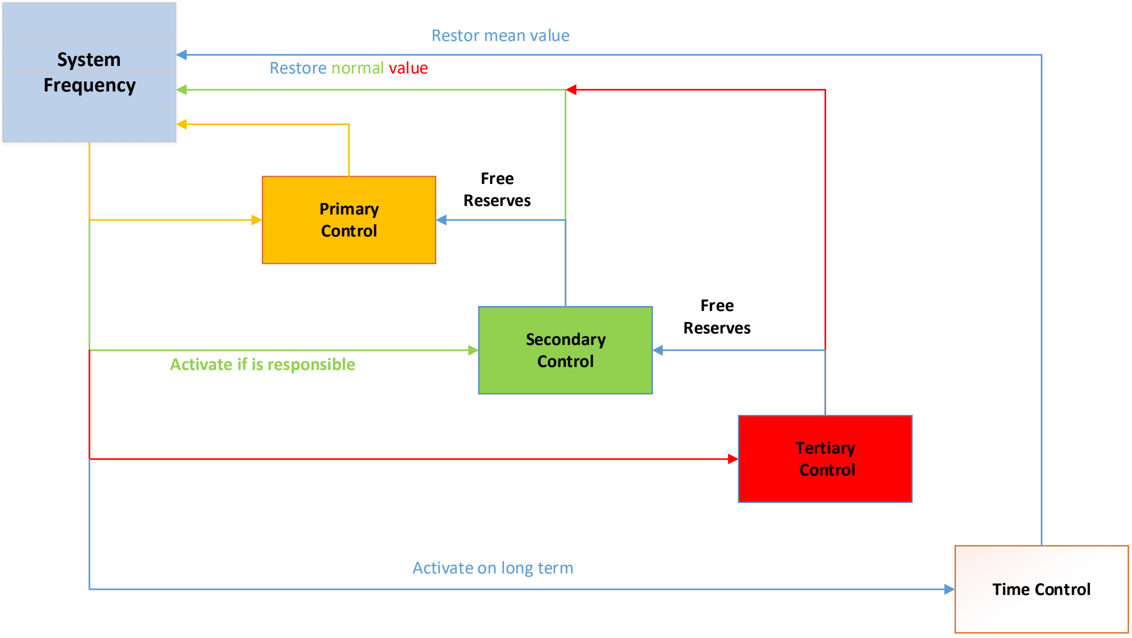

Figure 2.2: Control scheme and actions in the system frequency, based on [24].

2.2.1 Primary Regulation

When an increase of the load is observed, this phenomenon is accompanied by an increase of the electrical production and could be obtained with the opening of the admission valves of turbines or AC motors. However, this action is not instantaneous. Meanwhile, the load will be satisfied with the kinetic energy storage in the spinning mass of the generators (decrease of frequency). From an analog principle, the diminishing of the load will increase the kinetic energy storage and increase the frequency. The goal of primary control is to preserve a balance between generation and consumption (demand) within the synchronous area [20] , [22],

By the coordinated actions of all interconnected TSOs, primary control aims to guarantee the operational reliability of the power system of the synchronous area, and stabilises the system frequency at a stationary value after any disturbance or incident in the time frame of seconds, but without restoring the system frequency and the power exchanges to their reference values. Adequate primary control depends on generation or load resources made available to the TSOs [24].

Each generator has a velocity regulator that ensures the primary control of the frequency. The regulator measures the rotation velocity of the group, comparing it with the reference value and acting in the admission fluid valve of the turbine. With this operation, the mechanical power of the generator and therefore the active power of the group will be changed [25].

The control system will vary the active power until equilibrium between the consumption and generation is achieved. However, the system will enter a quasi-stationary state if in a frequency value that is different from the desired frequency. All generators connected to the synchronous grid will contribute to this stability. So a disturbance on the grid will generate a modification of the interconnection flows.

It is mandatory that, in the event of the occurrence of a contingency or incident, such as the example of load or generation loss or even a power exchange interruption, the primary control maintains the reliability of the system operation. The primary control is based on a joint action principle to ensure the system reliability and interconnected operation.

2.2.2 Secondary Control Regulation

Unlike the primary control, the secondary regulation is only mobilised in the load frequency area or the block where the disturbance occurs. The activation of the secondary reserve is centralised and continuous and makes use of the AGC (Automatic Generation Control). The action starts a maximum of 30 seconds after being mobilised and must be concluded before 15 minutes. The goal of the secondary control reserve is to restore the balance between the consumption and the generation, maintaining the interconnection of the pre-established values. With this action, the primary reserves are also restored, to become available for future situations [25].

An important metric is the K-factor, which is a value given in megawatts per Hertz and is part of the secondary control, allowing the linking of the frequency and the power deviations in the secondary controller. This corresponds to the dependency between the system frequency deviation and deviation from power exchanges due to expected primary control activation in the control area and/or control block. The K-factor is defined every year for each country and can be grossly defined as the “weight” of each country in the synchronous ES.

A disturbance (or incident) in the European Electrical Grid (EEG) results in what is called an Area Control Error (ACE) occurrence, which is the resulting deviation in the secondary control. The ACE (for an assumed control area or control block) is the sum of the power control errors and the frequency control errors, i.e., $\boldsymbol{\Delta P} + \boldsymbol{K}.\boldsymbol{\Delta f}$. The power control error is the total power deviation calculated as the difference between the total tie-line active power flow P and the control program P0, which are previously established between TSOs. The frequency control error of a control area, or control block, corresponds to the product between the frequency deviation $\boldsymbol{\Delta f}$ and the pre-defined value K-factor [24], [20].

Virtual power plants are an integral part of advanced power systems, providing different ancillary services [26]. It is mandatory that each TSO operates with sufficient control reserves under an automatic control by the secondary controller. Also, the TSO has the obligation to continuously balance its generation and interchange the schedules to its load for the control area or block.

2.2.3 Tertiary Control Reserve

The tertiary reserve is (usually) activated manually by the TSOs when it is observed (or expected) that there may be a sustained mobilisation of the secondary control reserve, i.e., it has the goal of freeing up the secondary reserve in an unbalanced situation.

It is also activated as a supplement of the secondary reserve after large incidents to restore the system frequency and consequently the primary reserve. The tertiary reserve is operated under the responsibility of the TSO. Mobilising the tertiary reserve implies changing the generation (or load) in a contractual (market and regulated) basis. This reserve could be activated directly at any time, independent from the timeframe or scheduled activated with a predefined timeframe.

Each control block must have access to a sufficient tertiary control reserve to follow up the secondary reserve after an incident. The tertiary control reserve must be available to cover the largest expected loss of power (the largest generation unit, DC-link or load in the respective control area). Each TSO has to immediately activate the tertiary reserve in the case of an insufficient free secondary control reserve being available or expected to be available.

It is possible to exchange the tertiary control reserve across borders. The tertiary control reserves should be activated by modifying the generation (or load) in the control area.

When it is necessary to transfer tertiary control reserves cross-border, these should be transferred by updating the total exchange schedule of the corresponding control area/control blocks in parallel with the activation of the reserve. This subject will be developed in a later point. It is the TSOs' responsibility to allocate sufficient transmission capacity as reserve receiving, and the reserve connection between TSOs [24], [27].

2.3 Cross Border Balancing Cooperation

As mentioned before, one of the main goals of the System Operator is to maintain the balance between consumption and generation. Policy-makers can address the challenge of balancing market design by adopting a structured approach which includes design variables, performance criteria, market conditions, system developments, and resulting market incentives. With the increase of market integration around Europe, an evaluation of common and shared ancillary services should be seriously evaluated [28] [29].

It is important to define models to determine bidding prices and quantities for reserve offers, such as has been proposed for procuring reserves and clearing the day-ahead energy market, considering the scheduled reserve capacity and transmission constraints [30]. Examples such as the Northern European Power system show several benefits of incorporating the balancing markets [31]. Cross-border reserve markets are gaining attention in academia and industry, in light of the prospect of increased cost-effectiveness and enhanced system reliability [32]. For instance, in the European reserve markets, the TSOs bear the final responsibility for balancing the generation and consumption of electrical energy on an instantaneous basis within their control area [33].

Coordinating the sizing, allocation and activation of reserves among market zones can reduce the operational costs and enhance the system reliability; however, it increases the network limitations constraints, and the reserve coordination among zones [34]. In cross-border transactions reserve markets it is fundamental to investigate the value of inter-regional coordination of reserve sizing, allocation and activation, with the goal of maximising the economic value [35].

To avoid pan-European incidents such as in 2004, the Union for the Co-ordination of Transmission of Electricity (UCTE) area was divided into five Regional Security Coordinators (RSCs), with the purpose of helping the TSOs to give a holistic view of the electrical grid in the European operation region. These coordinators provide an analysis two days ahead of the real-time, where outages in the transmission grid and the generation available from each TSO are provided, evaluating also the coordination and common problems between TSOs [36].

Cross-border trade in electricity has unique characteristics: it is constrained to an integrated wide-area transmission grid and it is often two-way. A jurisdiction may import and export electricity over the course of a year, a single day, or even at the same time if there are multiple transmission lines (interties) across a border. As an example, a novel economic theory of two-way trade in a homogeneous good, electricity, was developed in [37]. Also, a methodology to optimise the share of the net transfer capacity between balancing areas for reserve exchanges has been presented in [38].

Innovative tools, e.g., for demand response or other forecasting features, and scheduling mechanisms usually help the TSOs in Europe to have a good approximation of how to deal with the unbalancing periods and to use the reserves, interchanging electricity between the cross-border TSOs [39].

The aim for cost-efficiency of the balancing process, as a follow-up to maximising the value of trading markets by integrating national balancing markets, has brought forward proposals for cross-border cooperation on power balancing. Initial estimations of the increased potential cost–benefits of coupling balancing markets in a European dimension were studied in [40].

2.4 Brief Remarks of Chapter 2

The role of a SO has changing dramatically in the last 20 years. If the main two goals for SOs did not change (maintaining the equilibrium consumption-generation and ensure the operational security), the way, and the mechanisms to achieve the changes, and other goals, change considerably. The first cooperation mechanism it was the interconnection tie lines and was explored from a static point of view. The interconnection programs are fixed by the TSO's and without considerable exchanges during several hours or days. The interoperability is much reduced.

However, in the last 20 years, the ES, mainly in the European continent, watched to tremendous changes that modify complete the paradigm of this sector. By one side, the massive investment in renewable generation introduces unpredictability to the sector, forcing the system operators to have a more active posture in managing the energy balancing and providing operational security. A more distributed generation introduces more uncertainty to the ES in terms of quantifying the amount of load that is necessary to supply. The unidirectional flow of the transmission grid ends, and it is necessary an adequate coordination with all energy players.

Moreover, the creation of electrical markets, in the several dimensions of electrical sector, not only the spot market, but also the secondary market and tertiary ones, obligates the TSOs to have a new attitude in what concern to the balancing mechanisms. A second phase is the markets integration in the European sphere. Providing AS, or sharing imbalances, from another TSO, is a new reality that increase and deep the interoperability and connectivity between SOs.

The creation of the Regional Security Centers allows observing from a holistic point-of-view the energy flows, and could provide an integrated analysis and an efficient coordination in outage planning. The TSOs reality maintains considerably statics until the beginnings of the century. However, the fast and inevitable changes are, and will, occurring, modifying substantially the ES as is known.

Chapter 3

Renewable Integration, Policies and Influence in the Electricity Markets

Compared with the end of the 90's, the evolution of renewable energy has surpassed all expectations. The global installed capacity and the respective production from all renewable technologies have increased considerably and the corresponding costs for the generality of the technologies have decreased substantially. Another important factor is the supporting policies from countries around the world. In the initial years of the present millennium, the development and manufacturing of renewable energy equipment were focused in Europe, Japan and the United States of America. Since then, the deployment and manufacturing have spread to other regions of the globe and China has become a world leader in the sector.

Remarkable and unexpected developments have been observed in the last few years, with the lowest ever fossil fuels prices and, on the other hand, the lowest ever prices for renewable power contracts, together with a historic climate agreement that has brought together the global community. It has also been observed that renewables have become cost-competitive with fossil fuels in many markets.

In the particular situation of wind power generation, the global installed capacity has increased significantly over the past 20 years, with approx. 50 GW of installed capacity every year and wind was the leading source of new power generating capacity in Europe, the USA and the second largest in the Chinese territory. In other countries such as Canada, Mexico, Brazil and India, wind power is growing considerably. Falling prices due to the strong competition and technological improvements are the drivers making wind power an economically feasible power generation technology [1].

One of the biggest challenges in ESs is how to deal with the high share of intermittent integration from renewable production, and with the social consumption behaviour, considering the importance of reducing rates of pollutant emission, and coping with the regional targets.

However, the effects of increased variability and the intermittent nature on the net load require that conventional production fulfills the demanding operational flexibility requirements, which is where the balancing mechanism comes into operation and, as a consequence, the operational costs increase. Widespread efforts made by the scientific community are producing adequate solutions for the ES in order to improve its flexibility [41].

Examples of the North American ES show the design of the Ancillary Services markets and examine the methods by which the same are procured, highlighting the procurement practices adopted by a number of different Independent System Operators (ISO) [42]. Nordic countries, pioneers in implementing renewable generation, or even Iberia have different approaches and views [43], [44].

Sub section 1 presents an overview and underlines the importance of the integration of renewables, with the main focus on wind generation. Wind generation, from the system operation point of view, is more difficult to manage and operate compared with other forms like solar PV. The effective impact of the wind integration and adequate procedures and strategies for a system operator to minimise the fluctuation effect will be analysed. Finally, the importance of renewable energy policies to start this renewable revolution, as well the importance of coordinated market mechanisms with the renewable reality, will be emphasised.

Sub section 2 provides an overview of electricity markets costs and prices. Moreover, this point highlights how energy prices are formulated.

3.1 Renewable Integration

As mentioned in the previous chapter, the main goal of the System Operator is to guarantee that the balance between consumption and generation is maintained at every moment. A system blackout has tremendous socio-economic effects. The security of the electrical system involves several operation procedures, where are included adequate levels of balancing reserves and operational flexibility, both necessary to preserve the integrity of the system under a range of conditions including a credible plant outage and the predictable and uncertain variations in demand and availability of generation resources [6].

To integrate considerable quantities of renewable production, the System Operator will need to deal with a system where generation needs to meet a more variable conditions (defined by net demand) and higher overall system uncertainty [45]. When there is a low penetration of renewables, this impact is negligible or very low. However, when a large penetration of renewables is observed, this may significantly affect the amount of operating reserves and regulating capability to maintain the balance between supply and demand [46]. Considering that wind generation output is hard to predict at various timescales – hours, days, years – it will impact both short and long-term system reserves requirements. The quantification of the impacts of Wind Generation on the frequency response is an important field of investigation [47], [48].

It is also important to estimate the balancing costs for different technologies and to compare their dynamics across specific hours. It is important to look beyond the impact of renewable generation on the evolution of the total economic costs associated with the operation of the electricity system, with the aim of estimating the sensitivity of balancing market requirements and costs with the variable and non-fully predictable nature of intermittent renewable generation [49]. The quantification of the system integration costs of wind generation for the UK region can be found in [50] . From these studies it is possible to conclude that wind generation brings additional costs to the system.

For instance, [51] analysed whether wind turbines in the future should participate in the balancing markets and thereby play a proactive role. The analysis is based on a real-life test of the proactive participation of a wind farm in West Denmark. It was found that the wind farm was able to play a proactive role regarding downward regulation and thereby increase profits.

In [52], a concise, complete and updated review of balancing arrangements in Spain was done. Also identified were market design aspects that may act as barriers to the participation of renewable producers in balancing mechanisms. Empirical data was used to support the discussion.

In [53] it was shown that, while renewable capacity in Germany has been growing, the balancing costs have actually been decreasing (which they denote as the “German paradox”). Part of the reason is efficient cooperation by German TSOs [54]. Other studies of the German market and the RES impacts are available in [55] and [56].

The global policy landscape has largely driven the expansion of renewable energy, with the attraction of the investment and creation or adaptation of markets that support technological advances. Since the last decade, an increasing number of renewable policies have been introduced around the world and not only in developed countries. At the end of 2015, 173 countries had renewable energy targets and more than 140 have some kind of energy support policies (at a national and/or regional level) [1].

Feed-in tariffs have been the traditional way to support renewable generation. However, several countries around the world, the majority of them with mature renewable energy markets, have been changing in recent years. In the case of Europe, many countries at a national level have made cuts in the feed-in tariffs, with a considerable impact on wind and solar generation [57].

In the particular case of Portugal, the first law that allows independent producers to use renewable energy sources was created in 1988. After that, several laws were introduced, but it is important to mention the law revision of 1999, which for the first time took into account the avoided costs of operating and maintaining a conventional power plant, the avoided environmental costs (CO_2 emissions) and the inflation rate [58].

3.2 Electricity Markets, Costs and Prices

The goal of all ESs, independently of where the ES is operated, is to ensure the reliable delivery of electricity at the most competitive price (lower price) for consumers. These objectives are rooted in a long path of regulatory issues that influence the entry of new market participants, set prices and obligate a utility to provide this service.

The EU was, by the end of 2015, part way through the process of further integrating EU electricity markets by rolling out the Target Electricity Model (TEM). Most EU Member States have effectively implemented the TEM for the day-ahead. The share of market coupling had risen from 60% in 2010 to 86% at the end of 2014. It is important to estimate the potential benefit of coupling interconnectors to increase the efficiency of trading day-ahead, intraday and balancing services across borders. Further gains are possible by eliminating unscheduled flows and avoiding the curtailment of renewables with better market design [59] [60].

There are three fundamental components of the wholesale electricity supply: generation, transmission and coordination services. Because of the extreme cost associated with a power system failure, the physical requirements of the system must be ensured, even though market and operational inefficiencies are introduced. Assuring this reliability requires research on adequate generation, transmission and coordination services, i.e., the resource adequacy. Electricity demand is relatively inelastic, variable in time, and uncertain in quantity, so both generation and transmission must be constantly coordinated to satisfy the load [61].

Simultaneously, these policies must avoid incentivising an overbuilt system or overcompensating inefficient units. In Europe, most of the available markets serve day-ahead and intraday trading. The power systems and energy markets are operated separately; the market clears a dispatch order, which can then be adjusted to accommodate the transmission limitations [58].

3.2.1 Energy Prices

The day-ahead market has an important role because it provides a hedge against the price volatility in real-time markets that can be caused by several reasons such as generator outages, load forecast errors and/or other imbalances. However, the uncertainty and variability are a constant in the power systems (change of meteorological conditions, load variation, variable resources and forced outages), and can take out resources and network facilities unexpectedly [62].

Many electrical markets also have intermediate mechanisms (procedures), such as one hour-ahead (called continuous market), few hours-ahead (intraday markets), that facilitate these processes in advance of real-time when the conditions are different, as verified in the day-ahead market.

It is important that the average prices of the day-ahead and continuous (or intraday) markets converge. If this does not happen, the market participants will have preferences for one type of market instead of another. One mechanism that helps price convergence is virtual traders. They have no requirement to have physical assets (they can produce and/or consume energy).

By taking advantage of either market when there is a preferred one, these virtual agents will drive down the difference in prices between these markets. Forecasting the hourly spot price of day-ahead and intraday markets is particularly challenging in electric power systems characterised by a high installed capacity of renewable energy technologies. Empirical evidence shows how creating day-ahead markets has generated significant volatility in the wholesale electricity price. An interesting study of that is the volatility prices analysis of the hourly prices from six sessions of the Spanish intraday electricity market [63].

In addition, a novel intraday session model for hourly price forecasting in six intraday sessions of the Iberian electricity market is reported in [64]. Another facet of this market design is the existence of a natural trend for traders to arbitrage across distinct markets. If the virtual trading was not allowed, there is a potential for a premium one market that can lead to uncompetitive and inefficient market behaviour [65].

Most European electricity markets have adopted or will adopt in the near future short-time dispatch intervals (the European standard is 15 minutes). This time-frame helps to improve the system flexibility by more closely matching the changes in variable generation and the net load. Another positive aspect of the existence of short-time dispatch intervals is the reduction of the regulating reserves (tertiary reserve) needed, which are the automatic resources that can respond to online fluctuations [66].

Furthermore, the balancing resources that will act on a timescale of a few minutes will increase the price of this service even more. An example of that is the ramp in the interconnections programs. Another possibility in some markets with a high degree of flexibility is negative prices. This could occur when serving the next increment of demand and would actually save the system money [67] [68].

Also, the markets require the inclusion of multiple explanatory variables, which increases the complexity of the model without guaranteeing an improvement of forecasting skill. To obtain a correct point and a probabilistic forecasting bias, it is relevant to explore the information from daily futures contract trading and forecasts of the daily average spot-price [69].

Furthermore, the compliance with CO_2 emissions aimed at reducing fossil fuel generation has significantly increased the generation from renewable sources, which is characterised by higher intermittency than the traditional generation. It is important to understand, from the power markets side, how to absorb the large amounts of wind energy [70] [71].

3.2.2 Influence of Renewable Generation on Market prices

In a wholesale spot market, in the generation for supplying demand, competition is observed in the submission bids to sell energy for every market time schedule (hours or smaller time slots). Utilities as retailers and other market agents submit offers to purchase energy at some price to meet the same market schedules. All offers are collected by a market operator and all selling offers are sorted according to the price, allowing the creation of a curve showing the price as a function of the cumulative quantities, which is called a merit order curve. The same is done for offers to buy energy, ranked from the highest to the lowest price, and this creates a demand curve. So, from the combination of the merit order and demand curves, the market price is obtained. All bids from the supply side with energy with prices lower than (or equal to) the market clearing prices are accepted. Likewise, all offers to acquire energy with prices higher than (or equal to) the market clearing prices are accepted.

Figure 3.1 shows two typical supply curves and a demand curve for an electricity spot market. The power portfolio is made up of a range of electric power generation technologies (several types of renewable and non-renewable generation), where each technology has a marginal cost associated, which corresponds to the cost of producing an additional unit of electricity at any moment. In the case of the renewable generators, which have no fuel costs and low maintenance costs, the marginal costs are near zero. In the case of fossil fuel fired power plants, the marginal costs are strongly related to the price of the fuel [72].

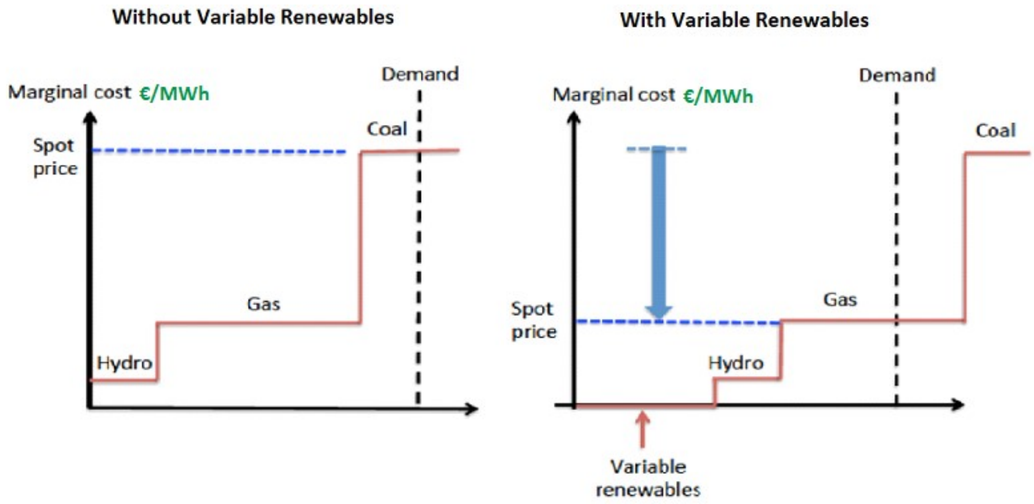

Figure 3.1: Demand and Supply without and with variable renewables

As observed in Figure 3.1, the first supply curve (left) represents the aggregated bids of several (different) production companies to provide energy, and goes from the least expensive to the most expensive power technologies without variable renewables. Accordingly, the bids provided from hydro comes at the bottom of the supply curve, followed by the non-renewable (fuel) power plants. The demand curves mainly represent the demand of retailers and big consumers. This type of curve is relatively stepped, meaning that the demand for electricity is considered inelastic – that is, it remains almost unchanged despite the energy spot price. This means that minor changes in supply may result in major price changes [58].

Since the renewable generators have low marginal costs (and for that reason are located near the bottom of the supply curve), when the supply of variable renewables are introduces and /or increases, a shifting effect of the supply curve to the right is observed (right in the figure). At a given demand, this results in a lower wholesale price, as illustrated.

The presence of wind power and/or solar PV in the electricity networks has beneficial impacts, reducing the need for non-renewable resources, and also reducing the polluting effects [73]. Moreover, wind power integration helps to reduce the operational costs, considering that less fuel will be consumed through conventional generation, and consequently emissions will be reduced. Hence, wind power also has capacity value for electricity systems. However, the possible negative impacts of wind power integration should be evaluated in order to ensure that its integration, along with its considerable benefits, is not impaired, and also, to ensure its availability through the system operation [74].

Comparisons of generation costs between renewable and conventional generation technologies are a key input to energy policy discussions. However, there are many pitfalls around the estimation of generation costs: even apparently reliable sources can quote widely divergent data. It is important to review the methodologies and data sources to determine the main sources of uncertainty in the estimation of the costs of wind, coal and natural gas generation [75].

It is mandatory to review the evolution of liberalised electricity markets and EU renewables and climate policies to enable the energy markets to adapt to the new reality and also to proceed to an adequate transition process between a feed-in tariffs reality, considering the competitive market environment [76] [77].

As observed, the massive introduction of renewable energy sources in the electricity markets is recognised to have induced a merit order effect on wholesale prices. While the day-ahead electricity prices are likely to decline as the production of renewable energy sources increases, the likely effects on balancing market sessions are more ambiguous. Taking into account the Northern Italian zone, which is characterised by a high penetration of solar power and hydro power, the empirical evidence shows that the balancing quantities have decreased while the costs have increased between two samples associated with low and high levels of renewable energy sources [78].

3.3 Brief Remarks of Chapter 3

The potential of renewable energy production is tremendous. Resources such as wind, solar and others can provide sustainable energy services based on available resources in all parts of the world. The transition to renewable energy based power systems is tending to increase, while their costs are continuously declining.

In the last decades, the demand for wind and solar systems has been continuously increasing, experiencing a reduction in capital costs and generated electricity costs. There have been continuous performance improvements and research and development activities in the sector in this period. Combined with the technological developments, the political actors are producing laws that incentivise and encourage investment in these types of technologies.

Without an adequate regulatory framework, it was impossible for these renewables to grow in the last 20 years. The biggest challenge is the coordination, from a market point of view, of these types of renewable technologies and the conventional ones. Each technology has an associated marginal cost (a corresponding cost of producing an additional unit of electricity at any moment). In the case of renewable sources, which have no fuel costs and low maintenance costs, the marginal costs are near to zero.

In the case of fossil fuel fired power plants, the marginal costs are strongly related to the price of the fuel. However, periods will occur when there is not enough sun or wind to sustain the European electrical system and a backup is necessary to maintain the balance between consumption and generation. Besides that, if it is not economically competitive to maintain a thermal power plant, the producers will shut down permanently.

For the aforementioned reasons, it is extremely important to have an integrated market in the European sphere, not only as a spot market, but also including more services markets that allow regions with different features, and with different production portfolios, to trade the energy and optimise consumers' welfare.

Research, Investigation & Results

Chapter 4

Cross Border Replacement Reserves: The Iberian Case in the Competitiveness of Balancing Markets

The Ancillary Services (AS) plays a fundamental role in the operation of Electrical Systems (ES). Since mid-2014, in the Iberian Peninsula, AS have gained a trans-national dimension, namely through the introduction of cross-border balancing Replacement Reserves (RR), between the Portuguese and the Spanish TSOs. In one hand, the Iberian ES is one of the most influenced by a high penetration of intermittent renewables, and therefore, one of the best candidates to experience increased benefits from this cooperation. On the other hand, the Portuguese TSO (and also de Spanish one) is one of the most peripheral TSOs in Europe and may benefit more from the market integration in the different dimensions of the electricity sector.

4.1 Cross Border Replacement Reserves Overview

The RR is fundamental instrument to the SO in what concerns to the balancing mechanisms. Until recent past in Europe, each country generally had its own balancing market design, which applied to its own control area and internal energy suppliers [79], [80]. However, in the beginning the present decade regions as Northern Europe TSOs, composed by Finland, Sweden, Norway and Denmark started to work on the implementation of a Cross-Border Balancing reserve regulation mechanism, [81], [82].

Additionally, and in the framework of the Electricity Regional Initiative South West Europe, the involved TSOs (REN, REE, and RTE, in Portugal, Spain, and France, respectively) started to work together to implement a replacement reserve sharing mechanism. In 2013, two bilateral provisional solutions between REN-REE and REE-RTE were considered to allow the implementation of cross-border balancing mechanisms, more specifically the sharing of RR in a TSO-TSO model, according to the Network Code on Electricity Balancing published by ENTSO-E [83].

This solution was based on, and adapted from; the cross-border mechanism implemented between National Grid (the English TSO) and RTE (the French TSO), called BALIT (balancing inter-TSO) and was designed and developed by RTE [84]. Meanwhile, the involved actors were studying the design and the development of a long-term regional and permanent solution (REN-REE-RTE) multi-TSO platform, extensible to other interconnected areas. The exchange of tertiary reserves between Iberian countries started in June 2014 [85].

The introduction of the tertiary cross-border mechanism has the purpose of increasing and generating a certain level of market competition. The possibility of partial market coupling to the reserve exchanges will increase the economic welfare in the electricity sector [86]. As major example, the electricity market introduced in the Iberian Peninsula in the last decade yielded positive results in terms of integration for both countries.

When the Iberian Spot Market started, a considerable quantity (more than 80%) of market splitting was presented, motivated by the lower price of energy on the Spanish side. After more than a dozen years of the *Mercado Ibérico de Energia* (MIBEL) operation, the periods of market splitting have been reduced to less than 5% in some periods, with the electricity lower price on the Portuguese side [12].

In the current chapter, it will be intended to analyze the economic impact of the introduction of cross-border balancing services, in particular, the tertiary reserve mechanism in the Iberian ES from the Portuguese TSO perspective. The introduction of cross-border balancing mechanisms started operating between Portugal and Spain in mid-June 2014. As such, the current work will consider for the study the period between July 1, 2014, and December 31, 2017 [87]. In this process, it was created a model to define and categorize the energy mobilizations.

In Section 4.2 it will be described the tertiary (or replacement reserve) sector in the Portuguese ES, and also the operationalization of the energy mobilizations. In Section 4.3, it was created and defined the model and a description of the economic value of the exchange transactions is presented, comparing these transactions with the previous situation, the exclusive national tertiary market. Section 4.4 specifies the calculation process for evaluating the economic results. In Section 4.5 presents the results on a daily and monthly basis followed by the main remarks found in this current work.

4.2 Replacement Reserve: Importance and Operationalization

The energy sold in the spot market, i.e., the quantity of equilibrium, Qe, does not always match the reality of the national consumption needs. It is almost impossible to predict the exact consumption at a given hour. Over each hour, consumption exhibits dynamic behavior, with several upward or downward variations caused by multiple natural and social factors. Renewable generation, particularly the wind generation, has a significant impact on the market results. The difficulty in predicting wind resources with high accuracy has an impact on the energy sold in the spot market.

After the spot market, two different "markets" are organized at the national level. These are the tertiary reserve downward and upward markets for each of the TSO included in the Iberian Electricity Market (MIBEL). Table 4.1 resumes the tertiary balancing market during the 2015 to 2017 period. In the Portuguese case, the generation units that did not sell their energy on the spot market submit to the respective SO at the price that they are willing to receive to produce an additional quantity of energy. When all producers submit their prices (and respective quantities) to the SO, they are organized by ascending price (cheapest to most expensive) [80], [88], [89].

Table 4.1: Tertiary balancing market results.

Year	Spot Price (€/MWh)	Tertiary Upward (€/MWh)	Tertiary Upward (GWh)	Tertiary Downward (€/MWh)	Tertiary Downward (GWh)
2015	51.2	68.2	693	29.0	1269
2016	40.1	54.0	1154	22.8	1284
2017	53.2	71.3	971	36.8	1308

If the SO needs to mobilize a given quantity of energy upward, Qu (MWh), it will pay the marginal upward price, Pu (€/MWh) to the respective(s) producers(s). All suppliers who produce this extra quantity of energy, requested by the SO will receive Pu for the energy that suppliers provide, which corresponds to the price of the last (and most expensive) MW produced. This price is generally higher than the spot price, Ps, and corresponds to an "over-cost" for the ES. This over-cost is the difference between the tertiary regulation price upwardly mobilized and the market price (or spot price). In the case of tertiary activated upward, the upward over-cost is calculated by the given Equation 4.1:

$$OCu = (Pu - Ps)Qu \tag{4.1}$$

where Pu is the price of the tertiary activated upward (€/MWh), and Ps is the spot price (€/MWh). Qu is the quantity of tertiary reserve activated upward (MWh).

The generation units that sold their energy in the spot market submit to the SO the quantities and the corresponding price they are willing to refund (the ES) to reduce or stop production. When all producers submit their prices (and respective quantities) to the SO, his prices are arranged in descending order. In other words, the agents who are available to refund more € to stop/reduce production are prioritized on the list. If the SO needs to mobilize a given quantity of energy downward, Qd, the respective producer(s) will pay (refund) the ES the downward price, namely, Pd.

All suppliers who reduce this quantity of energy requested by the SO will refund the system the Pd , which corresponds to the price of the last (cheapest) MW reduced. Importantly, this producer(s) had already received Ps for the energy sold on the spot market. Generally, Pd is lower than Ps, and in this case, there occurs an over-cost to the ES: the difference between the spot price and the tertiary regulation downward price. In the case of the tertiary downward activation, the downward over-cost is calculated by the given Equation 4.2:

$$OCd = (Ps - Pd)Qd \tag{4.2}$$

where Pd is the price of the tertiary downward activation (€/MWh). Qd is the quantity of tertiary reserve activated downward (MWh).

A simple example is presented in Figure 4.1. In the Portuguese ES, one product is only defined for balancing reserves activated manually for the SO. Operationally, in the analyzed period, and for the Portuguese SO, manual Frequency Restoration Reserve (mFRR) and RR are the same products and commonly defined as a tertiary reserve. In Table 4.2 the respective over-cost generated during the 2015 to 2017 period are expressed [89].

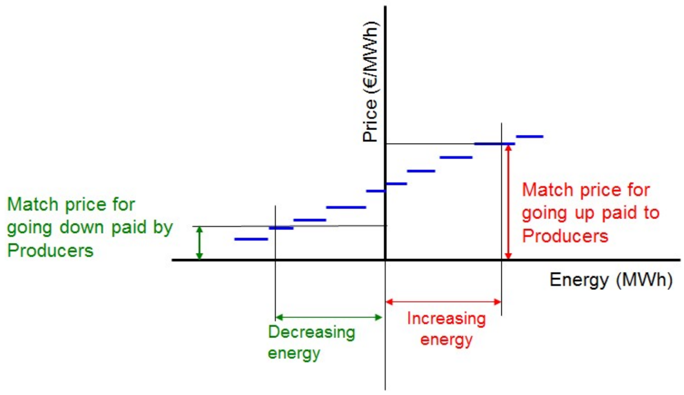

Figure 4.1: Tertiary reserve mobilization example.

Table 4.2: Overcost results in the Portuguese ES.

Year	Over-cost Upward (M€)	Over-cost Downward (M€)	Total Over-cost (M€)
2015	11.78	15.38	27.17
2016	16.04	19.96	36.00
2017	17.58	15.92	33.50

4.3 Economic Value Definition of the Cross-Border Replacement Reserves

The main goal of the cross-border tertiary regulation exchanges is to reduce the over-cost resulting from the gap between the market results and the real consumption needs [90]. When the sharing of a certain quantity of tertiary reserve, Q, occurs between TSOs, a business balance activation (BBA) has happened. The BBA can be of two types, from the perspective of the TSO: business balance import (BBI), if the reference TSO imports tertiary reserve from another TSO, or a business balance export (BBE), if the reference TSO exports reserve regulation to another TSO.

The Portuguese TSO (i.e., REN) will be the reference TSO [91]. In the case of BBI, the Portuguese TSO imports from the Spanish TSO a certain amount of reserve regulation, Q, at a certain price of balance import (PBI), which corresponds to the value of balance imports (VBI):

$$VBI = (Pi - Ps)Q \tag{4.3}$$

To calculate the profit on each BBI, it is necessary to examine the alternative path by looking for the Portuguese reserve regulation offers and the corresponding Q at the corresponding price, $P(Q)$, in the internal (national) market of reserve regulation. To calculate the profit (or savings) of the operation, again, it is necessary to compare the cost of the tertiary reserve mobilized, CM, plus the cost of buying this energy from the other TSO, instead of acquiring all the Portuguese tertiary reserve internally, to the cost of the potential mobilization CPM, from Equation 4.3.

$$Profit\ of\ BBI = CPM - (VBI + CM) \tag{4.4}$$

In the case of BBE, the Portuguese TSO sells (exports) to the Spanish TSO a certain Q, at a certain price of balance export, PBE (€/MWh), that corresponds to the value of balancing export, VBE (€).

$$VBE = (Pe - Ps)Q \tag{4.5}$$

To calculate the profit on each BBE, it is necessary to consider the value of the sale (VBE) and the difference between the cost of the tertiary reserve mobilized, the cost of mobilization, CM, (the sold energy that was contemplated), and the cost of the tertiary reserve, if a tertiary exchange had not occurred, the cost without mobilization, CWM, who represents "only" the national tertiary needs. See Equation 4.6.

$$Profit\ of\ BBE = VBE - (CM - CWM) \tag{4.6}$$

Each TSO sends to the platform the offers that are available for providing or acquiring tertiary balancing reserve, as determined by established rules and procedures. The main rule that all TSOs must follow is that any TSO is obligated to send offers for the sharing platform. Therefore, any TSO must consider in the operational planning of reserve calculation the energy provided in the exchange platform because there is no warranty that offers are made. These offers, which the TSO provides for the platform, are the tertiary offers sent by the national market agents for the respective TSO.

Before sending offers to the platform, the TSOs make an analysis here to identify the potential need for tertiary downward and upward with a considerable "degree of certainty". Only a part of the remaining offers was sent to the platform. Each TSO can provide for the platform a maximum of ten offers to sell and/or buy tertiary reserve.

Each offer is a 50 MWh block that is associated with a determined price (€/MWh). As mentioned before, it is not mandatory that any of the TSOs provide offers in any direction (buy or sell) or quantity for the platform. Each TSO has the possibility of activating between one and ten offers to another TSO.

Eventual energy traded in the tertiary exchange platform is added to the interconnection, and it is not possible to mobilize in the real-time. The reserve exchanges between TSOs do not integrally substitute the national tertiary mobilizations. Only this reserve can be mobilized or demobilized during the period [92].

4.4 Methodology: Calculation of the Virtual Scenarios and Profit of BBA

To evaluate the gains of cross-border transactions (from the Portuguese point-of-view), it was necessary to identify and organize the transactions occurring during the period for which the tertiary (or replacement) reserve was traded. This period was divided into two groups: buy (acquisition) or sell (provide) RR.

For each market period (hour), it was necessary to verify the mobilization of the internal RR. After that observation, the next step is to calculate the virtual scenario where the internal mobilization of the tertiary reserve is simulated as if the cross-border transaction had never occurred. After crossing the virtual mobilization with the tertiary that was effectively mobilized, six distinct patterns were identified that allow for categorizing cross-border transactions: three for acquisition and three for provision. Using this categorization, the third step compares the economic result of the cross-border transaction with the virtual impact of the internal energy mobilization.

CPM and CWM are scenarios of tertiary reserve that did not happen. These situations would have occurred if the cross-border balance reserve regulation offers had not been activated. To identify the energy and the respective price of the potential mobilization (import) or the scenarios where mobilization (export) has not occurred, it is necessary to compare the energy activation (bought or sold) with the following data information [93]:

- The previous tertiary offers (available by the producers) upward and downward at each hour, where the producers indicate the quantity and the respective price that they are willing to produce for an extra quantity of energy or the quantity and price they are available to refund to the system for its reduction by a determinate quantity of energy;
- The tertiary offers (quantity and price) assigned to upward, Qu, and downward, Qd, mobilizations, for each hour.

The first step is to observe the tertiary reserve offers upward and extracting all the energy blocks related to thermal units that were stopped. The system operator, if intending to assign an offer from a stopped thermal unit, may consider the dynamic parameters and the related start-up costs. Power plants that do not participate in day or intra-day markets are represented in the upward tertiary offers, but they are not available in real time. The assignment may be planned several hours ahead and with extra costs, such as the start-up costs, and with several constraints related to the dynamic parameters [90]. These tertiary offers are simply not real-time offers. After they are removed, it is left with the net tertiary offers.

The second step is to calculate our virtual tertiary assignment. As mentioned, if the cross-border balancing services had not occurred, this amount of energy would have been assigned to the internal tertiary market. It is required to add Q to the assigned offers Qu or Qd and identify the quantity of energy upward without cross-border balancing mechanisms, $Quwb$, and the corresponding upward price without cross-border balancing mechanisms, $Puwb$, or the quantity of energy downward without cross-border balancing mechanisms, $Qdwb$ (MWh), and the corresponding downward price without cross-border balancing mechanisms, $Pdwb$. This corresponds to the potential internal offers assignment [94].

4.4.1 Cost of Potential Mobilization and profit of BBI

After the acquisition of tertiary reserve from the Spanish TSO, three situations were identified that could occur and influence the way that the profit is calculated. The first situation corresponds to the "classical" scenario.

In this scenario, upward (Qu) and downward (Qd) mobilizations of tertiary reserves could occur, as shown in Figure 4.2. Two specific situations exist that derive from the classical scenario: – the first is the existence of Qu and the non-existence of Qd. The second is $Qu = 0$, and $Qd = 0$. These two particular cases are represented in Figures 4.3 and 4.4, respectively. From the Figures 4.2 – 4.4 allow the easiest comprehension of the calculation process. Recall that if the BBI had not occurred, the amount of energy upward would have been $Quwb$ and not Qu. Another important correlation is: $Quwb = Qu + Q$. So, the potential cost generated, CPM, is obtained by the following equation:

$$\begin{aligned} CPM(€) &= (Puwb - Ps)Quwb + (Ps - Pd)Qd \\ &= (Puwb - Ps)(Q + Qu) + (Ps - Pd)Qd \\ &= (Puwb - Ps)Q + (Puwb - Ps)Qu + (Ps - Pd)Qd \end{aligned} \tag{4.7}$$

As was observed in Equation 4.5, in this scenario, the cost of internal mobilization is given by Equation 4.8:

$$CM = (Pu - Ps)Qu + (Ps - Pd)Qd \tag{4.8}$$

Therefore, all the conditions are met to proceed with the calculations and evaluation of the importation tertiary reserve profit. By re-formulating the Equation 4.4, it turns:

$$Profit\ of\ BBI = CPM - (VBI + CM) \tag{4.9}$$

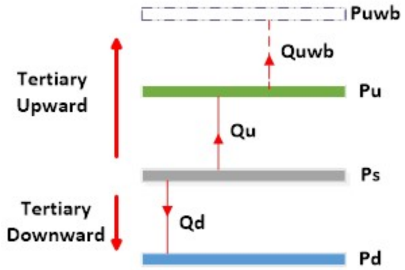

Figure 4.2: Mobilization of tertiary reserve in the classical scenario in CPM situation.

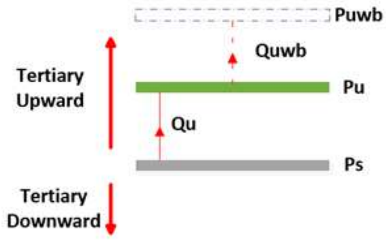

Figure 4.3: Tertiary reserve in the classical scenario in CPM situation ($Qd = 0$).

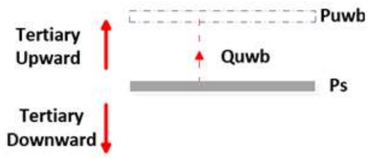

Figure 4.4: Tertiary reserve in the classical scenario in CPM situation ($Qu = Qd = 0$).

Carrying out the substitution, it is obtained the Equation 4.10:

$$\begin{aligned} Profit\ of\ BBI &= \big((Puwb - Ps)Q + (Puwb - Ps)Qu + (Ps - Pd)Qd\big) \\ &\quad - (Pi - Ps)Q - \big((Pu - Ps)Qu + (Ps - Pd)Qd\big) \\ &= Q(Puwb - Ps - Pi + Ps) + Qu(Puwb - Ps - Pu + Ps) \\ &= Qu(Puwb - Pu) + Q(Puwb - P) \end{aligned} \tag{4.10}$$

In the second scenario, it is observed that a tertiary downward occurs. However, if BBI did not occur, it would be necessary to mobilize tertiary upward ($Q > Qd$). Figure 4.5 represents this situation. In this scenario, the potential over-cost, CPM, is given by Equation 4.11:

$$\begin{aligned} CPM = (Puwb - Ps)Quwb &= (Puwb - Ps)(Q - Qd) \\ &= (Puwb - Ps)Q - (Puwb - Ps)Qd \end{aligned} \tag{4.11}$$

Retyping Equation 4.3, the cost of internal mobilization is given by Equation 4.12:

$$CM = (Ps - Pd)Qd \tag{4.12}$$

Carrying out the substitution, it is obtained the Equation 4.13:

$$\begin{aligned} Profit\ of\ BBI &= (Puwb - Ps)(Q - Qd) - (Pi - Ps)Q - (Ps - Pd)Qd \\ &= Q(Puwb - Ps + Pi + Ps) - Qd(Puwb - Ps + Ps - Pd) \\ &= Qu(Puwb - Pu) + Q(Puwb - Pd) \end{aligned} \tag{4.13}$$

In the third and last scenario, it is observed a mobilization of tertiary downward. However, if the BBI had not occurred, then, although there would still have continued to exist a tertiary downward, it would have been smaller ($Q < Qd$). Figure 4.6 helps to understand this scenario. In this case, CPM is given by Equation 4.16:

$$CPM = (Ps - Pdwb)Qdwb = (Ps - Pdwb)(Qd - Q) \tag{4.14}$$

By retyping Equation 4.3, the cost of internal mobilization, CM, is similar to the previous case, Equation 4.13, so, carrying out the substitution, the BBI profit can be calculated as Equation 4.15:

$$\begin{aligned} Profit\ of\ BBI &= (Ps - Pdwb)(Qd - Q) - (Pi - Ps)Q - (Ps - Pd)Qd \\ &= Q(Pdwb - Ps + Pi + Ps) - Qd(Ps - Pdwb - Ps + Pd) \\ &= Q(Pdwb - Pi) - Qd(Pdwb - Pd) \end{aligned} \tag{4.15}$$

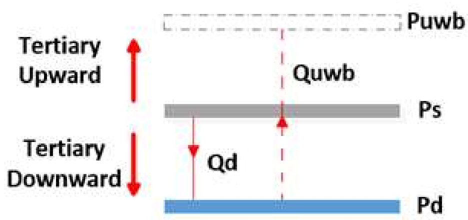

Figure 4.5: Tertiary reserve in the second scenario in CPM situation.

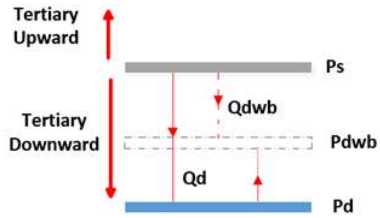

Figure 4.6: Tertiary reserve in the third scenario in CPM situation.

4.4.2 Cost of Without Mobilization and Profit of BBE

Conceptually, the following proceedings referring to exportation transactions are similar to the importation situations, only with a different direction. After a sale of the tertiary reserve, three distinct situations can occur. The first situation, which can be observed in Figure 4.7, is the base (or classical) scenario. In this scenario, mobilizations of tertiary reserve upward and downward both exist. Two particular situations derive from the base scenario. The first one does not have a tertiary upward, hence $Qu = 0$. In the second situation, It is not observed either upward or downward tertiary mobilizations, and hence $Qu = 0$, and $Qd = 0$.

Figures 4.8 and 4.9 allow an easier comprehension of the process. To calculate the potential scenario, the cost without mobilization, CWM, it turns:

$$\begin{aligned} CWM(€) &= (Pu - Ps)Qu + (Ps - Pdwb)Qdwb) \\ &= (Pu - Ps)Qu + (Ps - Pdwb)(Q + Qd) \\ &= (Pu - Ps)Qu + (Ps - Pdwb) * Q + (Ps - Pdwb)Qd \end{aligned} \tag{4.16}$$

Retyping Equation 4.5, in this scenario, the cost of mobilization is given as Equation 4.17:

$$CM = (Pu - Ps)Qu + (Ps - Pd)Qd \tag{4.17}$$

Therefore, it is possible to calculate the tertiary reserves' exportation profit. By retyping Equation 4.4 it is possible to obtain the BBE's profit by substituting in Equation 4.17 as follows:

$$\begin{aligned} Profit\ of\ BBE &= (Pe - Ps)Q \\ &-\big((Pu - Ps)Qu + (Ps - Pd)Qd - ((Pu - Ps)Qu + (Ps - Pdwb)Q \\ &+ (Ps - Pdwb)Qd)\big) \\ &= Q(Pe - Ps + Ps - Pdwb) + Qd(Pd - Ps + Ps - Pdwb) \\ &= Q(Pe - Pdwb) + Qd(Pd - Pdwb) \end{aligned} \tag{4.18}$$

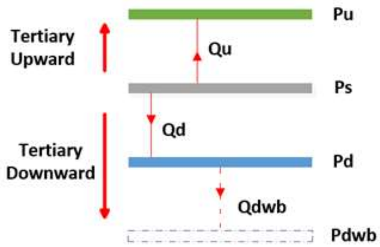

Figure 4.7: Mobilization of tertiary reserve in the classical scenario in CWM situation.

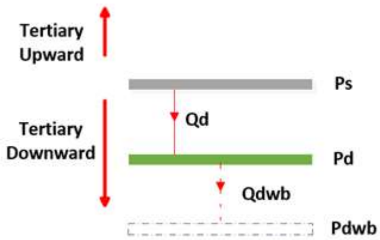

Figure 4.8: Tertiary reserve in the classical scenario in CWM situation $(Qu = 0)$.

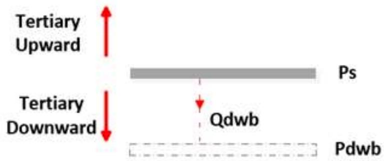

Figure 4.9: Tertiary reserve in the classical scenario in CWM situation ($Qu = 0$*).*

In the second scenario, there was an upward tertiary mobilization. However, if the sale had not occurred, it would have been necessary to mobilize tertiary downward ($Q > Qu$). It is possible to observe this situation in Figure 4.10. In this case, CWM is given by Equation 4.19:

$$\begin{aligned} CWM = (Ps - Pdwb)Qdwb &= (Ps - Pdwb)(Q - Qu) \\ &= (Ps - Pdwb)Q - (Ps - Pdwb)Qu \end{aligned} \tag{4.19}$$

By retyping Equation 4.3, in this scenario, the CM is given by:

$$CM = (Pu - PS)Qu \tag{4.20}$$

By substituting in Equation 4.20, the BBE's profit can be calculated by:

$$\begin{aligned} Profit\ of\ BBE &= (Pe - Ps)Q \\ &\quad - \Big((Pu - Ps)Qu - \big((Ps - Pdwb)Q - (Ps - Pdwb)Qu\big)\Big) \\ &= Q(Pe - Ps) - Qu(Pu - Ps) + (Ps - Pdwb)Q - (Ps - Pdwb)Qu \\ &= Q(Pe - Ps + Ps - Pdwb) + Qu(Ps - Pu - Ps + Pdwb) \\ &= Q(Pe - Pdwb) + Qu(Pu - Pdwb) \end{aligned} \tag{4.21}$$

The third and last scenario has a mobilization of tertiary upward. However, if the BBE had not occurred, then there would have still been a tertiary upward, but it would have been smaller. Figure 4.11 supports the understanding of this scenario. The CWM, in this case, is given by Equation 4.22:

$$CWM = (Puwb - Ps)Quwb = (Puwb - Ps)(Qu - Q) \tag{4.22}$$

By retyping Equation 4.3, and considering Equation 4.20, the BBE's profit in the third case can be calculated:

$$\begin{aligned} Profit\ of\ BBE &= (Pe - Ps)Q - \big((Pu - Ps)Qu - (Puwb - Ps)(Qu - Q)\big) \\ &= (Pe - Ps)Q - (Pu - Ps)Qu + (Puwb - Ps)Qu - (Puwb - Ps)Q \\ &= (Pe - Ps - Puwb + Ps) + Qu(Ps - Pu + Puwb - Ps) \\ &= Q(Pe - Puwb) - Qu(Pu - Puwb) \end{aligned} \tag{4.23}$$

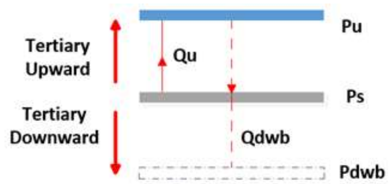

Figure 4.10: Tertiary reserve in the second scenario in CWM situation.

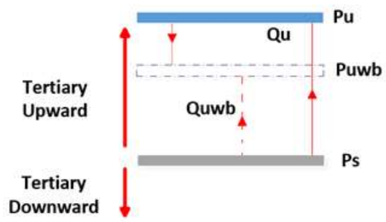

Figure 4.11: Tertiary reserve in the third scenario in CWM situation.

4.5 Result Analysis

First, a general (macro) analysis of the obtained results is performed, with the aid of some previous remarks and findings. Next, a more detailed analysis is performed, arranging the results in a different manner to enable two different types of reflections:

i) A daily analysis (short-term vision) where we can understand the behavior and the characteristics of both electricity systems over a complete market day;

ii) A more long-term perspective where it is possible to understand the evolution of these cross-border exchanges over the complete period of analysis, realized in a trimestral base.

4.5.1 General Overview of the Results

During the analysis period (3.5 years), tertiary reserves were shared, BBAs, in 3821 hours. Out of the total BBAs, 2948 were BBIs and 873 were BBEs. From this information, it is possible to make some preliminary conclusions:

<u>First finding</u>: The percentage of hours when BBAs occurred was 3821/21925 or ~17.5%. For 82.5% of the time, the reserve regulation prices are very similar in both Iberian TSOs, and it was not "potentially profitable" to buy or sell tertiary reserves in the remaining hours of the analysis period. The prices and quantities of the tertiary regulation reserves of the Iberian TSOs are directly influenced by climate conditions; both TSOs have in the portfolio a considerable quantity of renewable energy production, mainly hydro and wind generation.

When a "windy" day occurs in Portuguese territory, there will be a very large probability that it will has a “windy” day in Spain. Moreover, when long periods of rain occur in Portugal (wet years), there is a large probability they also occur in Spain too. Additionally, both TSOs share three hydraulic interconnections: three rivers that are shared by both countries in the production of electricity (two in the Douro River, and one in the Tejo River). This fact helps to understand the correlation between the characteristics of both TSOs [25].

<u>Second finding:</u> It was found that 77% of the BBAs are BBIs and only 23% are BBEs. Allegedly, the existence of more market players on the Spanish side, with greater relevance at the production level, contributes to the improvement of the competitiveness and in turn generates tertiary reserve offers that are cheaper on the Spanish side than on the Portuguese one.

Considering Figure 4.12, and as far as the Spanish TSO is concerned, it was verified that, on average, when tertiary reserves are shared, the quantity offered to sell, for most of the hours, is very close to the maximum tertiary reserve allowed (500 MW). Concerning the acquisition of tertiary reserve, the value that is offered is also nearly the maximum (but not as high as in the exportation cases), with a relative decrease in off-peak periods.

The Portuguese TSO, presents a predisposition to transact a smaller value than the Spanish TSO, whether in the acquisition or in the availability of energy. In the generality of hours, there is more importation availability, with the exception of peak periods when, as with the Spanish TSO, it is observed an increased availability to export. As seen in Figure 4.13, it is possible to observe the prices at which both TSOs were available to buy and sell tertiary reserves. In the situation of acquisition, as well as the availability of energy, the Portuguese TSO employs a higher price; it is willing to sell for a higher price than the Spanish TSO but is also available to buy energy for a higher value.

Furthermore, it is possible to observe a decrease in buying and selling prices, in both TSO's, during the off-peak periods, since both have more energy available. The price evolution shows a similar tendency in both countries, although it is more visible in exportation scenarios due to the time difference of one hour between the two countries.

The analyses presented in Figures 4.12 and 4.13 corroborate the tendency of the actual transactions, as explained in the general considerations. The importer profile of the Portuguese TSO, allied to the lowest prices of Spanish TSO (to import and export), validates the earlier findings. It is possible to observe that, for the generality of the hours, in exportation or importation scenarios, the Spanish TSO offers close to the maximum of energy allowed by the platform (system), while the Portuguese TSO only provides 60% to 80% of the maximum allowed. This fact is related to the dimensions of both electricity systems, connected with their domestic consumption. In Spain, the energy consumption is five to six times higher, compared to Portugal, so the impact of a transaction of 500 MW is significantly different for the two different systems.

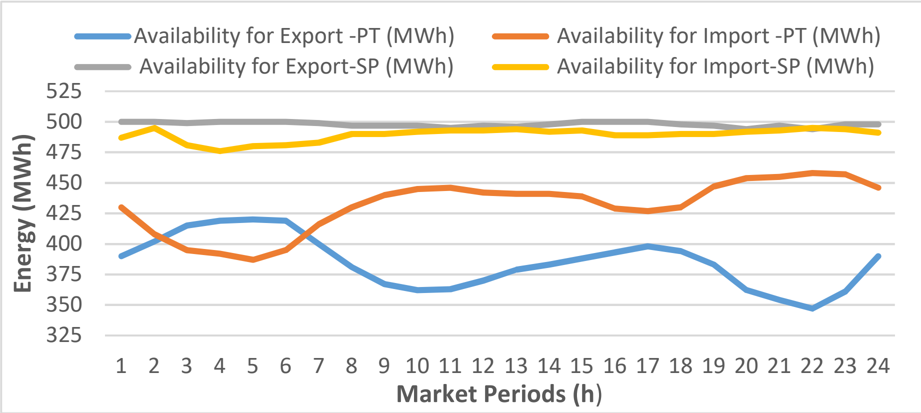

Figure 4.12: Available energy to trade between Portugal and Spain.

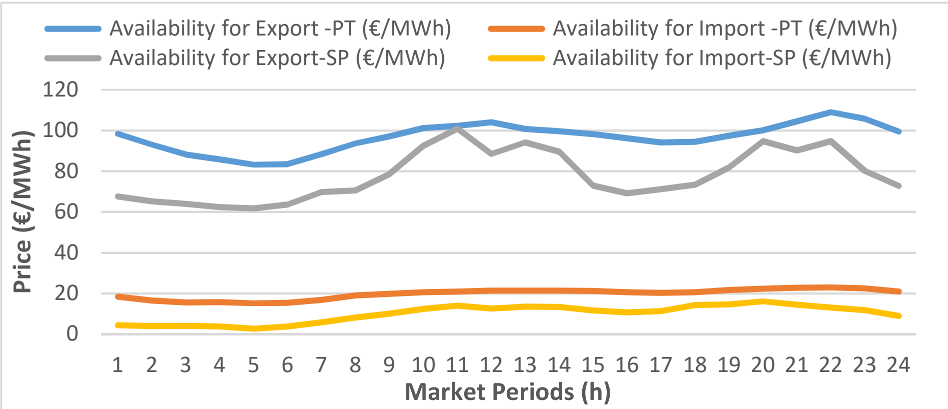

Figure 4.13: Available price to trade between Portugal and Spain.

In the next figures, it will be possible to observe the submitted offers by both TSO, in a long-term perspective. In detail, Figure 4.14 shows the amount of energy available for the transaction, for both TSOs. Starting with the Spanish TSO, it shows itself to be almost totally available to export, as well as at high disposal to import. These results corroborate the findings obtained previously, regardless of the dimensions of the two systems. In what concerns the Portuguese TSO, the long-term behavior is relatively consistent with the daily analysis.

A general predisposition to import, with the exception of the 2nd and 3rd quarters of 2015, is patent. It is possible to observe an increase in available energy (import and export) to trade during the five initial quarters. In the remaining period, a decrease of the exportation availability and stabilization of the import trend is verified.

The predisposition for importation of the Portuguese TSO is easily identified. Figure 4.15 shows the average value (€/MWh) of available offers, in both TSOs. In what concerns the price disposal for importation, the tendency is similar during the analysis, with oscillations both in Portugal and Spain. The Portuguese TSO is the one that is available to buy energy for a higher price.

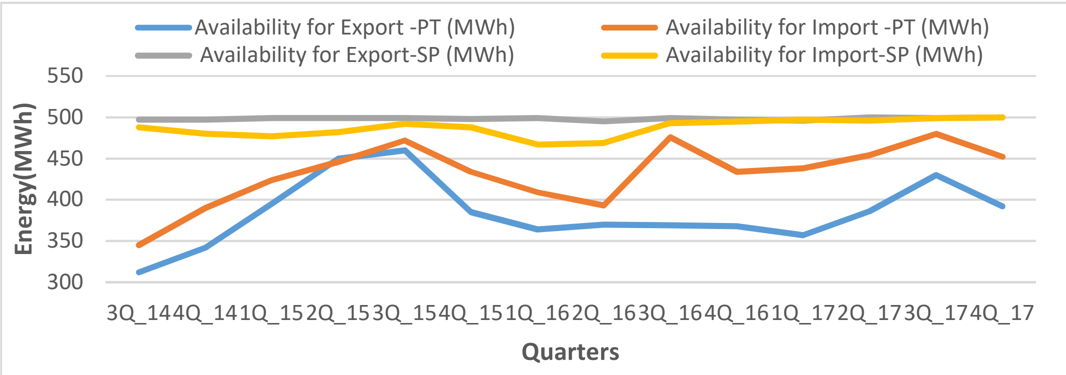

Figure 4.14: The amount of energy available for the transaction between Portugal and Spain.

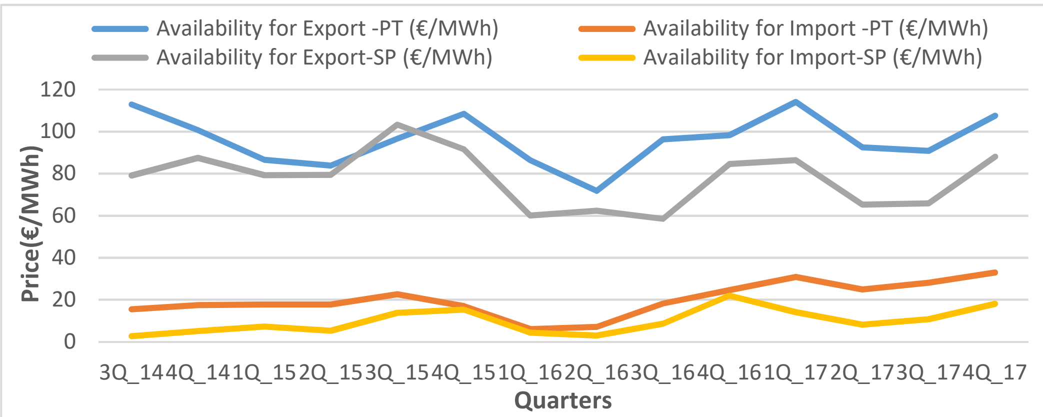

Figure 4.15: The available transaction price between Portugal and Spain.

Concerning the average value at which the TSOs are disposed to export, in almost all quarters (with the exception of one) the Spanish TSO is the most competitive TSO. This analysis considered the price and the quantities of offers by both TSOs.

No analysis was made of the actual transactions. This study will be carried out subsequently. However, the evaluation already carried out, mainly from the long-term perspective, shows an initial predisposition on the part of the Portuguese TSO for importation, which predicts that there will be a balance on the transactions, at the end of the period under review.

4.5.2 Daily Analysis

Figure 4.16 shows the effective transactions from a daily perspective. First, it is possible to perceive that there are more transactions during peak periods than off-peak periods, although it is a slight difference. Historically, the results of spot market show Portugal as an importer, in off-peak periods. The main reason for this trend is the existence of nuclear power plants in the Spanish electricity system.

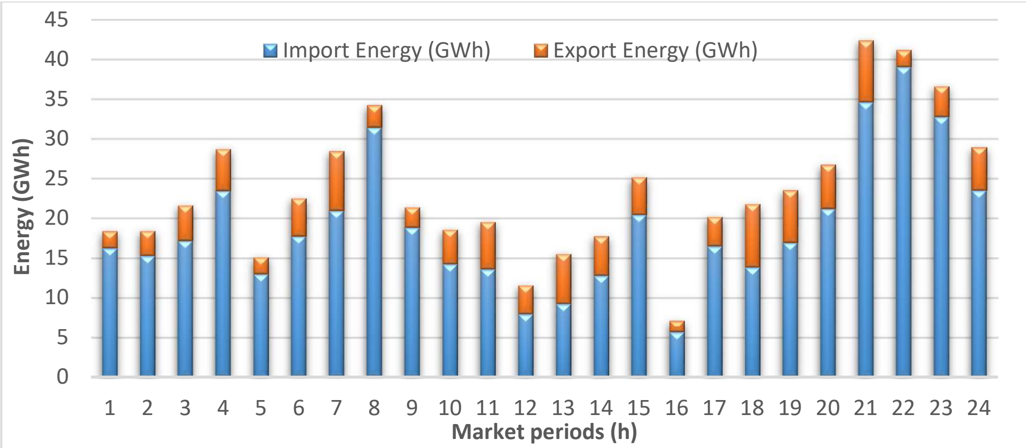

Figure 4.16: Effective energy transactions between Portugal and Spain in a Daily perspective.

The existence of this type of power plant reduces the price of electrical energy, mainly in off-peak periods. The "necessity" of working in a full power regime is the key motive [95]. In the peak periods, the sale of tertiary reserves from the Portuguese TSO is more visible.

The main motive is the existence of high penetration of hydropower plants in the Portuguese electricity system (not too pronounced), which allows the covering of the peak periods agilely and quickly compared to thermal power plants. One pertinent observation is the reduction of transactions in the first hour of each intraday market, IM (H01, H05, H09, H12, H16 and H22, which correspond respectively to IM2, IM3, IM4, IM5, IM6, and IM7) [88]. This reduction is more pronounced in the H05, H12, and H16 (IM3, IM5, and IM6).

This situation occurs because the Spanish TSO did not offer energy (to buy or sell) in this period. In each IM, the market producers may modify their tertiary prices. The predictable motive is the existence of a new price offer sent by the producers, which was not received in time to elaborate the offers. This time constraint is originated by the existence of different platforms from different entities.

The existence of more market producers on the Spanish side increases the difficulty of receiving the market offers in time to elaborate the final tertiary curve offers. From the Portuguese side, the existence of fewer market players reduces this problem because of the easier coordination it makes possible [64]. Figure 4.17 shows the average profit per hour. It is possible to revalidate some conclusions mentioned above: The savings (relatively to BBIs) are more pronounced in off-peak periods, and the selling profit (BBEs) are higher in the remaining periods.

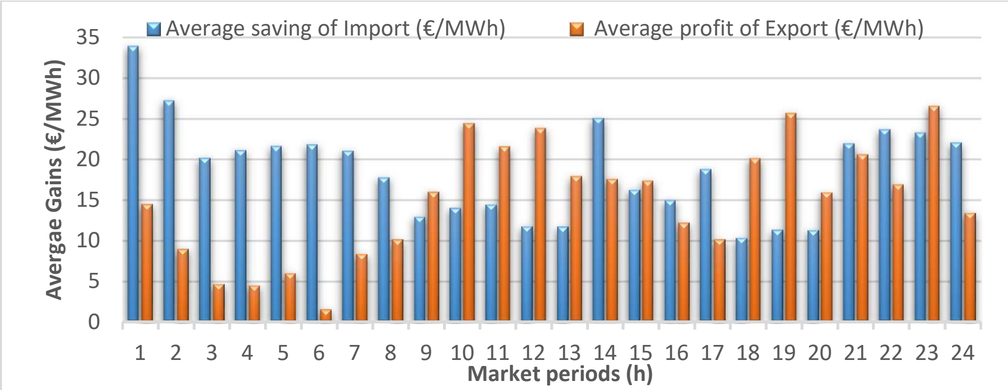

Figure 4.17: Average profit of the energy transactions between Portugal and Spain.

4.5.3 Long-Run Considerations

In Figure 4.18, it is possible to observe the evolution of the BBAs in the sharing mechanism period of analysis. The predominance of BBIs at the beginning of the transactions is clearly observable. In the case of the first and the second quarters, 88% of the real transactions are BBIs. Only 12% are BBEs. During the remaining period, it is possible to observe a slight decrease in the BBI transactions compared to the BBEs. The general tendency during the overall period of analysis is to have more occurrence periods of BBI, with 77% of the transactions and 23% of BBEs.

The main finding about the sharing mechanism is positive, because of the increase in the indirect competition of market agents. The predominantly importing transactions (from the Portuguese perspective) develop towards a more equilibrium situation (not sufficient yet), with the direct decrease of the Portuguese tertiary prices. The harmony created by the balanced division between the quantities traded proves the efficiency in the creation of this market.

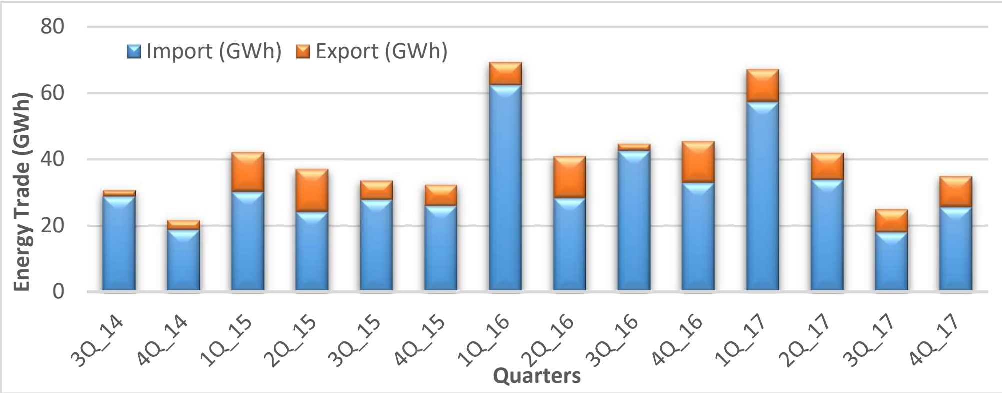

Figure 4.18: Energy traded between Portugal and Spain.

In Figure 4.19 depicts the revenue value of the transactions: the savings provided by the assignations and the profit from the sales. The revenues are directly related to the amount of energy traded in each period (observed in the previous figure). The importation trend of the Portuguese TSO reveals substantial profits when compared with the exportation scenario. Table 4.3 shows in resume, the numerical results provided by the Figures 4.18 and 4.19, respectively.

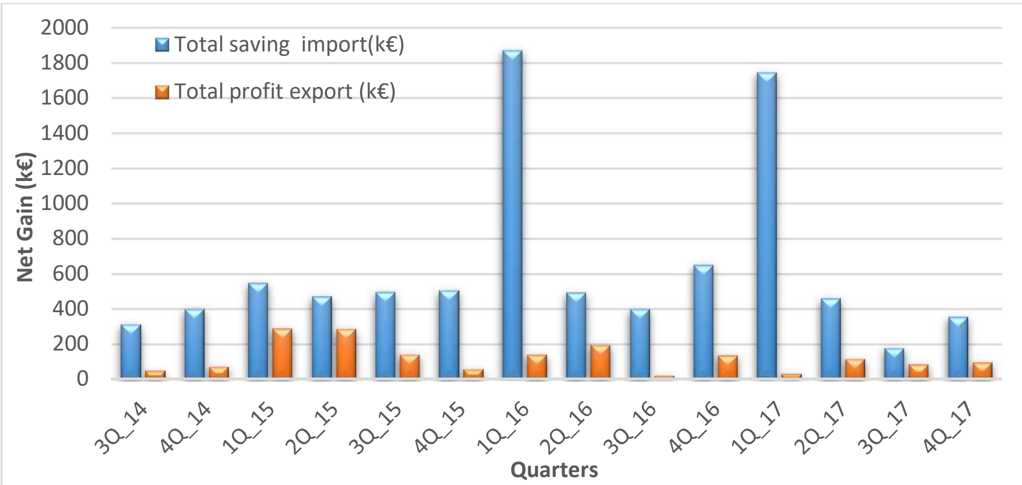

Figure 4.19: The net profit of transactions between Portugal and Spain.

Table 4.3: Energy traded and economic results.

Energy sold	109.3 GWh	**Profit of sold**	8,879,090 €
Energy assigned	455.5 GWh	**Saving of buying**	1,705,560 €
Energy traded	564.8 GWh	**Total profit**	10,584,650 €

4.6 Brief Remarks of Chapter 4

The outline of the cross-border exchange mechanisms, and particularly of the tertiary reserve, is the new reality for both participating SOs in the Iberian Peninsula. After three and a half years of this trading mechanism's implementation, profits exceed 10.5 M€. This corresponds to an average gain of more than 3 M€/year, only for the Portuguese ES. Comparing this value with the average tertiary over-cost, it was 32.22 M€, which corresponds to almost 10% of the tertiary balancing costs.

The profits obtained from the cross-border tertiary transactions would allow the market agents that are imbalanced (in a determined period) to proceed with their imbalance settlement at a more competitive price. On this basis, the cross-border exchange tertiary is a solution to be considered in the future. Besides the economic advantages that were observed in this chapter, the improvement is undeniable not only for the SOs who must deal with this new reality, but also for the market participants, especially suppliers, who must adapt their tertiary offers taking into consideration this new paradigm.

What was once a national market is now tending to toward a European, the introduction of more players in this sharing mechanism allows one to foresee improvement of the economic results for all stakeholders. The introduction of new projects, such as TERRE, MARI, and PICASSO, will allow changes to take place in the European Panorama relative to ancillary services, in particular the secondary and replacement reserves. The competition among market players will increase and more dynamic behavior will be introduced to the interconnection programs.

Chapter 5

The Importance of an Embracement Cooperation in Replacement Reserves: Benefits of Multilateralism

Market cooperation in the ES is crucial for competitiveness improvement. In the particular case of AS, it was only carried out within a national context until the recent past. In the Iberian case, since the middle of 2014, a bilateral mechanism has allowed tertiary reserve sharing between the Portuguese and the Spanish TSOs. This mechanism generates gains for the Portuguese ES, as observed in the previous sections. However, with a higher level of cooperation, these gains could be improved.

The Portuguese TSO is one of the most peripheral TSOs in Europe and, as such, it considerably benefits from market integration, in the various dimensions of the electrical sector. In this chapter it will be analyzed what would happen to revenues when sharing replacement reserves without any restriction, considering a full integration of Europe's southwest countries in contrast to the traditional bilateral solution that is currently in place.

5.1 Overview of Cooperation in Replacement Reserves

AS are crucial for the stable operation of the electrical systems and, in particular, the tertiary reserve is a key factor for the real-time balancing of mismatches between consumption and generation [80]. For TSOs in the European ES, this type of operation reserve is generally acquired via a market-based mechanism. The electrical regional initiative of southwest Europe, which involves the TSOs of Portugal, Spain and France, worked through the implementation of cross-border AS, in particular a tertiary sharing mechanism [96]. In 2013, the decision to implement two bilateral solutions was taken and these solutions started to work in the middle of 2014.

This bilateral solution allows tertiary exchanges between REN and REE, and between REE and RTE. For the Portuguese ES, one of the most peripheral TSOs in Europe, the implementation of this bilateral mechanism generates interesting gains. However, the profits could be improved if a high level of cooperation could occur. In this chapter it will be evaluated, from the Portuguese strategic perspective, what would happen to revenues when sharing RR without any restriction, considering a full integration of Europe's southwest countries in contrast to the traditional bilateral solution that is currently running.

After the bilateral comparison between all TSOs, the most competitive combinations are identified in terms of direction of transaction, assignation, or availability of energy. When a TSO is unable to transact energy with another one, a constraint is identified and the loss of economic value is calculated.

5.2 The Constraint of Bilateralism: An Integrating Strategic Perspective

The over-cost generated by the tertiary needs was identified in the previous chapters. The profits obtained from the implementation of the tertiary sharing mechanism were also reported. However, these profits could be increased. The actual mechanism only allows bilateral transactions between Portugal and Spain and between Spain and France in a contiguous way. The mechanism also exists between France and Great Britain, but there are some technical and procedural differences when compared to the southwest countries (Portugal, Spain, and France), so this mechanism was not considered in this study [97].

This chapter focuses on the study of a hypothetical situation where the three countries in the southwest of Europe could exchange tertiary reserve without constraints through the existence of a multilateral market instead of the two bilateral markets already in existence. Technically, this solution could be easily implemented. However, political and bureaucratic factors create obstacles to the implementation of a common platform that would enhance the dynamism in the transactions and raise even more profit. The main issue with a 3-lateral market is that the direct transactions between two non-adjacent TSOs require the intervention of a third one, which acts as an intermediary. This TSO incurs the operational effort of modifying its interconnections program to satisfy transactions without any internal energy transaction.

In this this chapter the main goal is to estimate the potential profit (or opportunity) that would be gained by the Portuguese ES through a complete cooperation between the three TSOs in the first three years of implementation, proceeding to a thorough analysis of the transactions, which allows the scrutiny of the process in detail. Traditionally, and almost all-year long, the French ES is a large exporter. The main French electrical production is provided by nuclear power plants. Usually, the interconnection capacity between Spain and France was fully congested, or near to its maximum, in the direction from France to Spain, for large periods of time. In 2014, the entrance into production of new interconnections between these countries helped to diminish the periods of full congestion.

The improvement of the electrical interconnection between France and Spain, such as the new lines in the Bay of Biscay, will increase the potential of trade between the Iberian system and the rest of Europe. These increases of trade capacity will potentially diminish the period of market splitting between both countries and indirectly allow the improvement of tertiary exchanges, which could affect market behavior [98], [99]. In the following section, the offers submitted by the three TSOs are discussed. Some simple comments related to the idiosyncrasies of the French ES are presented, to aid in the understanding of and to justify the types of offers submitted [100].

5.3 Three Party Submitted Offers

In this section, a comparison is made between the prices submitted by the three TSOs and the respective evolution, on a daily basis and in the long-run. A deeper comparative analysis is carried-out for the prices submitted between the French and Spanish TSOs with the objective of evaluating the advantages of a stronger cooperation with the Portuguese TSO.

5.3.1 Daily Analysis

Figure 5.1 shows the available prices for replacement reserve exports provided by the three TSOs. The first interesting observation is that the available prices of export reserves from the French TSO are, in general, the highest from the three TSOs that compound the Southwest electrical region. The existence of a considerable nuclear base portfolio has two considerable effects: on the one hand, the existence of lower electricity production costs; on the other hand, there is a less flexible generation to manage the energy balance.

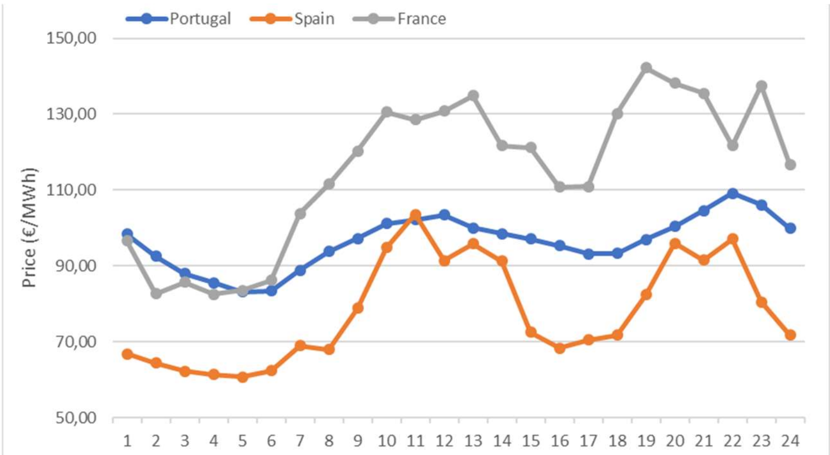

Figure 5.1: Export submitted offers prices between Southwest TSOs.

In this specific situation the importance of balance management is more important. The lower electricity production costs reflect more on Spot markets, which are not the focus of this work. In the majority of daily periods, the Spanish TSO is the most competitive in terms of submitted offers. The existence of a mixed portfolio helps to explain this observation [99], [101].

In Figure 5.2, it is possible to observe the available prices for replacement reserve import provided by the three TSOs. A uniform tendency during the day can be verified. The Spanish TSO is the one that offers to purchase energy at a lower price while the French TSO offers to purchase it at a higher price.

These results induces a loss of opportunity business between the Portuguese and French TSOs. In the mentioned periods, it could be interesting for the Portuguese TSO to sell reserve to the French TSO. As a first finding, by analyzing only the offers submitted by the TSOs, one can derive that if the market were multilateral, the liquidity of transactions would be improved.

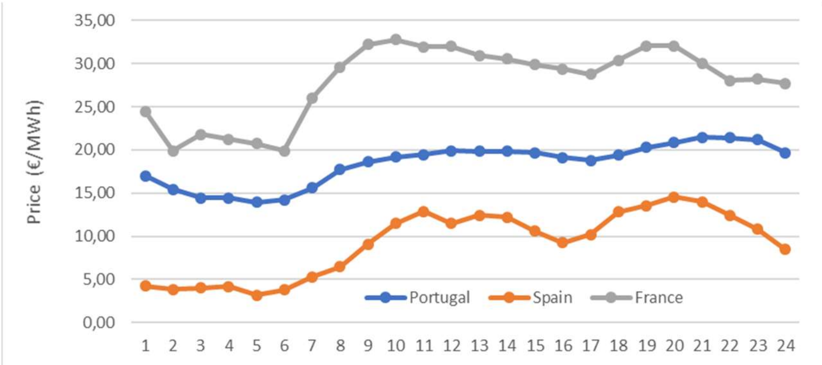

Figure 5.2: Import submitted offers prices between Southwest TSOs.

5.3.2 Long-Run Overview

Complementing the daily-basis analysis that was elaborated to observe the market in one day, a long-run analysis allows the investigation of the market in a more strategic way and to observe the market players' evolution tendency. This will be explained according to the first three completed years of the TSOs' submitted offers, as organized by quarters.

In Figure 5.3, the export prices submitted by the three TSOs are illustrated. The apparently irregular variation of the submitted prices is greater in the French TSO than in the Iberian TSOs. In the Portuguese case, the price is almost controlled, and in the Spanish case, stabilization is carried out. The high number of France's interconnections with different countries when compared to Portugal or even Spain, implies a greater variation in the spot price of electricity and, indirectly, in the tertiary offers.

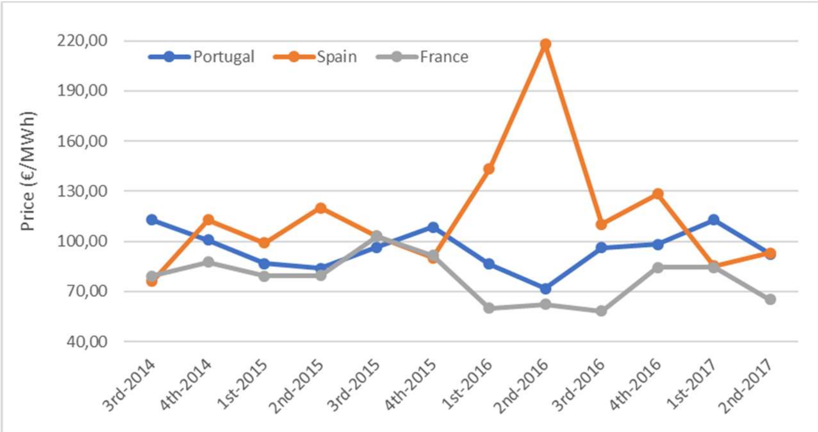

Figure 5.3: Export submitted offers prices between TSOs by quarter of the year.

Thus, it is more difficult to identify a simple and continual explanation of the price evolution. An interesting observation is the first quarter of 2016, which represents the winter period in Europe. This period (where electrical consumption is naturally higher) was conjugated with a period of considerable nuclear power plant in outage.

In Figure 5.4 the available prices for import submitted by the three TSOs are shown. The French TSO, as was observed in the daily-basis analysis, is the TSO that is able to buy energy at a higher price. This trend is consistent with the analysis of the evolution occurred during the first three years. In May and June, the price decreases again, reaching similar values as those of the Portuguese TSO.

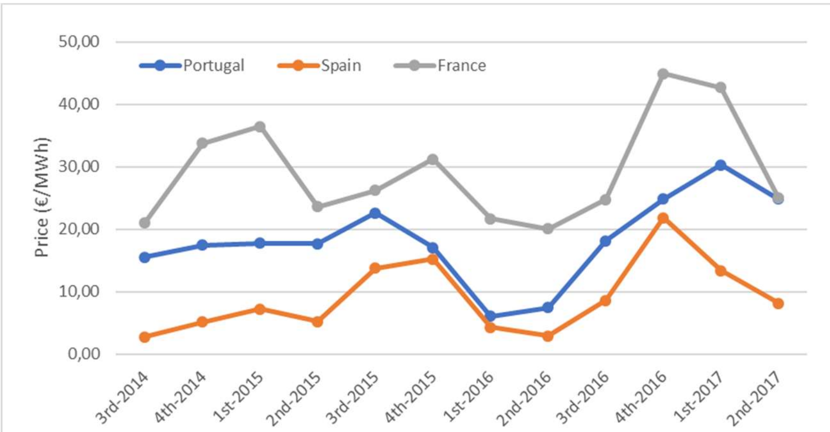

Figure 5.4: Import submitted offers prices between TSOs by quarter of the year.

On the other hand, due to considerable penetration of hydraulic power plants in the Iberian countries and taking into account that wet periods occur precisely during winter, the increase of available energy compensates for the increase in consumption.

5.4 Economic Constraints of Non-Cooperation

In the previous sections the offers submitted by the three TSOs have been introduced, indicating an interest in buying or selling tertiary reserve. One of the findings, which is mainly qualitative, about the absence of a common platform that would allow direct transactions between all TSOs has also been shown. However, as mentioned, only the average value of buying and selling tertiary reserve, at which each TSO proposed to trade, was presented.

In order to estimate more accurately the potential earnings from cooperation, it is crucial to know the effective value of the transactions. These values are the result of the comparison made between all TSOs regarding their selling and buying offers. This means that in the case of buying tertiary reserve, these values could be obtained in two different ways: the TSO that is interested in importing accepts the selling offers made by the other TSOs (exporter). Moreover, the TSO that is interested in selling (exporting) accepts the buying offers made by the other TSOs. In selling scenarios, the opposite assumption is made. The average price of transactions is a combination of the two possible ways in which they can happen.

Now, the effective prices at which the transactions are made are analyzed, as well as the cross between the French and Portuguese TSOs' offers, in order to estimate the economic loss from non-cooperation. In what concerns the structure of the results presentation, in the previous point, two types of analysis are carried out based on the daily and long-term data, for either import or export scenarios. In this case, in which the potential incomes resulting from greater cooperation will be estimated, the long-term analysis is not crucial for the comprehension of the study or for the intended estimate. The calculation of the potential incomes is presented on an hourly basis because this is the perspective on which market agents' prices and strategies are based.

5.4.1 Analysis of Traded Export

It is possible to observe and draw some findings about the imports by the Portuguese ES, observing the exportation price of other players, and also, from an eventual cooperation. In the periods 05, 08, 13, 14, 18, 19 and 23, the selling price to the French TSO, PsF, is lower than the selling price to the Spanish TSO, PsS, which means that the impossibility of transactions between the French and the Portuguese TSOs generated a decrease in income for both countries, which is expressed in (5.1). Figure 5.5 shows the effective price of exports traded by the three TSOs.

$$PsF < PsS \rightarrow Loss\ of\ additional\ savings\ when\ buying \quad (5.1)$$

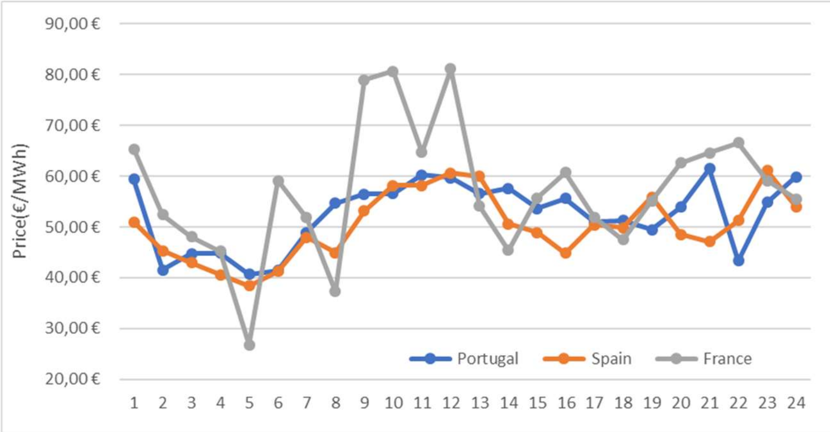

Figure 5.5: Effective exportation prices between TSOs.

5.4.2 Analysis of Traded Import

During the majority of off-peak periods, it was the French TSO that bought tertiary reserve at a higher price. In the remaining periods, the competitiveness of the RR prices is very volatile. In the periods 02, 03, 04, 05, 06, 07,10, 13, 17,18 and 19, the assigned price of the French TSO, PaF , is higher than the assigned price of the Spanish TSO, PaS , which allows a potential loss of transactions to be identified for the Portuguese ES, in these hourly periods. If it were possible, the Portuguese TSO could sell to the French TSO instead of the Spanish TSO, when the situation in (5.2) happens. Figure 5.6 illustrates the effective import prices of the three TSOs.

$$PaF > PaS \rightarrow Loss\ of\ additional\ profit\ from\ selling \quad (5.2)$$

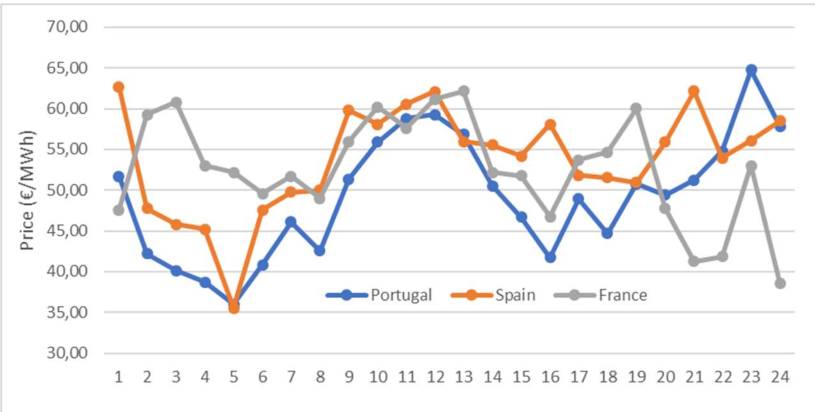

Figure 5.6: Effective importation price between TSOs.

5.5 Opportunity Gains from a Multilateral Market

This point aims to estimate the opportunity of a high level of cooperation for the Portuguese electrical system, creating a hypothetical multilateral market of tertiary reserve. The starting point is the two existing bilateral tertiary reserve markets, where the agents make offers based on current reality. If a multilateral market were to exist, as conjectured, the offers, mainly from the French and Portuguese TSOs, which suffer the most restrictions from bilateralism, could have a different strategy. An estimation process is carried-out so that some findings can be drawn from the results. The principle used to calculate the opportunity is based on the offers traded, as identified in the previous sections.

5.5.1 Export Opportunity for France

Figure 5.7 indicates the price of import transactions in Spain and France. In the periods 02, 03, 04, 05, 06, 07, 10, 13, 17, 18 and 19, the average imported tertiary reserve by France was higher than the Spanish one. In the same periods, the potential tertiary reserve exported, $Qetotal$, from Portugal to France is the sum of the Portuguese TSOs exports, QPe, and the French TSOs imports, QFi. This is expressed from Equation 5.3. Furthermore, the additional profit from exportation, APE (in euros), if the multilateral market is implemented, can be given in Equation 5.4.

$$Qe_{total} = QPe + QFi \tag{5.3}$$

$$\begin{cases} PaF > PaS \\ APE = (PaF - PaS) \times Qe_{total} \end{cases} \tag{5.4}$$

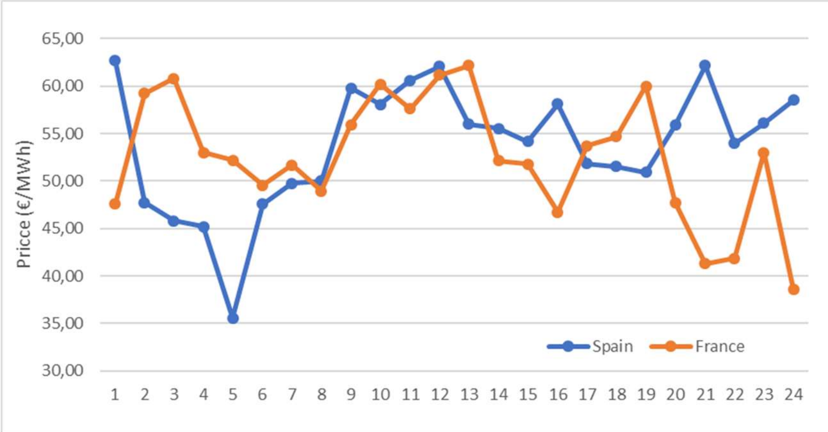

Figure 5.7: Export opportunity prices for France and Spain.

5.5.2 Import Opportunity from France

Figure 5.8 shows the export prices of the Spanish and French TSOs. In order to identify the potential for importation, principles opposite to those used in the previous point are followed. The hourly periods are identified in which, on average, the French TSO sold tertiary reserve at a lower price than that of the Spanish TSO.

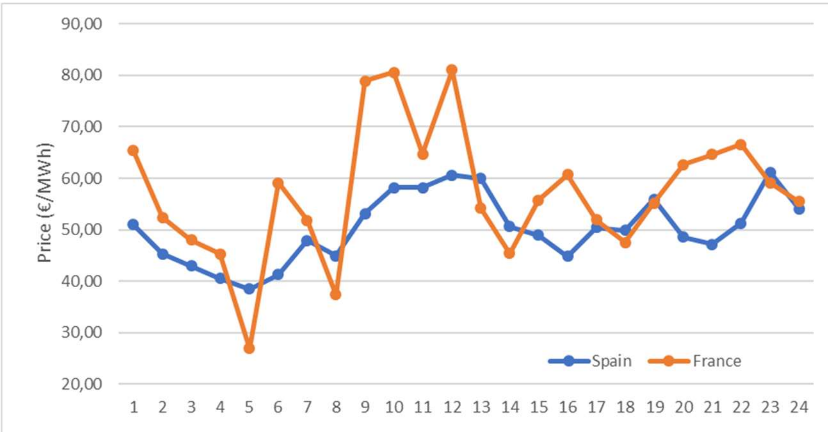

Figure 5.8: Import opportunity prices from France and Spain.

Those periods are the ones in which, from the Portuguese TSOs strategic perspective, an improvement in the potential savings could be gained in comparison with the transactions with the Spanish TSO. The potential tertiary reserve imported, Qi_{total}, in this scenario would be the sum of the Portuguese TSO imports, QPi, and the French TSO exports, QFe, expressed in Equation 5.5. Furthermore, the additional savings from importation, ASI (in euros), if the multilateral market is implemented is given by Equation 5.6.

$$Qi_{total} = QPi + QFe \tag{5.5}$$

$$\begin{cases} PsF < PsS \\ ASI = (PsS - PsF) \times Qi_{total} \end{cases} \tag{5.6}$$

5.5.3 Calculation of Opportunity Gains

In the previous points, the Spanish and French TSOs' prices for exports and imports were considered to identify the potential transactions that could improve between the Portuguese and Spanish TSOs. Otherwise, the hours in which, on average, the French TSO price is more competitive than that of the Spanish TSO were identified. In this point, the opportunity gains are calculated or estimated. The additional gains are the sum of APE and ASI can be calculated by the Equation 5.7:

$$AG = APE + ASI \tag{5.7}$$

Tables A1 to A3 in **Appendix A** show, in a condensed form, the hourly periods and respective values, with respect to the opportunity generated for the Portuguese ES, if the multilateralism of the market were real and effective. For each hourly period (of the 24 hours of the day), it is possible to consider two kinds of transactions: selling or buying tertiary reserve, which means there are 48 possible transactions.

Regarding the majority of results, the final values of the potential economical incomes, if Portugal and France could transact with each other, are 2,317,070 € in what concerns APE, and 991,991 € in what concerns ASI , which results in a value higher than 3,308,981 € for AG. Considering these results, the potential incomes would be considerably higher in the cases of importation of tertiary reserve when compared to exportation.

The total profits gained through the selling and buying operations of tertiary reserve would result in incomes of 1,554,952 € and 8,521,288 €, respectively, achieving a total of 10,076,240 €. If it is added-up the increment of the profits resulting from the existence and implementation of multilateralism, the total incomes for the Portuguese ES could surpass 13,385,221 €, as shown in Table 5.1, considering the three years under analysis.

Table 5.1: General results for a possible cooperation southwest TSO's RR.

First Year	
Profits of Sales	694,842.15 €
Saving Assignation	1,731,492.75 €
$\boldsymbol{APE}$	143,218.39 €
$\boldsymbol{ASI}$	301,730.36 €
Second Year	
Profits of Sales	544,370.56 €
Saving Assignation	3,377,794.00 €
$\boldsymbol{APE}$	621,569.69 €
$\boldsymbol{ASI}$	213,234.86 €
Third Year	
Profits of Sales	315,739.16 €
Saving Assignation	3,412,001.07 €
$\boldsymbol{APE}$	1,552,281.87 €
$\boldsymbol{ASI}$	476,945.86 €
Potential Gain (with multilateral market)	13,385,220.72 €
Total Gain (bilateral market)	10,076,239.68 €

Comparing the actual profits resulting from the bilateral solution already implemented with the possible results obtained from the existence of a multilateral tertiary-reserve market between the three countries, the latter option would generate an increment of income of approximately 30% for the Portuguese ES. However, it is a belief that the obtained results are conservative considering the possibility of multilateral transactions between Portugal, Spain, and France.

The analyzed results have as their basis the values practiced in two existing distinct bilateral markets (Portugal–Spain and Spain–France). The cooperation of the third agent would automatically lead to an increase of tertiary reserve's sharing demand, and a reorganization of the prices for either buying or selling.

The major idea of a European unique electrical market, in its most varied dimensions (where the tertiary exchanges are included), is intended to be embraced by all players, without the risk of harming the peripheral TSOs. The idea of free fees increases the competitiveness between market agents and improves the cooperation between all the players involved. This study did not consider any type of transmission fees charged by any TSO.

5.6 Brief Remarks of Chapter 5

The importance of the coupling of electrical markets is crucial for improving the competitiveness and welfare provided by the market environment. The gains achieved by the bilateral sharing of tertiary reserve between the Iberian countries confirm this idea. However, a high level of cooperation would enable high gains for the European electrical systems.

This study, based on the first three years of implementation of a tertiary reserve sharing mechanism, showed that the constraint generated by a bilateral market instead of a multilateral market involving the southwest systems' operators, generated lower profits and diminished the economic welfare, with greater impact on peripheral countries, as in the case of the Portuguese electrical system. The losses from non-cooperation were around 30% of the total value of transactions.

Balancing mechanisms are crucial for a proper management of the electrical systems. Like other cooperation processes in the electrical field, as with the spot market, the importance of the creation and cooperation of ancillary services markets is crucial to develop a more unified European electrical environment.

Chapter 6

Coordinated Actions in Secondary Reserve: A Changing Paradigm

The massive integration of renewable sources, which brings more intermittency and volatility, together with the natural variation of consumption, poses greater challenges that should be mitigated with adequate tools, as offered by a liberalized and organized electrical market. To help cost reduction in a market environment, the coordination between different TSOs is of utmost importance.

The objective of this chapter is to provide a framework analysis for the sharing of AS in the context of the Iberian ES, in particular a techno-economic analysis for the secondary reserve (SR) control. The secondary reserve control is fundamental to correct load variations and help stabilize the electrical systems where the TSOs are inserted. To this end, the main goal is to control the regional imbalance of the Iberian Peninsula, in a coordinated way, with a minimization of costs. There are enough reasons to implement the coordination procedures between the Iberian TSOs in order to manage their own SRs in a profitable and reliable way, and to become more competitive when exchanging with other European TSOs.

6.1 Overview About Coordinated Secondary Reserves

Electrical markets worldwide are a crucial structure of the ES even considering their differences and the players' various responsibilities, and moreover when excluding their locations, wholesale electrical markets are employed and joined considering the regional electrical markets. One of the biggest challenges in ESs is the way in which to deal with the high share of intermittent integration from renewable production, and with the social consumption behavior, considering the importance of reducing the pollutant emission rates, and coping with the regional and global targets.

However, the increased variability and the intermittent nature effects in the net load require that conventional production fulfills the demanding operational flexibility requirements, where the balancing mechanism comes into operation and, as a consequence, the operational costs increases. The efforts to harmonize the balancing capacity between different TSOs and the possible share of their balancing mechanism may help the ESs.

The present chapter focuses into extend the cooperation already exist in RR markets to a cross-border cooperation between TSOs in the Iberian market, with the focus on reducing the operational costs, by sharing and optimizing AS like the SR in the Iberian Peninsula.

6.2 Secondary Reserve Control: An Overview

As mentioned previously, the AS is crucial for the operation of the ES. Table 6.1 and Table 6.2 show the results of the annual mobilization and the average price of both Iberian TSOs, during the years 2015 and 2016, respectively. It is important to note that an adequate balance of the ES results from the combination/management between SR and RR. This process and operation is managed by each country's system operator. First of all, a general (macro) analysis of the obtained results is made, containing some previous remarks and findings.

Table 6.1: Secondary and Tertiary Energy Mobilization between the Iberian TSOs.

Secondary Control (GWh)	**2015**		**2016**	
	Upward	**Downward**	**Upward**	**Downward**
Portugal	425	68	439	81
Spain	1,366	1,193	1,530	1,012
Tertiary Control (GWh)				
Portugal	693	1,269	1,154	1,284
Spain	3,126	1,627	2,557	1,553

Table 6.2: Secondary and Tertiary Energy Mobilization Prices between the Iberian TSOs.

Secondary Control (€/MWh)	**2015**		**2016**	
	Upward	**Downward**	**Upward**	**Downward**
Portugal	68.20	29.00	54.00	22.80
Spain	53.70	38.50	43.00	32.40
Tertiary Control (€/MWh)				
Portugal	68.20	29.00	54.00	22.80
Spain	63.70	24.80	50.20	19.40
Band Price of the Secondary Control (€/MWh)				
Portugal	20.46		16.67	
Spain	19.58		15.56	

Then, a more detailed analysis is carried out, focused exclusively on SR control, arranging the results in a different manner to enable two different types of reflections:

i) A daily analysis (in the short-term perspective), where it is possible to understand the behavior and the characteristics of both ES over a complete market day;

ii) A long-term perspective where it is possible to understand the evolution of these SR characteristics over the complete period of analysis, developed on a quarterly (trimestral) basis. In the Portuguese ES, the secondary upward regulation (SUR) quantity is considerably bigger than the secondary downward regulation (SDR). Compared to the Spanish ES, it has a relative equilibrium in the secondary mobilizations.

Two reasons that may help explain this phenomenon are related and correlated, i.e., the first one is that the rules in place, since the beginning of the electricity market, requires that secondary reserve providers to offer a band of reserve which is split according to a ratio of 2/3 for upward and 1/3 for downward regulation, respectively. At the same time, the TSO, which is mostly focused on the technical conditions of the system, tries to have the secondary band centered at the midpoint, i.e., with an equal amount of upward and downward regulation availability.

The second phenomenon is because the SR is mobilized automatically by the Automatic Generation Control (AGC), so the TSO indirectly controls the secondary band by manually dispatching RR, and thus, forcing the AGC to adjust the SR in the intended direction. In this sense, the latest explanations may help to understand why in the Portuguese ES more energy is mobilized to downward regulation in order to maintain the equilibrium point.

In terms of electricity prices, in the Portuguese ES the secondary control used is paid at the same price as the tertiary mobilization energy. Hence, the Spanish ES has an independent system of electricity prices. Comparing the prices of secondary mobilizations in the Iberian countries, the Spanish system is more competitive in both directions: it is cheaper to mobilize in the upward and downward directions, and the same happens for RR. The existence of more players in the Spanish ES, in the generation sector, may justify this situation. In terms of band price, in €/MWh, the same trend is verified in SR and in RR. However, the difference is very small.

6.2.1 Daily Analysis

Figure 6.1 shows the average net mobilization of both Iberian ES during the 24 hours of a market day. The net value is obtained by subtracting the downward value from the upward reserve. The average value of the net mobilization in the Portuguese ES is 40.7 MWh, and in the Spanish ES is 39.4 MWh. The absolute value is very similar, and the Spanish TSO is 5 times bigger (as it was described previously). From the Portuguese TSO, during 2015 and 2016, the average secondary band offered in the market was 170 MW for upward regulation and 85 MW for downward regulation. The total band was thus, on average, 255 MW, having an equilibrium midpoint of 42.5 MW. This value is very similar to 40.7 MWh, which is the period analysis average value.

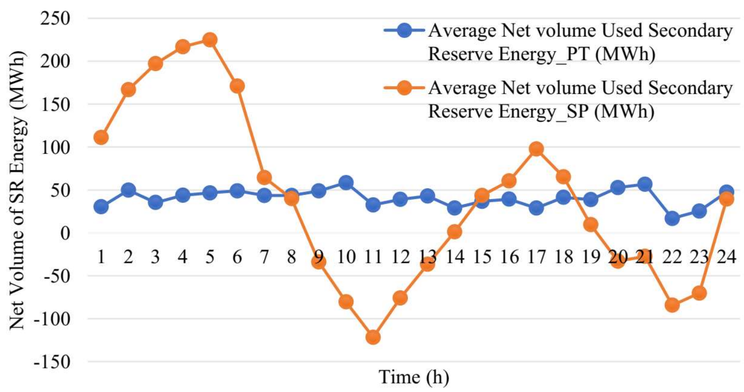

Figure 6.1: Average net volume used on the SR with Iberian TSOs.

Comparing the previous values with the values in Table 6.1, for the Portuguese TSO, the net secondary control in 2015 was $425 - 68 = 357$ GWh, and in 2016 it was $439 - 81 = 358$ GWh, which corroborate the results obtained. Another explanation for this fact is that it is a strict, stable and positive dominance of the secondary allocation to upward regulation which corresponds to 200% of the downward regulation. The oscillation verified is situated between 17 MW and 59 MW.

In terms of the Spanish ES, it is 39.4 MWh (as mentioned previously). For the Spanish TSO, during 2015 and 2016, the average secondary band offered in the market for upward regulation was 683.5 MW, and for downward regulation it was 510 MW. The total band was thus, on average, 1193.5 MW, which has an equilibrium midpoint of 86.7 MW. When compared to the Portuguese TSO, in absolute terms, it approximately doubles its value (42.5 MW to 86.7 MW), but in relative terms, the difference is not so high (the Spanish system is 5 times bigger, with an equivalent midpoint at $86.7\text{ MW} / 5 = 17.4$ MW in the "Portuguese scale").

The difference between the allocation band for upward and downward regulation is 173.5 MW, which corresponds to 25% more upward allocation than downward allocation. This may help to explain a bigger volatility in the secondary band of the Spanish system, in comparison with the Portuguese one. Again, comparing these with the values, the net secondary control in 2015 was $1366 - 1193 = 173$ GWh, and in 2016 it was of $1530 - 1012 = 518$ GWh, corresponding to an average value of 345.5 GWh, corroborating the results shown in Table 6.1.

Figure 6.2 shows the ratio between secondary utilization and secondary available band for upward and downward regulation, in both TSOs. In the case of SUR, the average ratio of utilization for the Portuguese TSO is 29%, and in the case of SDR it is 10%. For the Spanish TSO, the average ratio of utilization is 25% in the case of SUR, and 24% for SDR. The first deduction is that the SES has a more balanced utilization of its resources. In the Portuguese TSO, the utilization of SDR is considerably low. In a first and localized analysis, when confronted with Figure 6.1, Table 6.1, and with the allocation ratios of 2/3 for upward regulation and 1/3 for downward regulation, it is revealed that it is not necessary to contract more secondary downward band and it is necessary contract more upward band.

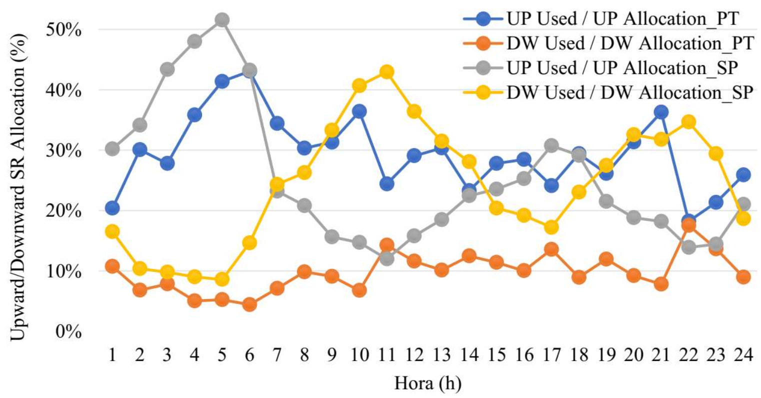

Figure 6.2: Upward and downward SR allocation between the Iberian TSOs.

Nevertheless, it is important to take into account that the tertiary downward regulation (TDR) is considerably high. The coordination between these two mechanisms is responsible for the downward balance. Hence, considering the TDR, in the same table, it is possible to observe that it is considerably mobilized when compared with the SDR. The Portuguese Electrical System has certain idiosyncrasies that help to explain this imbalance between the SUR, SDR and tertiary regulation systems. One of the reasons is the dimension of the PES when compared to the SES.

The PES's scale helps to maintain more stability. Another important reason is the existence of two main consumers in the PES: the national steel industries, which together totalized a peak power consumption of, approximately, 350 MW.

Another characteristic of the Portuguese steel industry is its profile consumption. It is a highly intensive energy industry (more than 90% of the costs are related to electricity), with the electric arc furnace working in step mode. For an ES such as the Portuguese one, the secondary control band cannot cover all variation scenarios (the average value of total band is 255 MWh), especially in scenarios when the steel industries stop and start working, but truly mainly when the steel industries start and stop instantly, because the downward secondary control band is 1/3 of the total band.

The Portuguese system operator, during the periods when the steel industries are working, creates an artificial imbalance with TDR in order to maximize the SDR. It is important to note that the secondary band is faster when controlling the deviation than the tertiary control band is. Another situation is that the steel industry usually works with more intensity during the night, when the consumption levels decrease. This is another reason why the Portuguese TSO needs to anticipate for the "loss" of consumption. This idiosyncrasy helps to explain the secondary results observed for the Portuguese ES.

In Figure 6.3 it is possible to observe a new parameter in the evaluation of the ES, i.e., the "*Electrical Variability*" (MWh). This measure intends to assess the main factors that incite variability and fluctuations during a particular period in the ES and that must be corrected with a first action of the secondary control ("unpredictability" factors), where the average of the "*Electrical Variability*" in a market day is also shown.

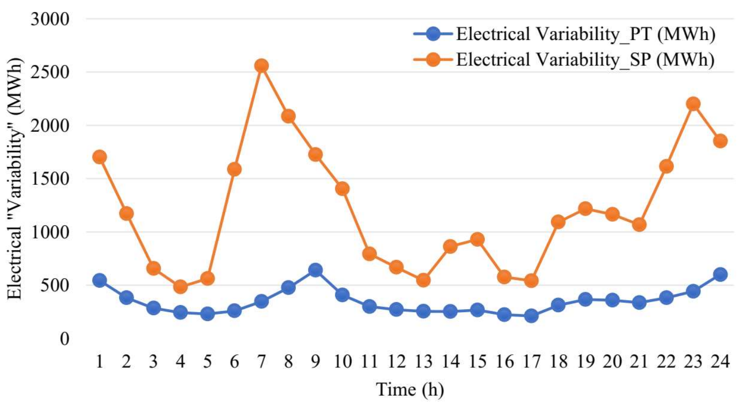

Figure 6.3: "Electrical Variability" between the Iberian TSOs.

The factors that incite a certain instability for the period h are the variation of production Δ_{Prod}, the variation of consumption Δ_{Con}, and the variation of interconnection Δ_{Inter}, described by the electrical variation EV in MWh, is expressed in Equation 6.1:

$$EV\ (MWh)_h = abs\left(\Delta_{Prod_h} - \Delta_{Load_h}\right) + \Delta_{Inter_h} \tag{6.1}$$

where the first term is the absolute value difference between the programmed generation variation and the load variation. The programmed generation variation is the producers' imbalance market indicator (the real production $Prod_{effective}$, minus the production market sold $Prod_{market}$).

This market producer imbalance is mostly related to the imbalance of the wind producers. Concerning the other dispatchable generation, typically, when losing one generator, the producer has some mechanisms (as other power plants, for instance) to compensate the loss of the unit with other means of production, in order to reduce the imbalance. This is explained in Equation 6.2:

$$\Delta_{Prod_h} = Prod_{efective_h} - Prod_{market_h} \tag{6.2}$$

In terms of the variation of consumption Δ_{Load}, it is the value of the difference between the level of consumption at the end, and at the beginning of the market period h, expressed in Equation 6.3:

$$\Delta_{Load_h} = Load_{h(minute\ 59)} - Load_{h(minute\ 0)} \tag{6.3}$$

Moreover, focusing on the interconnection Δ_{Inter}, for the different market periods (in MIBEL it is the hour step), different interconnection programs could take place between TSOs. The variation of interconnection is given by the Equation 6.4:

$$\Delta_{Inter_h} = (abs(Inter_h - Inter_{h-1})/12) + (abs(Inter_{h+1} - Inter_h)/12) \tag{6.4}$$

The transition between different periods is not processed in a step-mode. The transition from the period h to the period $h+1$ is given by a ramp that starts in the last 5 minutes of the period h with the interconnection value of h, and finishes in the 5th minute with the interconnection value of the period $h+1$. In other words, it is a ramp with 10 minutes that corresponds to 1/6 of the market period. For each market period h, the first 5 minutes are used to adapt to the energy interconnection program of the period h, and the last 5 minutes of the market period h are used to adapt to the energy interconnection program of the period $h+1$.

The variation of the interconnection for each period h is the sum of the difference between the interconnection value in the market period $h-1$ and h divided by 12 (which corresponds to the share of the interconnection program of the period $h-5$ minutes) with the difference between the interconnection value in the market period h and $h+1$ divided by 12.

The concept of "*Electrical Variability*" is crucial to define in a certain way the internal dynamism/intermittency of an ES as well as to quantify the SR control that a specific TSO needs to ensure the reliability of its operation. In Figure 6.4, it is possible to observe the relative value of "*Electrical Variability*", divided by the secondary total band. The SR is able to effectively correct the load variations, which is directly linked to the variability under analysis, and within the period that it is necessary to take an action to correct the deviation, thus dividing the SR by the available band.

In the case of an enduring or critical lack in the requested SR balancing, this is solved through the mobilization of the RR, which starts its operation by means of a formal request to the producer and not automatically like the SR, or automatic Frequency Restoration Reserve (aFRR), and therefore, the necessary time for the assertive corrections will be higher.

When the "*Electrical Variability*" is attended, in relative terms, for both Iberian countries, it is possible to observe some interesting results: instead of the Spanish TSO having more absolute "*Electrical Variability*", in more than 90% of the market hours during the time range in analysis, the Portuguese TSO is subject to a higher "*Electrical Variability*" in relative terms. Only in the periods 6 and 7, the Spanish TSO has more relative "*Electrical Variability*". In the period 23, the values are very similar (however, superior for the Portuguese TSO). The periods 6 and 7 represent the end of the beginning of the load growth for the Spanish ES, however for the Portuguese ES it represents the end of the off-peak values.

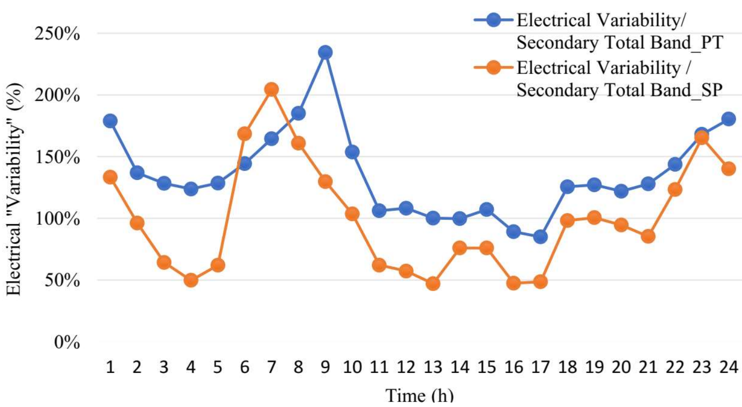

Figure 6.4: Relative value of "Electrical Variability" divided by the secondary total band between the Iberian TSOs.

This phenomenon is due to the different time zones, i.e., while in Spain the time zone is the Central European Time, in Portugal the time zone is the Western European Time. The average value of "*Electrical Variability*" for the Spanish TSO is 100%, and for the Portuguese TSO it is 134%. The assessment of "*Electrical Variability*" in relative terms gives more effective information about the internal variability that a TSO is subject to, and also, allows an adequate comparison between the different TSOs.

6.2.2 Quarter Analysis

In this section the main goal is to trace the evolution during the time of the measurements obtained in order to provide eventual trends. In Figure 6.5, it is possible to observe a similar behavior as in Figure 6.2, but it is possible to notice some differences, mainly for the Spanish TSO. In the first and second quarters of each year, (which essentially corresponds to the winter and spring seasons in Europe), the Spanish TSO has a net volume of the secondary band used (the quantity of SUR is higher than SDR). On the contrary, in the third and fourth quarters (summer and fall seasons) the net volume used is near zero (or even negative), which means that SUR and SDR are more balanced.

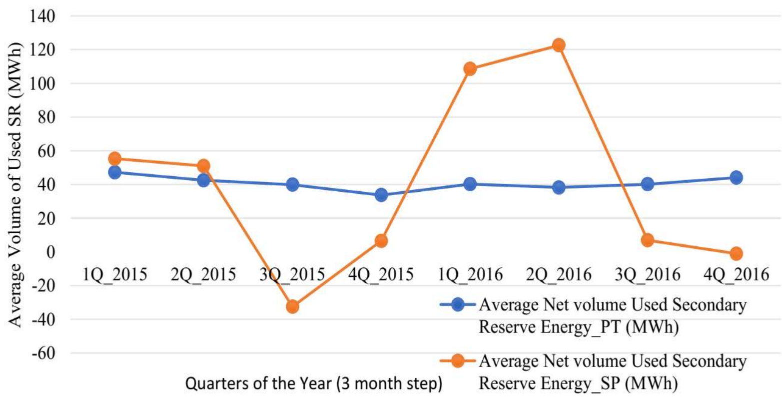

Figure 6.5: Average volume of used of SR between the Iberian TSOs.

In Figure 6.6 it is possible to note the prices for SUR and SDR prices of the SR for both TSOs. The first and second quarters (winter and spring seasons) of both years under analysis, in both TSOs, have lower prices than the third and fourth quarters (summer and fall seasons). It is a predictable result because in both ES there are a considerable amount of hydro power plants.

The rainy periods are mainly during winter and the beginning of spring, so it is natural to have a general decrease in the electricity prices, in their most varied dimensions (spot, tertiary, secondary).Moreover, it is possible to observe from Figure 6.5 that the first and second quarters of 2016 have a lower price than same period in 2015. The main reason is due to the fact that in the Iberian Peninsula on the year 2015 was a "dry" year, with less rain than normal, and 2016 was a "wet" year, with a considerable amount of rain for that period.

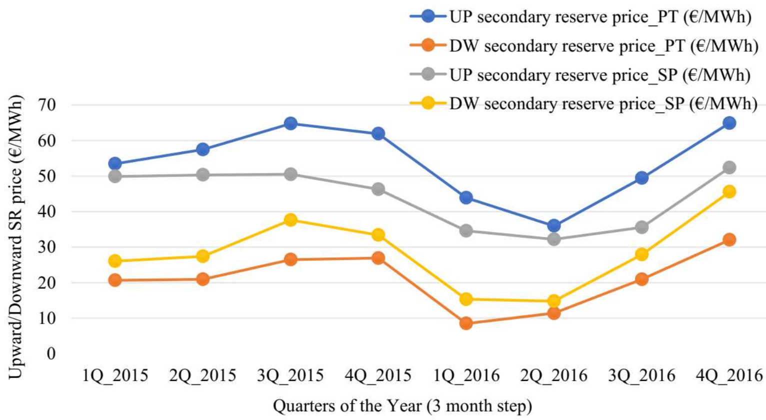

Figure 6.6: Upward and downward SR prices practiced by the Iberian TSOs.

Figure 6.7 shows the "*Electrical Variability*" during the eight quarter periods under the analysis. The average value for the Spanish TSO is 1200 MWh, and for the Portuguese TSO it is 350 MWh. During the time range in analysis, it is possible to observe more stability of the Portuguese ES than in the Spanish ES. An interesting observation is the fact that, in both TSOs, and in both years, the first quarter was the period when the "*Electrical Variability*" was higher.

This may happen because it is the beginning of the rainy period, which precipitates an additional level of variability with an increase of the interconnection programs (with more exportation), and of the production. Also, in this quarter, the peak load takes place.

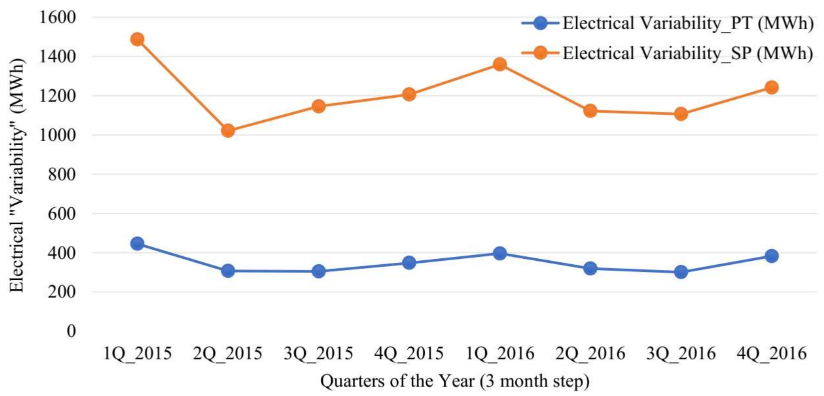

Figure 6.7: "Electrical Variability" comparison behavior between the Iberian TSOs.

In Figure 6.8, when divided by the secondary available band, it is possible to observe that the "*Electrical Variability*" is lower, in relative terms, for the second and third quarters of the years under analysis. This figure is the equivalent to Figure 6.5, the differences is that the former presents a long-term perspective. It is possible to observe that, in relative terms, the Portuguese TSO is subjected to a higher "*Electrical Variability*" when compared to the Spanish TSO.

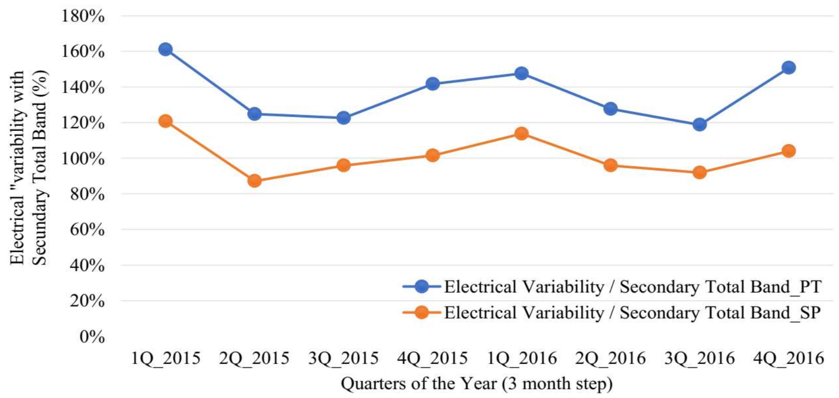

Figure 6.8: "Electrical Variability" through the secondary total band between the Iberian TSOs.

6.3 Methodology and Mathematical formulation

The Iberian TSOs exchange the actual imbalance capacity in their control areas through an individual optimization model. Optimizing the shared SR synergy between each TSO can only run if the optimization SR in each electrical grid has been completely used.

The needless SR energy is exchanged through the following rule: the TSO with more SR energy on its own control area supplies to the control area with lower SR energy. In this sense, a reduction in SR energy needs may occur in each TSO, and consequently the need of SR energy is mitigated by considering the remaining demand. So, the main goal of sharing the SR between the Iberian TSOs is to fairly split-up the savings made through the prevented use of SR energy between the TSOs [102]. The computational model implemented could be observed in the figure/flowchart 6.9:

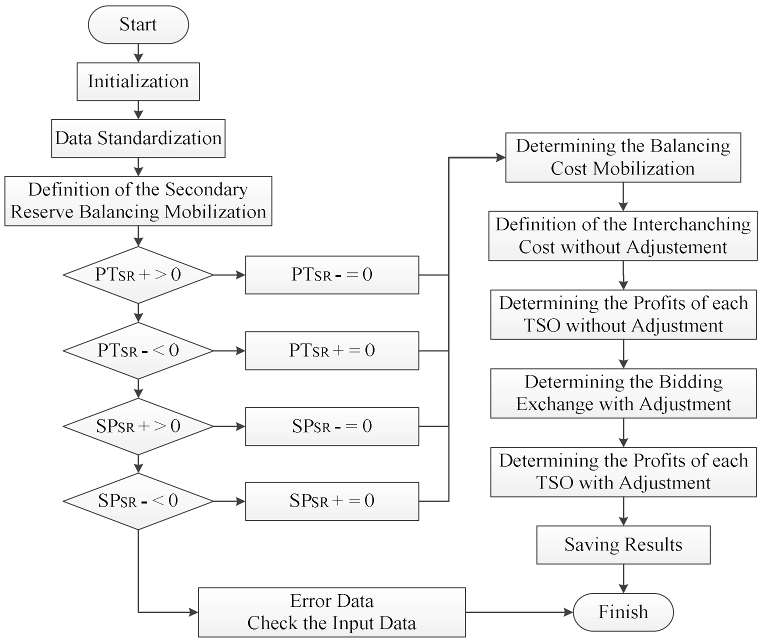

Figure 6.9 - Techno-economic flowchart with TSOs synergies analysis between Portugal (PT) and Spain (SP).

To this end, it is necessary to initially define the interchanging SR cost between the Iberian TSOs considering a sharing synergy framework. Accordingly:

$$TISRE_h = \left(ISRE_{PT_h} \times SMPD_{PT_h}\right) + \left(ISRE_{SP_h} \times SMPD_{SP_h}\right) \tag{6.5}$$

where $TISRE_h$ is the total cost of imported SR energy at time h; $ISRE_{PT_h}$ is the imported SR energy from the Portuguese TSO at time h; $SMPD_{PT_h}$ is the SDR market price asked to the Portuguese TSO at time h; $ISRE_{SP_h}$ is the imported SR energy from the Spanish TSO at time h; $SMPD_{SP_h}$ is the SDR market price asked to the Spanish TSO at time h.

Considering the same idea about the exported SR energy, the information can be expressed as:

$$TESRE_h = \left(ESRE_{PT_h} \times SMPU_{PT_h}\right) + \left(ESRE_{SP_h} \times SMPU_{SP_h}\right) \tag{6.6}$$

where $TESRE_h$ is the total cost of exported SR energy at time h; $ESRE_{PT_h}$ is the exported SR energy from the Portuguese TSO at time h; $SMPU_{PT_h}$ is the SUR market price asked to the Portuguese TSO at time h; $ESRE_{SP_h}$ is the exported SR energy from the Spanish TSO at time h; $SMPU_{SP_h}$ is the SUR market price asked to the Spanish TSO at time h.

The total SR transacted between the Iberian TSOs is expressed as:

$$TSRG_h = ISRE_{PT_h} + ISRE_{SP_h} + ESRE_{PT_h} + ESRE_{SP_h} \tag{6.7}$$

So, the costs of the sharing SR between the Iberian TSOs and the resulting payments or benefits without adjustments are expressed as:

$$CIGCC_h = (\,TISRE_h + TESRE_h)/\,TSRG_h \tag{6.8}$$

where $CIGCC_h$ is the cost of the Iberian grid control cooperation at time h, and:

$$MIGCC_{PT} = \left(\,ISRE_{PT_h} - ESRE_{PT_h}\right) \times CIGCC_h \tag{6.9}$$

$$MIGCC_{SP} = \left(\,ISRE_{SP_h} - ESRE_{SP_h}\right) \times CIGCC_h \tag{6.10}$$

And so, $MIGCC_{PT}$ and $MIGCC_{SP}$ represent the individual grid control cooperation costs from Portuguese and Spanish TSO. Thus, the benefits for each TSO without adjustments are expressed as:

$$BGC_{PT_h} = \left(\left(ISRE_{PT_h} \times BCSDR_{PT_h}\right) - \left(ESRE_{PT_h} \times BCSUR_{PT_h}\right)\right) - MIGCC_{PT} \tag{6.11}$$

$$BGC_{SP_h} = \left(\left(ISRE_{SP_h} \times BCSDR_{SP_h}\right) - \left(ESRE_{SP_h} \times BCSUR_{SP_h}\right)\right) - MIGCC_{SP} \tag{6.12}$$

where $BCSDR_{PT_h}$ and $BCSDR_{SP_h}$ are the bidding costs of SDR for the Portuguese and Spanish TSOs, respectively; $BCSUR_{PT_h}$ and $BCSUR_{SP_h}$ are the bidding costs of SUR for the Portuguese and Spanish TSOs, respectively. The group SR sharing, without adjustment, is given by:

$$BCGT_h = BGC_{PT_h} + BGC_{SP_h} \tag{6.13}$$

6.4 Synergies in Iberian Secondary Control: Identification and Evaluation

In this point, the possibility of synergies generated if both Iberian TSOs cooperate with the sharing of imbalance control, by the possibility of minimizing energy mobilization, will be analyzed. The way of cooperation between TSOs could be done by multiple mechanisms, methodologies and processes.

The chosen way for analyzing the possible cooperation is one where the model used does not request the sharing between TSOs of a considerable amount of information that could be classified as confidential by each TSO, like the prices or market agents. More efficient and complex ways of cooperation are possible, but it is necessary to share a considerable amount of information, that in normal situations the TSOs have some reluctance to do in real-time.

The major hindrance in the present analysis is the existence of hourly data instead of quarter-hourly data or smaller periods, which would give more precise results to our analysis. The existence of smaller periods would certainly increase the periods of cooperation. However, for the PES, the data in time-steps smaller than the hourly period is not available, and to this end, for coherence and fair analysis, the hourly data for both TSOs was implemented and analyzed.

Summarizing the process methodology described in the previous point: In a first step, it compares only the direction of both AGCs. If both ES have positive or negative imbalances, any possibility of cooperation is possible. However, in a second step, if one of the ES has a positive imbalance and the other system has a negative one, there is a singular opportunity of cooperation.

The value of the imbalance is traded between TSOs and a subtraction is made, i.e., the value of the positive imbalance minus the value of the negative imbalance. If the remaining imbalance result is positive, the TSO who needs to activate SDR will decrease this new imbalance value. However, if the remaining imbalance result is negative, the TSO who needs to increase the SUR remains imbalance.

In other words, e.g., if the Spanish ES has 40 MW of positive imbalance and Portuguese ES has 20 MW of negative imbalance, in reality, the Spanish SDR will decrease 40 MW and the Portuguese SUR will increase 20 MW.

However, this proposal intends to minimize the control executed by the Iberian TSOs, and considering the previous example, it is suggested to decrease the Spanish SDR by 20 MW, and the Portuguese SR will not be activated, so the Iberian system is, at this period, balanced.

A similar mechanism could be implemented in Europe as a whole, because the main objective is to maintain the EEG balanced. In this sense, the current work intends to analyze the possibility of cooperation at a regional level (from the Iberian electrical grid perspective), quantifying the periods and the amount of energy that could be involved, and analyzing in a second step the savings for both electrical systems with the suggested cooperative association.

Like in the previous sections, in this section a more detailed analysis will be done, focused exclusively on the possible synergies between both Iberian TSOs, arranging the results in a specific manner that enables two different types of reflections:

i) A daily analysis (a short-term perspective) where it will be possible to understand the possibility of synergies between the TSOs in a market day;

ii) A more long-term perspective where it will be possible to understand the evolution of the possible exchanges over the complete period of analysis, carried out in a quarterly (trimestral) basis.

6.4.1 Daily Market Analysis

In Figure 6.10 it is possible to observe the periods, according to the adopted mechanism, where the synergies could occur. The average value of synergies between TSOs occurs in 45% of the periods. The synergies occurred with more frequency in the peak periods and during the load increases. In the off-peak periods, the synergies decrease significantly. This is an expected result because the similar time zone due to the geographic proximity makes the load behavior very similar in both countries.

Considering to the absolute average value of the Iberian TSO synergy, in off-peak periods this value is lower than average. The reasons are related to those previously described. For such reasons, in off-peak periods, as shown in Figure 6.10, fewer transactions occurred, containing lower quantities. From Figure 6.10, despite having similar time zones, the one-hour difference makes the load increase, because of the different waking up hours in both countries, generating more synergies during this period.

Moreover, in Figure 6.11 it is possible to observe the average value of each synergy moment. The results are in accordance with the previous observations, i.e., the average value of synergy between the TSOs is lower in off-peak periods. However, when a certain degree of stability in the load periods is observed, as is from 12 to 18, the price of the synergies tends to decrease. This trend could be associated with price similarity in different electrical systems. The set of Figure 6.10 to Figure 6.12 corroborates that in off-peak periods the Iberian TSOs have fewer possibilities of synergy, less average value per synergy and less profit per synergy. These conditions are reflected and demonstrated in Figure 6.13. It is possible observe the trend established in the previous figures. The decrease not only occurs in volume but also, considerably, in revenues between periods 12 to 18.

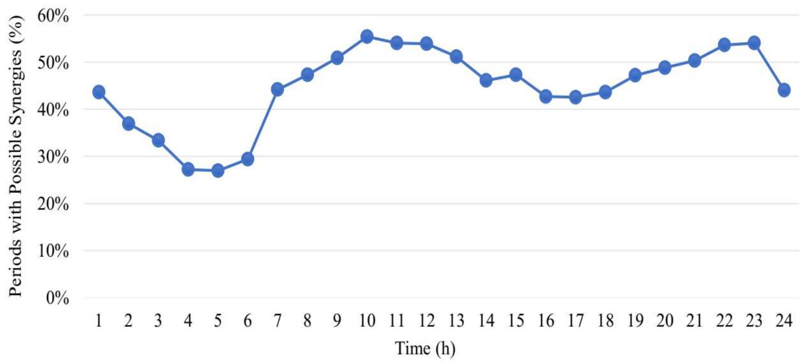

Figure 6.10: Periods of possible SR synergy between the Iberian TSOs.

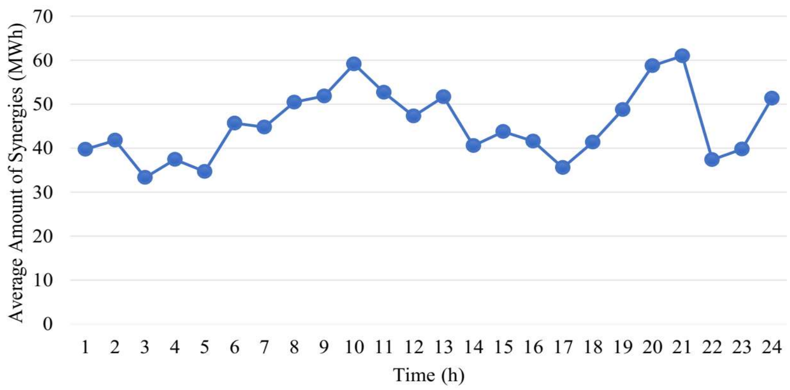

Figure 6.11: Average amount of SR synergy between the Iberian TSOs.

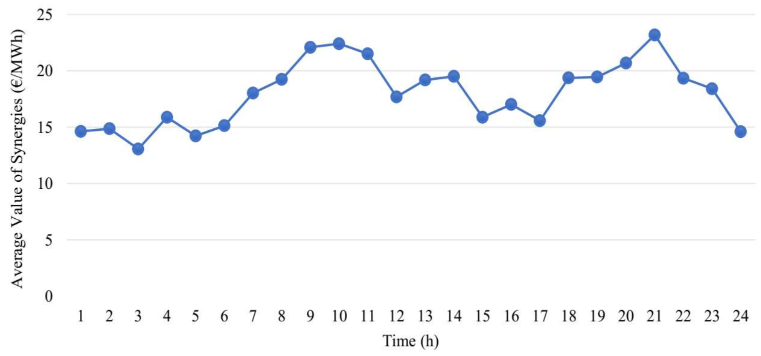

Figure 6.12: Average price value of synergy occurred between the Iberian TSOs.

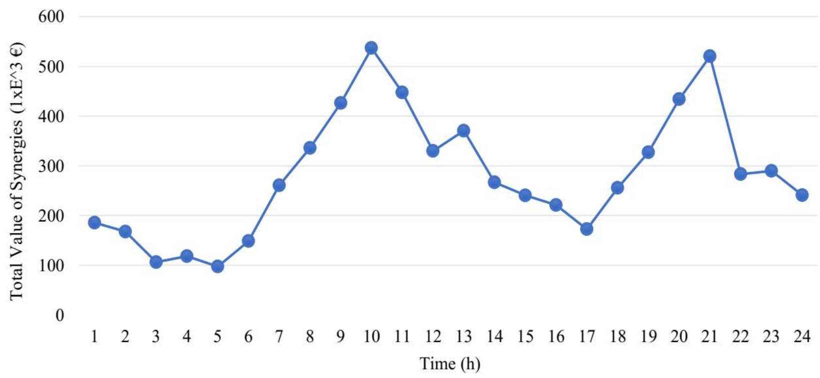

Figure 6.13: Total value of synergy analysis between the Iberian TSOs.

6.4.2 Long-Run Analysis

In this section, the possible Iberian synergies are analyzed in a time evolutionary perspective, in order to understand the seasonal behaviors. In Figure 6.14 is possible to observe the percentage of periods when the synergies are possible. The possibilities of synergy slightly diminish in the first and second quarters of both years under analysis.

In the Figure 6.15, the period under analysis, in both ESs, it can see that the hydro power plants have more capacity to produce and the energy available in both systems is higher, making the energy price, and the associated services decrease on both sides, and consequently, it makes the synergy possibility less attractive. Due to similarities and geographical proximity, as well as to a mix in energy production from both TSOs, it is natural to observe a certain degree of stability in the periods when the synergies occur.

Figure 6.16 shows the total amount of energy traded from each TSO in each quarter of the years under analysis. As observed, the traded energy does not have the same stability as seen in the percentage of periods when synergy between the Iberian TSOs occurred.

Moreover, in Figure 6.16, it is possible to observe the total economic value of the synergies in each quarter of the years under analysis. In line with Figure 6.15, it is possible to observe considerable variations. The periods when it is possible to have more profits are the summer and the fall seasons, considering the reasons previously described.

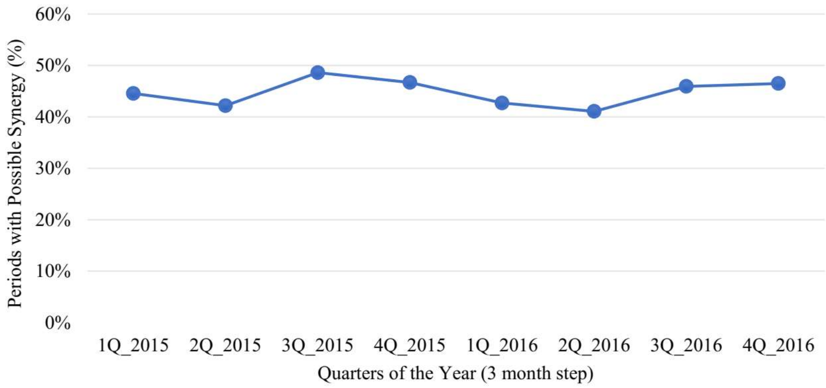

Figure 6.14: Periods of possible synergy analysis between the Iberian TSOs.

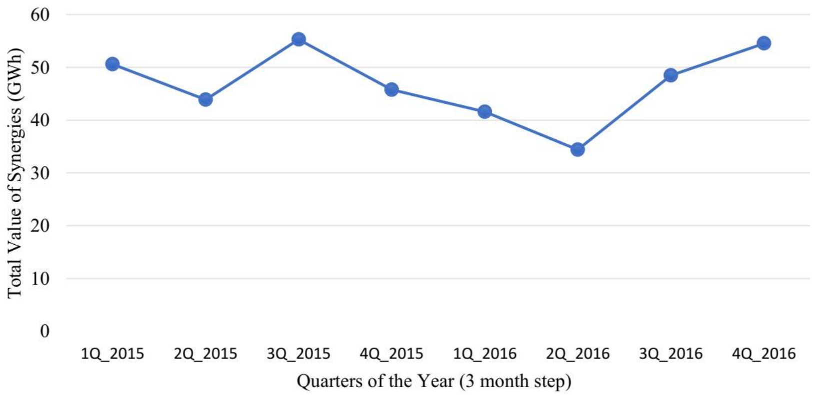

Figure 6.15: Total value of synergy transacted between the Iberian TSOs.

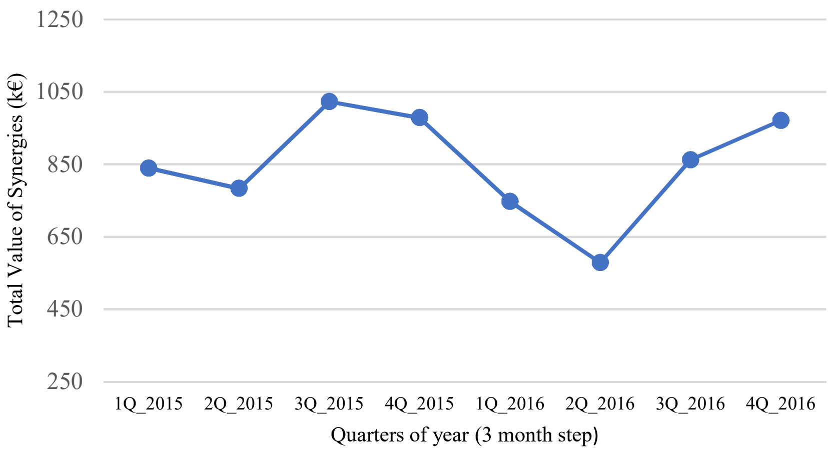

Figure 6.16: Total value of benefits synergy transacted between the Iberian TSOs.

6.5 General Result Analysis

In this point, the main goal is to analyze the general results of the Iberian synergies in the secondary reserve. Considering the synergy occurrences, with the adopted method described previously, it became possible for Iberian TSOs to cooperate in approximately 45% of the time periods. The yearly difference corresponds to only 1.4%, which is not a significant difference.

The same happened with the energy that the Iberian TSOs could avoid to mobilize. It is the synergies' energy. The quantity of synergy decreased 7.5% when comparing 2016 (189 GWh) to 2015 (175 GWh), where not only the periods of possible synergy decreased but also the quantity of synergy was higher in the beginning. One of the main reasons for these decreases is related to the "wet" winter registered in 2016, in comparison with the same period of 2015.

As previously described, both ESs are considerably exposed to the hydro power production, with a considerable amount of water on both sides of the borders. That means that there is more available energy on both ESs. This fact has a direct impact on electricity price (which decreases) and an indirect impact on other services such as tertiary or SR control. In term of the potential value of savings, the same occurred with the quantity of energy. The prices' reduction originates a lower potential for savings, with a decrease of, approximately, 12.5% when comparing the year 2016 (3.62 M€) to 2015 (3.16 M€). Table 15 summarizes the results explained here.

Table 6.3: Secondary and Tertiary Energy Mobilization between the Iberian TSOs.

Year	2015	2016
Sinergy Periods (hours)	3988	3871
Percentage of Synergy Periods	45.50	44.10
Quantity of Sinergy Transacted (GWh)	189	175
Total Value of Synergy Benefits (Millions of €)	3.62	3.16

6.6 Brief Remarks of Chapter 6

Over the last decade, the ESs strengthening of sharing became a reality, not only by market developments but also the considerable increase of renewable generation in the EEG, mainly wind and solar.

However, new challenges came up in the operation of ESs. These new ways to produce electricity scattered and with more or less expression in all of Europe, have a certain degree of intermittency that forces system operators to adapt to such fluctuations and to a certain degree of production variability. To this end, one of the measures was the increase of the AS, in particular the aFRR. However, the increment of the aFRR in a market environment increases the overall costs.

The main goals for the TSOs in EEG sphere are to maintain the ES reliable and to supply the consumers at lowest possible costs. With a European interconnected grid, it does not make sense for TSOs to think only in terms of their own control block. An electrical incident in one TSO could generate a partial or even a total blackout in its neighborhoods.

It is worthless to keep the individual ES balanced if a problem may arise in the nearest TSO. In certain circumstances, maintaining the system imbalanced could help to maintain the frequency in adequate levels, avoiding global and major problems. This can be an adequate measure to improve the reliability of ESs, and to reduce the costs for the providers of AS, proven that an adequate coordination between TSOs is carried out.

For TSOs that share the same regional area, as the Iberian ones, the main goal is to maintain this regional area balanced. To maintain the region balanced, at the lowest possible cost, a constant and adequate coordination must be provided.

Historically, to keep the region balanced, each TSO takes care of its own internal imbalance. The present chapter showed that it is possible to maintain the region's balance with both TSOs imbalanced, reducing the costs with the operating reserves. In economic terms, the possibility of synergies in, approximately, 45% of the market periods, generates global savings around 3.4 M€. The sharing of secondary reserve in a regional, or even continental context, has multiple advantages as observed.

Chapter 7

Renewable Balancing Costs in a Power System with High Renewable Penetration – Evidence from Portugal

The growth of intermittent renewable power generation has been drawing attention to the design of balancing markets. Portugal is an interesting case study because wind generation already accounts for a high fraction of demand (23% in 2012–2016), but still there are no economic incentives for efficient wind forecasting (wind balancing costs are passed to end consumers).

It is analyzed the evolution of the balancing market from 2012 to 2016. Using actual market data, we find wind balancing costs around 2 euros per MWh of generated energy. One main reason for these low costs is the existence of a robust transmission grid, which allows for the compensation of positive with negative wind imbalances across the system. Nevertheless, the results suggest that final consumers could save several million euros per year if wind generators were made responsible for the economic cost of their imbalances, in line with other European markets.

7.1 Brief Overview

Renewable wind power generation has been increasing across the world, already reaching very significant levels in some markets. Portugal is one such case, with wind installed capacity growing from 4529 MW in 2012 to 5313 MW in 2016. Wind accounted for 23% of all electricity consumed in Portugal from 2012 to 2016. The growth of intermittent generation puts more strain on TSO, which must use balancing markets to compensate for any deviation between what wind plants were expected to generate and what they actually deliver in real time. The dispatch of balancing reserves is typically more expensive than energy contracted in day-ahead markets. Imbalances therefore create an extra cost, which could be avoided if agents were able to forecast their generation perfectly.

For several reasons (such as the incentive to increase renewable generation), wind balancing costs have traditionally been paid by the end user, rather than by the wind plants with deviations. However, there are different views on the best market design. Allocating balancing responsibility to wind producers incentivizes them to forecast more accurately. For example, wind generators in Spain have been responsible for their imbalances since 2007. This has led those generators to minimize expected imbalances by trading in the intraday market and has also led to a continuous improvement in wind forecasting technology.

Moreover, balancing responsibility may be disproportionately expensive for small producers with fewer forecasting and financial resources, thus hindering competition. Different countries have followed different rules for allocating balancing responsibility, but European regulators favor a move towards subjecting wind producers to the same market exposure as traditional generators.

Wind generation in Portugal has been incentivized through guaranteed feed-in tariffs (FiT), which fully isolate wind plants from market price risk [103], [104]. While wind generators have to go through a formal market process, where they first have to sell their energy in the power exchange (at a price typically lower than the FiT) and their real-time imbalances are valued (representing a further cost), they then receive an additional remuneration such that, in the end, wind producers always make a revenue equal to the promised FiT. In other words, wind imbalance costs are socialized, that is, split over final consumers. Portugal is thus an interesting case of a system with large wind penetration, but without price mechanisms to induce low forecasting errors and economic efficiency.

The main goal of this chapter is to measure wind balancing costs, using real market data, in a setting of high wind penetration. Furthermore, it is necessary to understand the economic and technical factors that influence the aforementioned costs. The data obtained from the Portuguese TSO at the hourly frequency, for the period between 2012/Jan/01 and 2016/Dec/31.

To understand the drivers of balancing costs, in this chapter a detailed analysis of the unique Portuguese imbalance pricing method was done. It was demonstrated that the particular market design is not the reason for low imbalance costs, as in general the pricing system provides inefficient price signals. It was identified several technical factors that help to explain the relatively low wind balancing costs.

The most important is the aggregation of all wind generators into a single balance responsible party (BRP), which cancels positive with negative deviations of wind plants across the country. Since the aggregation into a single large BRP requires a robust transmission grid, the results highlight the fact that investments in transmission capacity help to reduce the balancing costs of intermittent renewables. The results in this chapter also suggests that this improvement in market design could save consumers several millions of euros per year.

7.2 Imbalance Pricing System

The Portuguese TSO computes an hourly imbalance cost or revenue, V_i , for each agent i, through the Equation 7.1:

$$V_i = (D_i P + K_i R) \tag{7.1}$$

where V_i is defined in euros from the point of view of the TSO, that is, $V_i > 0$ represents cash flowing from agent, i, to the TSO.

The first term in the sum is the value that the imbalanced energy would have in the day-ahead market. More precisely, P (in €/MWh) is the electricity price for that specific hour determined in the day-ahead market. D_i (in MWh) is the imbalance of agent i. It is computed as the difference between:

(i) The energy actually generated or consumed during the delivery hour, and;

(ii) The energy transacted in the day-ahead market, plus in all the intraday auctions up to the delivery hour.

A long imbalance is codified as a negative Di, meaning that BRP i is contributing to generation being higher than load in the overall system. If i is a producer, $D_i < 0$ means that it is generating more than what was programmed; if i is a consumer, $D_i < 0$ means that it is using less energy than programmed.

Similarly, a short imbalance is codified as $D_i > 0$ (i is generating less or consuming more than the market program). While these definitions may feel counterintuitive at first pass, they allow the same formulas and procedures to be applied directly to both consumers and producers. The second term in Equation 7.1, $K_i R$, penalizes the imbalance relative to its day-ahead value. R (in €) is the extra cost for balancing the whole system during that hour, expressed in Equation 7.2:

$$R: = \left(P - \underline{P}\right)\underline{E} + (\overline{P} - P)\overline{E}) \tag{7.2}$$

where $\underline{E}$ (in MWh) is the total amount of downward regulation energy dispatched by the TSO during the hour, including both secondary and tertiary reserves, $\overline{E}$ (in MWh) is the total amount of upward energy, and $\underline{P}$ and $\overline{P}$ are the corresponding market clearing prices of downward and upward reserves.

Note that the TSO may need to use both downward and upward reserves during the same hour, though obviously at different instants. The allocation of K to each agent is determined through Equation 7.3:

$$K_i := \frac{|D_i|}{\sum_{j=1}^{I} D_j} \tag{7.3}$$

where I is the total number of balance responsible parties participating in the market.

The term $K_i R$ is denoted the balancing cost of agent i. It can be interpreted as the cost of imperfect forecasting. For example, if wind delivers less energy than contracted, it has to refund the day-ahead value, plus an additional $K_i R$. If wind delivers more energy than expected, the amount paid to wind is reduced by $K_i R$ relative to the day-ahead value, thus representing an opportunity cost[1].

Example (single deviation): Suppose that the only BRP with an imbalance is wind ($i = w$), and that it generated 100 MWh more than programmed, $D_w = 100$ MWh. The TSO thus has to dispatch $\underline{E} = 100$ MW at a price of, say, $\underline{P} = 30$, assuming that $P = 40$. Since $K_w = 1$, so:

$$V_w = -100 * 40 + 1[(40 - 30) * 10] = -4000 + 1000 = -3000 \text{ €}$$

If wind had sold the 100 MWh in the day-ahead market, it would have received 4000 €. However, now it is only receiving 3000. The balancing cost, $K_w R = 1000$, represents lost revenue, or an opportunity cost. Note that this is a zero-sum mechanism for the TSO because the exact 3000 € paid to wind are coming from the downward reserve provider. **Appendix B** shows that this is a general result, that is, the mechanism is always zero-sum for the TSO.

While the previous example shows a case where an imbalance is priced at its marginal cost, the pricing system does not always ensure this result. In fact, the Portuguese system is only guaranteed to behave optimally, in the sense that it prices all imbalances at their true marginal cost, under the conditions of the following proposition.

[1] In the first case, $\boldsymbol{K}$, $\boldsymbol{R}$, and $\boldsymbol{i}$ compensates the system for the higher cost of upward reserves. In the second case, $\boldsymbol{K_i R}$ corresponds to the amount that the downward reserve plant does not transfer to wind, that is, the reserve plant gets paid $\boldsymbol{K_i Rjust}$ to sit idle without generating energy.

Proposition 1. If all agents are imbalanced in the same direction, then each agent pays/receives exactly the marginal cost/value of its deviation, that is,

$$V_i = \begin{cases} D_i\overline{P} > 0, & if\ D_i > 0, \quad \forall i \in \{1 \dots I\} \\ D_i\underline{P} < 0, & if\ D_i > 0, \quad \forall i \in \{1 \dots I\} \end{cases} \tag{7.4}$$

Proof: See **Appendix B.2**.

This means that when all agents deviate in the same direction, the Portuguese pricing system is similar to a single-price system (as described below). However, when there are deviations in both directions, which is often the case, the system no longer behaves optimally, as discussed next.

7.3 Comparison with Alternative Pricing Systems

There are two standard imbalance pricing schemes used in several countries: single-price systems and dual-price systems[2]. **Appendix B** summarizes the two systems [105]. The Portuguese imbalance pricing system behaves like a single-price system only in the special case when all BRPs are imbalanced in the same direction (as in Proposition 1).

When there are imbalances in both directions, the Portuguese system departs from a single-price system. However, contrary to what might be expected, it goes in the opposite direction of a dual system, in the sense that the agents causing the imbalance pay even less than they would pay under a single-price system. The following example illustrates this effect.

Example (multiple deviations with different signs): Assume again that wind generated 100 MWh more than programmed, $D_w = -100$ MWh, but now suppose that a consumer ($i = c$) exceeded its programmed load by 300 MWh, $D_c = +300$ MWh. The system thus requires a net upward reserve of $\overline{E} = 200$ MWh at a price of, say, $\overline{P} = 50$. Assume again $P = 40$, for wind, it turns:

$$V_w = -100 \times 40 + \frac{1}{4}[(50-40) \times 200] = -4000 + 500 = -3500\,€ \tag{7.5}$$

and the consumer BRP is:

$$V_c = 300 \times 40 + \frac{3}{4}[(50-40) \times 200] = 12000 + 1500 = 13500\,€ \tag{7.6}$$

The previous example is summarized in Table 7.1, which shows the cash flows to the SO under three different alternative imbalance pricing mechanisms. A positive value means that cash is flowing from the agent to the SO. The example assumes that $\bar{P} = 50$, $P = 40$, and the imbalance values $D_c = 300$, and $D_w = 100$.

As expected, the pricing mechanism is zero-sum for the Portuguese SO. The total amount collected from the imbalanced parties, 10,000 € in this example, is exactly the amount paid to the upward reserve provider. In this regard, the mechanism behaves like a single price system. The cost allocation to each BRP, however, deviates from single-price systems.

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[2] Countries that use one-price systems include Belgium since 2012, Germany, and the Netherlands. Countries that use dual-price systems include Belgium until 2011, Denmark, Finland, France, and Spain.

The consumer BRP is the one causing the whole system to be short. In a single-price system, the imbalance of 300 MWh would be charged at its marginal cost of 50 €/MWh, for a total of 15 000 € ($D_c\overline{P}$). In a dual-price system, it would be charged an even higher value due to a penalty. In the Portuguese system, however, the BRP that is aggravating the system imbalance pays only 13 500 €. This implies a cost per unit of imbalance of 45 €/MWh, which is actually less than the marginal cost the consumer is imposing on the system.

As detailed in Equation 7.6, the consumer BRP is only paying 3⁄4 of the cost of net imbalances.

Moreover, the excess wind generation of 100 MWh is helping the system to balance. In a single price system, wind would be paid the full value of the injected energy, at the marginal cost of the alternative reserve provider, for a total of 5000 €. In a dual-price system, it would be partly penalized, and receive only a value corresponding to the day-ahead price, 4000 €. In the Portuguese system, however, the excess energy is penalized even further, and receives only 3500 €.

As detailed in Equation 7.5, wind still needs to pay 1⁄4 of the total system balancing cost. Even though the BRP is helping the system, it receives less than what it could have received in the day-ahead market. In summary, the Portuguese imbalance pricing system penalizes all deviations from the market program, in the sense that all BRPs are worse-off than if they had perfect forecast and traded the correct amount of energy in the day-ahead market.

Table 7.1: Compare alternative imbalancing pricing systems.

	Portuguese	**Single-Price**	**Dual-Price**
Consumer (short, $D_c = +300$ MWh)			
Total cash flow (€)	13,500	15,000	>15,000
Implicit Price (€/MWh)	45	50	>50
Wind (long, $D_w = 100$ MWh)			
Total cash flow (€)	-3,500	-5000	-4,000
Implicit Price (€/MWh)	35	50	40
Upward reserve provider ($\overline{E} = 200$ MWh)			
Total cash flow (€)	-10,000	-10,000	-10,000
Implicit Price (€/MWh)	50	50	50
System Operator			
Total cash flow (€)	0	0	>1,000

However, the penalties applied are optimal only in the special case where all BRPs are imbalanced in the same direction. In general, the penalties work in the opposite direction of what might be expected, dampening the cost of BRPs that deviate against system requirements and also dampening the profit of BRPs that deviate in favor of system requirements.

7.4 Organization and Procedures

The data of all generation, imbalances, and reserves is provided by the Portuguese TSO for all hours (market periods) between 2012 and 2016. Table 7.2 shows descriptive statistics. The Portuguese total system hourly load varied between 3364 and 8578 MWh, with an average value of 5594 MWh. Wind generation is, on average, 1316MWh during each hour of the sample.

The average hourly wind penetration (that is, the amount of load fulfilled by wind) is 24%. However, this average masks considerable variation at the hourly frequency, with wind sometimes even exceeding 100% of load. In fact, there is a total of 6h when wind generation exceeds system load. The maximum of 104% was at 05:00 a.m. on 21/Nov/2016, when wind generated 4365 MWh and load was 4202 MWh.

The excess generation was compensated by 1476 MWh of upstream pumping hydro (note that other plants, such as coal and run-of-river were still generating). There are four more hours when excess wind is used in upstream pumping, and one additional hour where surplus was exported to Spain. The descriptive statistics for the total system Load (L), Wind generation (W), Wind Imbalance (WI), total System Imbalance (SI), and the corresponding ratios are provided. All raw variables (L, W, WI, SI) are in MWh. Hourly data, 2012/01/01–2016/12/31.

The TSO provided to the public with hourly data on total system imbalance and wind imbalance. The wind imbalance has a distribution that is reasonably symmetric and centered close to zero, as shown in Table 7.1 [3]. More precisely, the full sample average of wind imbalances is −32 MWh, meaning that wind generators, on average, deliver 32 MWh more than programmed. There is, however, a large dispersion around this mean, with the standard-deviation being 260 MWh. Furthermore, the tails of the distributions extend out to very large values. Over the full time period, the minimum hourly wind deviation is −1613 MWh and the maximum is +1497 MWh. These are large values when compared to the system load. As it is shown in Table 7.2 the wind imbalance as a fraction of load ranges from 38% to + 29%.

[3] Since a few hours display very extreme values, we consider as outliers imbalances that are more than three standard-deviations away from the mean. Table 2 describes the data after removing these outliers

Another way of gauging the significance of wind imbalances in Portugal is to compare them with other markets, in particular with Spain, where the wind resource will presumably be reasonably similar. Figure 7.1 shows that in 2014 (which corresponds to the middle of our sample period), the mean absolute wind forecast error in Spain ranges approximately from 5% to 10% of mean production, depending on the forecast lead time.

Table 7.2: Generation and imbalances.

Variables	L	W	W/L	WI	WI/L	SI	SI/L
Moments							
Mean	5594	1316	0.24	-32	-0.01	-7	0.00
Stdev	971	953	0.18	260	0.05	337	0.06
Percentiles							
Min	3364	11	0.00	-1613	-0.38	-1969	-0.42
5 %	4164	169	0.03	-479	-0.09	-546	-0.10
25 %	4750	529	0.10	-176	-0.03	-215	-0.04
Median	5597	1083	0.20	-15	0.00	-9	0.00
75 %	6333	1931	0.36	121	0.02	192	0.03
95 %	7193	3207	0.59	363	0.07	549	0.10
Max	8578	4423	1.04	1497	0.29	1953	0.36
Cross-Correlations							
L	1.00	0.03	-0.22	0.00	0.02	0.10	0.09
W		1.00	0.95	-0.28	-0.28	-0.11	-0.13
W/L			1.00	-0.28	-0.28	-0.14	-0.16
WI				1.00	0.98	0.77	0.78
WI/L					1.00	0.76	0.80
SI						1.00	0.98
SI/L							1.00

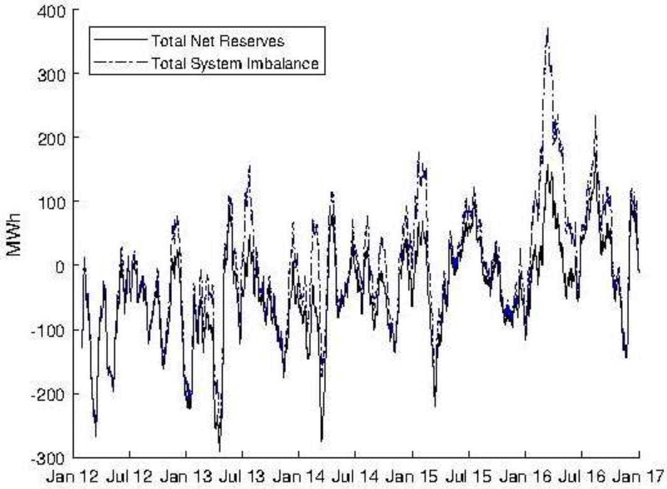

Figure 7.1: Total imbalance net reserves.

In contrast, the mean absolute imbalance in Portugal is 194 MWh, which represents 15% of the mean wind generation during our sample period, 2012–2016. The error is thus substantially larger in Portugal. In fact, the level of error in Portugal during 2012–2016 is comparable to the average error in Spain during the earlier 2007–2008 period, the beginning stage of the market. Much of this difference is likely to result from the lack of economic incentives for accurate wind forecasting in Portugal.

Moreover, Figure 7.1 shows the total net reserves and total system Imbalance per hour. Rolling 30-day averages of hourly values, 2012/01/01–2016/12/31. The total system imbalances range from −1969 MWh to +1953 MWh, and from 42% to +36% of load. The distribution of system imbalances is somewhat more dispersing than the distribution of wind imbalances, but not much more. Together with the high correlation of 0.77 between wind imbalances and total system imbalances, these numbers suggest that wind is a major driver of the whole system imbalance.

Table 7.3 shows descriptive statistics on the hourly quantity of secondary and tertiary reserve energy used for upward and downward regulation. SR is typically used in small amounts, with an average of 8MWh for downward regulation and 50MWh for upward regulation. In contrast, tertiary reserve is used in higher quantities, with an average of 167MWh for downward regulation and 83MWh for upward regulation. Both directions of tertiary reach much more extreme values than SR does. There is also an asymmetry in the use of the two types of reserves: upward mobilization is typically higher than downward for SR, while the opposite is true for tertiary reserve. This fact has an explanation related to the design of the Portuguese market, as detailed in **Appendix B.**

The columns for the "Secondary" and "Tertiary" describes the quantity of reserve energy, (in MWh), which are used for upward and downward regulation. The last three columns describe the prices (in EUR/MWh) of tertiary reserves and the day-ahead (DA) price. The cross-correlations under "Secondary" and "Tertiary" are between quantities, whereas the cross-correlations under "Prices" are between prices. The hourly data is related from 2012/01/01–2016/12/31.

Table 7.3: Secondary and tertiary reserves.

	Secondary		**Tertiary**		**Prices**		
	Down	**Up**	**Down**	**Up**	**Down**	**Up**	**DA**
Moments							
Mean	8	50	167	83	27	57	45
Stdev	16	41	209	151	16	21	16
Percentiles							
Min	0	0	0	0	0	0	0
5 %	0	0	0	0	0	30	12
25 %	0	13	0	0	18	45	37
Median	0	44	87	0	29	55	47
75 %	10	78	270	112	37	69	56
95 %	46	126	584	401	51	95	68
Max	151	271	2129	1568	100	180	112
Cross-Correlations							
Sec. Down	1.00	-0.49	0.01	0.03			
Sec. Up	-0.49	1.00	0.05	-0.04			
Ter. Down			1.00	-0.38	1.00	0.50	0.71
Ter. Up						1.00	0.62

Also, Table 7.3 shows the market-clearing prices of upward and downward tertiary reserves (recall that SRs are also paid at the tertiary price). The full-sample average price of upward regulation is 57 EUR/MWh, while the average price downward regulation is 27 EUR/MWh (recall that the downward price represents a refund from the agent that is reducing its day-ahead-scheduled generation). These values compare with an average day-ahead market price of 45 EUR/MWh.

Figure 7.2 compares the evolution of these three variables. The series display the expected pattern, with the upward price above the day ahead, and the downward price below it. The prices of downward and upward tertiary reserves and day-ahead price are rolling 30-day averages of hourly values, from 2012/01/01–2016/12/31.

7.5 Drivers of Balancing Reserve Mobilization

As described previously, the cost of balancing reserves is allocated to imbalanced agents. However, in addition to imbalances, there may be other causes for the use of reserves. This section compares the importance of the different drivers of reserves. Since it is not possible to identify the events that lead the TSO to manually dispatch tertiary reserves in the hourly data, in this work it was aggregated the secondary with tertiary reserves. Furthermore, since imbalances can be either positive or negative, the work was focused on net reserves. Hence, the variable of interest is “Total Net Reserves” (TNR), computed for each hour as and described in Equation 7.7:

$$TNR = (Secondary\ Upward + Tertiary\ Upward) - (Secondary\ Downward + Tertiary\ Downward) \quad (7.7)$$

Furthermore, Figure 7.2 compares the TNR and total system imbalance. Clearly, a very large fraction of reserve usage is explained by total system imbalance. On average, the amount of reserve usage that does not correspond to system imbalance is only 63MWh (mean absolute difference between the two series). However, there are some hours when the difference becomes very large, from a minimum of 1394 MWh to a maximum of +1584 MWh (not visible in the figure, which plots smooth averages of hourly values over 30-day windows).

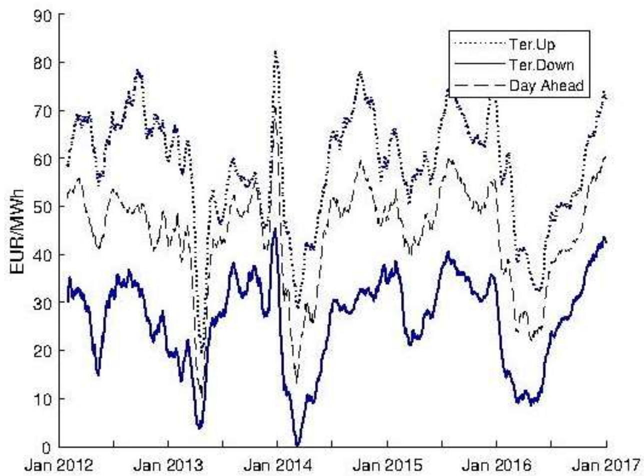

Figure 7.2: Prices of tertiary reserves.

So, the present work proceeds to investigate other determinants of balancing reserves. In addition to deviations from the market program, there are at least two more factors that may drive the use of reserves. One factor is the change in load. While load evolves as a continuous function of time, the generation that is dispatched in the day-ahead market is a step function constant over each hour. The difference between the two has to be fulfilled with balancing reserves. Hence, it was tested whether the changes in load relative to the previous and next hour are significant[4].

A second factor that may drive the use of reserves, it is with the change in trade with neighboring markets (Spain, in this case). While market agents may trade any desired quantities, if these result in large changes in trade from 1h to the next, the TSO manually dispatches reserves to ensure that the system is able to remain balanced during the transition.

For example, if a large amount of generation is scheduled to start at the first minute of the coming hour due to an export trade, the TSO will smooth the transition by dispatching upward reserves in the last few minutes of the current hour, and then downward reserves in the first few minutes of the coming hour. To consider all potential drivers simultaneously, the proposal regress to the hourly TNR, as defined in Equation 7.7), considering the following variables expressed in Equation 7.8:

$$
\begin{aligned}
TNR_t = \beta_0 + \beta_1 WindImb_t + \beta_2 OtherImb_t + \beta_3(Load_t - Load_{t-1}) \\
+ \beta_4(Load_{t+1} - Load_t) \\
+\beta_5(Trade_t - Trade_{t-1}) - \beta_6(Trade_{t+1} - Trade_t) + \varepsilon_t
\end{aligned}
\tag{7.8}
$$

where $WindImb_t$ is the total wind imbalance (all wind generators are aggregated in a single balance responsible party), $OtherImb_t$ is the aggregated imbalance of all other agents (computed as the difference between total system imbalance and wind imbalance), and $Trade_t$ denotes the amount of energy exported from Portugal to Spain minus the amount imported into Portugal during hour t.

This is a statistical model, i.e., there is still an error term, t, for the following reasons. First, there is the usual possibility of data errors. Second, the TSO may use balancing reserves to solve technical grid constraints in real time, like transmission bottlenecks or generators tripping offline unexpectedly, but it was not possible to have the necessary data on these events.

[4] We assume that the future load is known ahead of time. While this assumption is not strictly true, balancing reserves are dispatched in time frames of a few minutes, and the TSO can forecast load changes for the next few minutes with a high degree of accuracy.

Table 7.4 shows the estimation results, with the main results in the first two columns. As expected, imbalances have a strong effect on reserves. On average, 1 MWh of wind generation below the market program requires 0.87 MWh of upward reserves (recall that a positive imbalance means that the generator is delivering less than programmed, as defined in section 2).

Imbalances from other agents (which in our data come mostly from demand imbalances) have a similar impact. For example, one additional MWh of unexpected demand (which would be registered as + 1 in "Other Imbalances") induces, on average, 0.79 MWh of upward reserves. These two imbalances are able to explain a very large fraction, 87%, of the variation in TNR.

Table 7.4: Regression of balancing reserves

	Model 1	Model 2	Subsamples	
	TNR	TNR	TNR>0	TNR<0
Intercept	-35.590*** (1.374)	-35.724*** (1.374)	40.420*** (3.050)	-73.739*** (4.056)
Wind Imbalance	0.869*** (0.007)	0.0868*** (0.007)	0.691*** (0.016)	0.797*** (0.013)
Other Imbalances	0.788*** (0.010)	0.790*** (0.010)	0.604*** (0.018)	0.744*** (0.017)
$\boldsymbol{Load(t) - Load(t-1)}$		-0.045*** (0.003)	-0.058*** (0.005)	-0.0255*** (0.003)
$\boldsymbol{Load(t+1) - Load(t)}$		0.012*** (0.003)	0.023*** (0.005)	0.000 (0.003)
$\boldsymbol{Trade(t) - Trade(t-1)}$		-0.011*** (0.002)	-0.011*** (0.003)	-0.009*** (0.002)
$\boldsymbol{Trade(t+1) - Trade(t)}$		0.002 (0.002)	0.001 (0.002)	0.001 (0.002)
$\mathbf{R^2}$ $\mathbf{R^2}$ **Adjusted** **Number of Observations**	0.8675 0.8675 43558	0.8695 0.8694 43356	0.6626 0.6625 19514	0.7843 0.7842 23841

The ordinary least squares regression of TNR, as defined in Equation 7.8, the last two columns show the results for two subsamples, namely the hours when upward reserves are larger ($TNR > 0$) or smaller ($TNR < 0$) than downward reserves. Numbers in parenthesis are Newey-West heteroscedasticity and autocorrelation consistent standard errors (HACSE) estimated with 24 lags. Stars denote significance at the 10% (*), 5% (**), or 1% (***), of confidence level, respectively. The hourly data is from 2012/01/01–2016/12/31.

Changes in load have the expected sign. Namely, if the hourly load increases by 1MWh relative to the previous hour, the corresponding step-wise increase in day-ahead dispatched generation is smoothed with, on average, 0.045 MWh of downward reserves (presumably during the beginning of the current hour). Likewise, if the load will increase 1MWh during the next hour, the TSO dispatches 0.012 MWh of upward reserves (presumably in the last minutes of the current hour).

Changes in exports and imports have a similar impact. An increase in trade due to, for example, an increase in exports, can be seen as an increase in load for the purpose of interpreting the coefficients in Table 7.3. Importantly, the inclusion of changes in load and in trade has only a tiny effect on the explanatory power of the model: the adjusted R^2 barely changes from 86.75% in model $1 - 86.94\%$ in model 2.

Hence, it is possible to find that, for the purpose of cost allocation, it is reasonable to ignore these other drivers of balancing reserves. In the next section, it will follow the Portuguese TSO procedure and split total balancing costs among wind generators and other imbalanced agents, even though those total costs may include a (small) amount unrelated to energy imbalances.

Finally, to check whether the explanatory variables have different effects on upward and downward reserves, the last two columns show regression results for two subsets of the data, namely the hours when upward reserves exceed downward reserves ($TNR > 0$), and then the opposite case ($TNR < 0$). Note that, say, $TNR > 0$ for a given hour does not mean that only upward reserves are used in that hour.

In fact, in 72% of the hours in the sample the system uses both upward and downward reserves. Nevertheless, the regression results suggest that the effect of the explanatory variables, particularly imbalances, is reasonably similar across hours when more upward or more downward reserves are used.

7.6 Balancing Costs of Wind Power

This section starts by describing the wind balancing cost under the current Portuguese market rules. Then, it assess the impact of the unique Portuguese pricing system by comparing the current cost with the cost under a hypothetical single-price system, and also with costs reported in the literature for other markets. Finally, the section discusses the potential factors that explain wind balancing costs.

7.6.1 Costs under the Actual Portuguese System

In this step the work was done with the data provided by the TSO on the hourly wind imbalance full value that is, on the V value defined in Equation 7.1, exactly as computed by the Portuguese TSO (REN) for the wind balance-responsible party. Then, it separates the series into two subsets, depending on whether the wind imbalance during that hour was long ($D < 0$) or short ($D > 0$) to describes the data.

The two initial columns describe the full imbalance value per unit of absolute imbalance ($V/|D|$). Table 7.5 shows the wind power imbalances statistics under the Portuguese system. A short imbalance ($D > 0$) means that wind is not generating all the energy contracted in the market program and therefore has to pay money to the system. The average cost of short imbalances is 57.15 €/MWh_{imb} [5].

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[5] It is wrote MWh_{imb} or MWh_{gen} to stress whether the value is per unit of imbalance or generation.

Table 7.5: Wind imbalance values under the current Portuguese system.

	Full Value (per MWh imb.)		Penalty Term (per MWh imb.)		(per MWh generation)		
	$D < 0$	$D > 0$	$D < 0$	$D > 0$	$D < 0$	$D > 0$	$All\ D$
Moments							
Mean	-29.64	57.15	14.75	12.36	2.86	3.43	3.13
Stdev	22.27	21.80	17.68	15.19	4.40	7.98	6.35
Percentiles							
Min	-1532	-155	-1469	-205	-30	-19	-30
5%	-58	23	0	-1	0	0	0
25 %	-43	45	5	3	0	0	0
Median	-31	57	12	9	1	1	1
75 %	-17	69	21	17	4	3	4
95 %	1	91	40	38	11	14	12
Max	255	343	305	303	75	302	302
VW Avg	-25.67	52.16	14.07	13.41	2.17	2.18	2.17

In the other direction, a long imbalance ($D < 0$) means that wind is generating more than planned, and therefore receives a payment from the system. The average price received by wind for long imbalances is 29.64 €/MWh_{imb}.

In this sense, Table 7.5 shows the descriptive statistics on hourly wind imbalance values. The columns labeled "Full Value" show the total imbalance value, V_i, expressed in Equation 7.1, and the following columns show the penalty term, KiR. The data subsets correspond to the hours when wind has a long ($D < 0$) or short ($D > 0$) imbalance. The last row, "VW Avg", shows a wind-generation value-weighted average. All values are in euros per unit (MWh) of either absolute imbalance ($|D|$) or true wind generation, as denoted in the headings. A positive/negative sign represents a cash inflow/outflow to/from the system operator. The hourly data is described from 2012/01/01–2016/12/31.

These average prices of short and long imbalances are remarkably close to the average prices of the reserves that would be necessary to compensate wind imbalances: respectively, 57 €/MWh for upward tertiary and 27 €/MWh for downward tertiary. These results are somewhat surprising because, as described previously, the Portuguese system does not always have the price imbalances at their marginal value.

Furthermore, imbalanced parties also have to pay the cost of reserves used for other purposes, which may help explain why the distribution of wind imbalance prices reaches extreme values in a few hours (see the minimum and maximum values in Table 7.5) [6]. Nonetheless, these results suggest that the specificities of the Portuguese system have little impact, and in the end the actual price of wind imbalances turns out to be, on average, very close to marginal value.

From the point of view of a wind generator, the relevant balancing cost is the penalty term KiR, as defined in Equation 7.1. The values in Table 7.5 show that shortfalls in generation ($D > 0$) cost, on average, 12.36 €/MWh_{imb}, while excess generation ($D < 0$) has an average opportunity cost of 14.75 €/MWh_{imb} relative to the alternative of having sold the correct amount in the day-ahead market [7].

For comparison with other markets, it is more useful to standardize the imbalance surcharge by the amount of wind energy generation, rather than by the amount of imbalance. As shown in Table 7.5, the average penalties for both long and short imbalances decrease substantially when divided by the (large) amount of wind generation, dropping to values close to 3 €/MWh_{gen}.

Furthermore, since the penalty term does not depend on the sign of the imbalance, we pool short with long imbalances. Additionally, since the amount of wind generation varies through time due to seasonality and installed capacity, we compute a value-weighted average, where the weight for each hour equals the ratio of wind generation in that hour relative to total wind generation in the sample period.

Note that this value-weighted average gives more importance to recent years where wind penetration is higher. The last row of Table 7.5 shows that the full-sample value-weighted average of wind balancing costs is 2.17 €/MWh_{gen}. This is the main feature in this analysis. It indicates that wind creates an extra cost of 2.17 € per each MWh of electricity generated due to imperfect forecasting. In relative terms, this cost represents approximately 5% of the average day-ahead market price (45 €/MWh). Finally, since this work presents a relatively long time-series of balancing costs, it is interesting to analyze how the market has evolved through time. Figure 7.3 shows the hourly penalty term, for all imbalances, in euros per MWh of wind generation, from 2012 to 2016.

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[6] The sign flipping in the tails of the distributions may appear counterintuitive, but results from the following. For long imbalances ($\boldsymbol{D} < \boldsymbol{0}$), the right tail of $\boldsymbol{V}$ may reach positive values in hours with either low day-ahead prices that make the $\boldsymbol{DP}$ term relatively small in $\boldsymbol{V} = \boldsymbol{DP} + \boldsymbol{KR}$, or in hours where the cost of total system regulation, $\boldsymbol{R}$, is abnormally high due to factors unrelated to imbalances. For short imbalances ($\boldsymbol{D} > \boldsymbol{0}$), the left tail of $\boldsymbol{V}$ reaches negative values due to $\boldsymbol{R}$ is being negative in some hours, as detailed below.

[7] During a few hours, the penalty term $\boldsymbol{K},\ \boldsymbol{R},\ \boldsymbol{i}$ is negative, which must result from $\boldsymbol{R} < \boldsymbol{0}$. In turn, the total cost of system regulation may be negative due to the following reasons. First, prices may sometimes deviate from "normal" market conditions, that is, prices may not satisfy $\underline{\boldsymbol{P}} < \boldsymbol{P} < \underline{\boldsymbol{P}}$, leading to a negative term in equation (7.2). Second, since June 2014 there is a market where the Portuguese and Spanish TSOs trade tertiary reserves. While the amount of trading in this market is very small, it sometimes leads to net revenue that the Portuguese TSO splits among imbalanced agents.

It is possible to observe that after an initial year with high values, the balancing cost of wind has dropped down significantly. This is consistent with improvements in wind forecasting technology and learning by market agents. Interestingly, the Figure 7.3 shows that even during periods of very high wind penetration, balancing costs remain relatively low. The solid blue line is the wind balancing cost (left axis), measured as the penalty term $K_i R$, in Equation 7.1) in euros per MWh of wind generation. The red dotted line is the fraction of wind on total system load (right axis). The rolling 90-day averages of hourly values are from 2012/01/01–2016/12/31.

7.6.2 Costs under a Single Price System

The Portuguese imbalance pricing system is different from the standard systems described in the literature. To better understand the impact of the Portuguese mechanism on wind costs, in this work it is estimated what the wind balancing costs would be under a hypothetical single-price system. Denote by V_i^* the full imbalance value. Using the single-price formulas from Section 7.2, it turns:

$$V_i = \begin{cases} D_i\overline{P}, & if\ system\ is\ short\ (Gen < Load); \\ D_i\underline{P}, & if\ system\ is\ long\ (Gen > Load). \end{cases} \tag{7.9}$$

Note that now what wind pays/receives depends only on its own imbalance, with the system state determining the unit price. It is estimated that V_i^* for wind using the observed imbalances, D_i, market clearing tertiary reserve prices ($\overline{P}$, $\underline{P}$), and total system imbalance. The estimates should obviously be taken only as approximations of what the true costs would be, as market agents might behave differently if the pricing rules were different.

Table 7.6 shows the full wind imbalance value per unit of absolute imbalance ($V^*/|D|$) in the first columns. Imbalance prices do not reach the extreme values that they did under the Portuguese system (Table 7.5) because they are now naturally limited to the administrative price range for tertiary reserves (0 to 180 €). Interestingly, we note that the average values (31.44 €/MWh$_{imb}$ for long and 54.68 €/MWh$_{imb}$ for short imbalances) remain very similar to the current Portuguese system.

In this sense, Table 7.6 shows the descriptive statistics on hourly wind imbalance values. The columns labeled "Full Value" show the total imbalance value, V_i^* in Equation 7.9, and the following columns show the penalty term, C_i^*, expressed in Equation 7.10:

$$C_i = V_i^* - D_i P \tag{7.10}$$

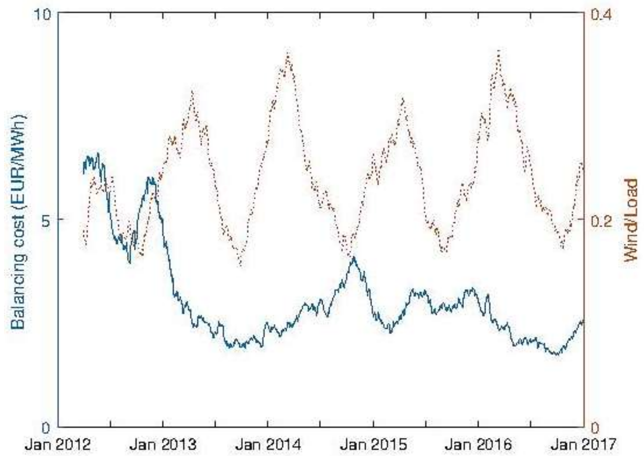

Figure 7.3: Wind balancing cost and penetration.

Table 7.6: Wind imbalance values under a single-price system.

	Full Value (per MWh imb.)		Penalty Term (per MWh imb.)		(per MWh generation)		
	$D < 0$	$D > 0$	$D < 0$	$D > 0$	$D < 0$	$D > 0$	$All\ D$
Moments							
Mean	-31.44	54.68	12.96	9.86	3.16	3.51	3.32
Stdev	22.50	26.35	19.89	24.27	5.39	11.83	9.01
Percentiles							
Min	-180	0	-147	-90	-38	-111	-111
5%	-73	14	-22	-28	-2	-6	-3
25 %	-42	38	3	-2	0	0	0
Median	-30	53	15	9	2	1	1
75 %	-18	70	25	21	5	5	5
95 %	0	99	42	50	13	21	16
Max	0	180	90	159	93	199	199
VW Avg	-27.56	52.00	12.19	13.21	2.51	2.77	2.61

From Equation 7.10 and Table 7.6, the data subsets correspond to the hours when wind has a long ($D < 0$) or short ($D > 0$) imbalance. The last line, "$VW\ Avg$", shows a wind-generation value-weighted average. All values are in euros per unit (MWh) of either absolute imbalance ($|D|$) or true wind generation, as denoted in the headings. A positive/negative sign represents a cash inflow/outflow to/from the system operator. The Hourly data is from, 2012/01/01–2016/12/31. Hence, the balancing cost from the point-of-view of the wind producer is likewise defined as the opportunity cost relative to having traded the correct amount of energy at the day-ahead price ($\overline{P}$), expressed in Equation 7.10

Contrary to the Portuguese system, now this cost "penalty" can be either positive or negative, even under normal market conditions ($\underline{P} < P < \overline{P}$), because the signed imbalance multiplies a price differential that depends on the system state.

For example, if wind generates less than programmed, but that helps a system that is overall long, then the wind "penalty" is negative. The cash flows are still defined with signs from the point of view of the system operator, so a negative penalty represents a cash flow from the system to wind.

Table 7.6 shows that, even though the support of the penalty distribution would become more symmetric under a single price system, the average value would remain very close to the current system. In particular, the value-weighted average of wind balancing costs would be 2.61 €/MWh_{gen}, which is very close to the current 2.17 €/MWh_{gen}. In summary, these results suggest that the Portuguese imbalance pricing method is not the reason why wind balancing costs are low.

7.6.3 Comparison with other markets

To the best of the knowledge in this matter, there are only four published contributions on wind balancing costs using observed market prices observed **Appendix B.** The studies observed cover several European countries and different time periods. There is also a diversity of imbalance pricing systems: some markets use single pricing, while others prefer dual pricing. Portugal seems to be alone in the socialization of wind imbalance costs, as most other countries make wind generators pay for their imbalance costs. Wind balancing costs in Portugal, 2.17 €/MWh, are mostly in line with the other countries.

In most cases, wind balancing costs are below 3 €/MWh. The only two cases with costs above 6 €/MWh are Austria, 2008, and Poland, 2008–2009. Note, however, that most studies present estimates for early periods, when wind forecasting techniques were presumably less developed. Nevertheless, the results of this chapter, together with the results for Western Denmark, encouragingly suggest that wind balancing costs can remain relatively low, even at high penetration rates [106].

7.7 Analyzing Cost Factors

There are several factors that may help explain the low wind balancing costs in Portugal. First, all wind generators in Portugal are included in the same Balance Responsible Party (BRP), thus reducing the aggregate variability. This setup has the advantage of fostering the entrance of small wind producers, as it exempts them from the cost of having to forecast and trade their individual production. Aggregating all wind into a single BRP requires, however, a strong electrical grid.

There must be enough transmission capacity between all relevant points in the network, such that, a wind plant that is generating too little in point A can really be compensated by excess electricity from some other wind plant in point B. The Portuguese transmission grid satisfies this requirement, and thus contributes to lowering wind balancing costs.

A second factor contributing to low wind balancing costs is that most of the current wind farms in Portugal are located in sites with good capacity factors. This helps to reduce the variability costs due to the cubic shape of power curves for typical wind turbines.

A third potential factor is the large capacity of hydropower in Portugal. Hydro power plants have zero marginal cost, and therefore are able to underprice thermal balancing reserve providers. Furthermore, there is also a large capacity of upstream pumping, which can act as downward tertiary reserve, again at a more favorable price for the system. There is evidence that hydropower contributes to stabilize day-ahead and intraday prices, so it seems reasonable to assume a similar effect for balancing markets [107].

Despite these favorable effects, one should ask whether wind balancing costs could be even lower. Given that wind forecast errors are much larger in Portugal than Spain, the answer is probably yes. This is important because wind balancing costs still amount, in absolute terms, to a significant sum of money.

To put this findings in perspective, and considering the total wind generation during the time of 2012-2016 sample period, the wind surcharge amounts to a total of 124 million euros, or an average of 24.8 million euros per year. This is the amount of money that is effectively transferred from final energy consumers to balancing reserve providers. If wind generators had to actually pay for the cost of their imbalances, they would surely find it economical to invest in better forecasting technology, and thus bring their imbalances closer to the levels of comparable countries.

7.8 Brief Remarks of Chapter 7

In this chapter it was showed that the cost of wind randomness can be relatively low, even at high wind penetration rates. In Portugal, where wind already accounts for 23% of load, the average wind balancing cost is 2.17 € per each MWh of wind energy generated.

The results are surprising due to the lack of economic incentives for wind generators to minimize their imbalances, that is, wind imbalance costs are effectively paid by final consumers in our market. Even though Portugal uses a unique imbalance pricing system, it has shown that this is not the reason for low imbalance costs.

Instead, one important mechanism to reduce wind balancing costs is the aggregation of all wind producers into a single balance-responsible party. Since this aggregation requires an electrical grid with enough transmission capacity, the results imply that in other markets facing high balancing costs for intermittent renewables, it may be economical to invest in upgrades to the transmission grid.

For the specific case of Portugal, even though wind balancing costs are relatively low in “per MWh” terms, the costs still add up to a significant amount of money. At the current stage of market development, we see no reason to keep wind producers immune to the cost of their imbalances.

Making wind producers balance responsible would create the proper incentives for better wind forecasting, and save several millions of euros per year for final consumers. It is important to stress that this change in market rules would not imply any change in the revenue of wind producers, which would remain equal to the promised feed-in-tariff.

Wind generators would only see a small reduction in net profits due to the lower remaining wind unpredictability. The only agents who would probably lose significant revenues would be balancing reserve providers.

Likewise, it would probably make sense to change from the current Portuguese imbalance pricing system to a standard single or dual-price system, similar to other European markets. If the market evolves in that direction, it would also seem fair to properly account for regulation reserves that are used for other technical purposes that are not related to imbalances (like load and trade smoothing, or indirect AGC control, as described in this chapter), and make sure that the corresponding costs are not allocated to imbalanced agents.

Closure

Conclusion

8.1 Outlook

While the exact composition of future electrical systems is uncertain, one certainty is that it will be necessary to incorporate a considerable amount of neutral carbon production technologies on different scales, with different operating specifications, and connected in new places throughout the network.

Operating an electrical system will be a challenging task. Large-scale integration of renewable generation, in particular wind generation as studied in this thesis, will increase the fluctuations and uncertainty on the generation side. This will change the nature of the operational flexibility needed to ensure the generation and demand balance and maintain system security. The main implication of this is the likely increase in balancing costs. One of the most important solutions for obtaining this new renewable paradigm is the cooperation in ancillary services between TSOs, as studied in this thesis. The possibility of sharing balancing reserve mechanisms allows System Operators to reduce the cost of the balancing while maintaining the system security at adequate levels.

This section summarises the conclusions drawn in this work. The main research question is answered: Can cross-border ancillary services contribute to a significant reduction of the costs of balancing mechanisms in a scenario of increasing renewable penetration?

Research was carried out on cross-border ancillary services cooperation by balancing areas to generate economic advantages with an adequate cooperation. This allows for the TSOs involved to mobilise balancing reserves at more competitive prices and also to minimise the energy balancing mobilisation in the case of the secondary control reserve.

Cross-border cooperation for ancillary services requires several considerations and a deep interconnectivity between the TSOs involved. In this work, a deep study was made of the advantages deriving from the coordination of the tertiary reserve and the economic benefits for the Portuguese TSO of embracing cooperation within the Southwest Europe electrical zone were investigated and estimated.

8.2 Contributions and Findings of the Research

This thesis performs fundamental research aimed at quantifying the techno-economic impact of sharing ancillary services in the Southwest of Europe. The following sections present the key findings of this work in response to the detailed research question outlined in the first chapter.

8.2.1 Economic Impact of Cross-Border Tertiary Sharing: Investigating the Advantages of Embracement Cooperation.

Bilateral cross-border cooperation for balancing the replacement reserve was implemented in the Iberian region in mid-2014. In this work, the economic impact of this mechanism in balancing costs in the Portuguese electrical system was studied. A method was defined and proposed for calculating the impact of the energy traded and the value of its substitution or existence in the case that this mechanism did not exist. For each trading possibility (buying or selling energy) three situations of the replacement reserve that could occur were identified.

The first research question was: What is the economic impact of the cross-border replacement reserve mechanism between Portugal and Spain? It can be concluded that the current framework of cross-border cooperation has a good economic impact between balancing areas due to the differences in local area characteristics. The different price offers for tertiary balancing from both sides, motivated by the existence of different market players, allows greater competitiveness in the balancing mechanism. From the data analysis of activated reserves, it is concluded that there are benefits from cross-border cooperation.

As mentioned in chapter four, the cross-border exchange mechanisms introduced, and particularly the tertiary reserve, are the new reality for both participating SOs in the Iberian Peninsula. After three and a half years of this trading mechanism's implementation, profits now exceed 10.5 M€. This corresponds to an average gain of more than 3 M€/year, just for the Portuguese electricity system. Comparing this value with the average tertiary over-cost, which was 32.22 M€, these profits correspond to almost 10% of the tertiary balancing costs.

The second research question was: Could the profits of cross-border replacement reserves in a multilateral cooperation be improved significantly compared with a bilateral one? The answer is affirmative. These profits could be improved. As mentioned before, the actual mechanism only allows bilateral transactions between Portugal and Spain, and between Spain and France in a contiguous way. Technically, this solution could be easily implemented. The losses from non-cooperation were around 30% of the total value of transactions

8.2.2 Extending the Cooperation to Another Dimension: Secondary Balancing Reserve.

As related in the background, there are three types of load-frequency control reserves: primary, secondary and tertiary. The primary reserve (when activated) is an automatic mechanism shared by all connecting TSOs. As concerns the tertiary reserve, as mentioned in the previous point, the cross-border tertiary reserve mechanism was implemented in Iberia in 2014. The sharing of tertiary reserve between Iberian countries allows obtaining a considerable amount of savings relating to the balancing mechanism. At the same time, it enhances operational security by making available the balance reserve of other TSOs.

Currently, in the Iberian sphere, as concerns the secondary reserve control, all that remains is to implement cooperation on the secondary reserve. That is what led to the third research question: Is it possible to extend the cross-border replacement reserve to the secondary reserve regulation, with considerable cost reductions? The answer is also positive. The results show that it is possible to generate synergies in 45% of the market periods and an average profit of 3.4M€ per year for both TSO's. An interesting point is the concept of the electrical variability and the impact of secondary mobilisation to reduce the imbalances. This new concept, developed on this investigation allows corroborate the conclusions that related with the necessity of an adequate cooperation in the secondary reserve.

There are enough reasons to implement the coordination procedures between the Iberian TSOs in order to manage their own secondary reserve in a profitable and reliable way, and to become more competitive when exchanging with other European TSOs.

8.2.3 The Balancing Costs with High Renewable Penetration

The growth of intermittent renewable power generation has been drawing attention to the design of balancing markets. It is inevitable that the increase of VRE introduces a different approach from the TSO side in respect to the balancing mechanisms and in particular the associated costs.

Portugal is an interesting case study because wind generation already accounts for a high fraction of demand. The last research question is: Can the improvement of variable renewable generators introduce relevant balancing costs for the Portuguese electricity system? The answer is difficult to define categorically. The evolution of the balancing market was analysed from 2012 to 2016. Using actual market data, wind balancing costs of around 2 euros per MWh of generated energy were identified. One main reason for these low costs is the existence of a robust transmission grid, which allows for the compensation of positive with negative wind imbalances across the system.

Nevertheless, the results suggest that final consumers could save several million euros per year if wind generators were made responsible for the economic cost of their imbalances, in line with other European markets. There are no economic incentives for efficient wind forecasting because the balancing cost of feed-in tariffs is actually passed on to the end consumers.

8.3 Reflection and Pathway for Complementary Investigation

The electricity sector is undergoing a dramatic transformation since its creation. Technology cost reductions and policy supports are facing to a fast growth in the multiples renewable sources, putting the electrical sector in the frontline of emissions decrease efforts, but requiring the entire system to operate differently in order to ensure a reliable supply. In most OECD countries, the growth in electricity demand is modest, but the investment required is still huge as the generation mix changes and infrastructure is upgraded. Today's power market designs are not always up to the task of coping with rapid changes in the generation mix.

For that reason, the cooperation between System Operators for balancing electrical systems has a capital importance as concerns the flexibility of electrical systems. Moreover, adequate cooperation allows the balancing costs to be reduced at the same time as increasing the operational security. Particularly in the European sphere, the System Operators will lead in the near future with a considerable increase of renewables in the electricity generation mix. It will be mandatory to create synergies to overcome the electrical transition without increasing the cost of the electrical system. It is necessary to harmonise markets and products to ensure transparency in the process. With adequate cooperation, the heterogeneity and idiosyncrasies of each will strengthen the whole system.

This thesis is now concluded. However, the investigation will never end because it is not possible for humanity not to innovate. Innovation is the basis of cultural change and progress. The thesis provides some suggestions for further research in this field of investigation. A pertinent topic is the study of a potential reduction of replacement and secondary reserve control by each of the TSOs involved and an adequate quantification of this reduction in a scenario of regional cooperation as studied in this thesis. Another interesting study would be to identify the individual net imbalance of renewable energy by market player and to estimate the possible value of the associated economic imbalance. Currently, obtaining certain types of data at a European level is very difficult. For motives such as confidentiality and security of supply, they are not published. However, with the increasing transparency of mechanisms, in the near future it will be mandatory for TSOs to publish a considerable amount of data. An interesting observation could be a comprehensive study of the secondary and tertiary reserve at the European level.

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Appendix A

Appendix A.1 – Potential Transactions per Year

Regarding the previous data, it is possible to observe that, in the first year, 13 transactions between Portugal and France would be, on average, more profitable for the Portuguese electrical system than the actual transactions with Spain. In the second year, 14 would be more profitable and in the third year, 22.

Table A1: General data of potential transactions – Profit of transactions in 1st year.

Market Hours	Increase of the Potential Profit with Import for France (€/MWh)	Potential of Import to France (MWh)	ASI(€)
1	0.08	2250	187.5
12	11.73	2550	29916.28
17	8.33	4900	40803.39
18	12.72	4100	52140.69
20	4.16	6050	25149.85
22	20.09	3900	78359.91
23	6.22	6800	42278.71
24	4.16	7900	32894.02
Total		38450	301730.4
Market Hours	**Increase of the Potential Profit with Export for France (€/MWh)**	**Potential of Export to France (MWh)**	**APE(€)**
7	1.25	3950	4950.67
9	1.43	6050	8663.02
10	4.10	7350	30099.36
12	6.43	5500	35374.43
19	6.45	9950	64130.92
Total		32800	143218.39

Table A2: General data of potential transactions – Profit of transactions in 2nd year.

Market Hours	Increase of the Potential Profit with Import for France (€/MWh)	Potential of Import to France (MWh)	ASI(€)
8	10.27	8400	86259.04
10	2.20	4250	9347.12
14	10.30	4650	47888.93
24	7.19	9700	69739.77
Total		27000	213234.86
Market Hours	**Increase of the Potential Profit with Export for France (€/MWh)**	**Potential of Export to France (MWh)**	**APE(€)**
2	0.16	3250	532.80
6	1.69	2750	4656.67
8	18.11	9050	163906.81
9	6.19	8650	53511.63
10	4.01	8650	34666.29
11	1.36	10900	14838.22
13	8.65	9700	83868.45
17	1.52	6800	10331.47
18	8.46	14450	122221.78
19	8.26	16100	133035.58
Total		90300	621569.69

Table A3: General data of potential transactions – Profit of transactions in 3rd year.

Market Hours	Increase of the Potential Profit with Import for France (€/MWh)	Potential of Import to France (MWh)	ASI(€)
2	3.01	8250	24809.52
3	6.35	7250	46019.09
5	24.20	7100	171803.40
8	1.47	19150	28158.93
13	9.20	4300	39542.13
14	2.23	5550	12398.7
15	1.90	8950	16977.26
17	0.52	8800	4562.02
18	6.56	5550	36394.52
19	6.68	8350	55798.03
23	3.11	13000	40482.23
Total		96250	476945.90
Market Hours	**Increase of the Potential Profit with Export for France (€/MWh)**	**Potential of Export to France (MWh)**	**APE(€)**
2	25.01	6300	157572.40
3	29.88	5850	174791.50
4	16.92	5600	94741.11
5	29.96	4150	124330.50
6	14.64	4800	70280.73
7	4.15	13000	53932.98
13	13.85	20500	283889.30
17	5.76	14000	80620.16
18	3.37	17650	59451.55
19	10.51	24750	260214.80
23	11.81	16300	192456.80
Total		132900	1552282

Appendix A.2 – General Statistics Overview

In Table A4 it is possible to observe the TSOs' price in the exportation scenario. Statistically, one can observe that the French TSO is the most competitive and the Portuguese one is the less competitive. The standard deviation in the French TSO is higher, which indicates a less concentrated amount of transactions' prices around the mean.

This alludes to a good distribution of the replacement reserve's prices. However, a negative skewness indicates a bigger amount of offers slightly above the average value. Considering the range, the Spanish TSO is the one who has less reach. The maximum value of the Portuguese one is considerably higher than the others. In terms of the minimum value, the French one is considerably lower than the others.

Table A4: Statistical data of exportation prices.

	Price – Portugal	Price – Spain	Price – France
Mean	53.63	51.68	48.56
Standard Error	2.47	2.30	3.19
Median	53.39	51.23	49.87
Standard Deviation	14.82	13.79	15.65
Variance	219.67	190.07	244.87
Skewness	0.78	0.13	-0.77
Range	76.58	57.35	77.67
Minimum	25.48	23.76	5.82
Maximum	102.06	81.11	83.48

Table A5 shows the TSOs' exportation quantities. In this situation, the French TSO is the most competitive when selling tertiary reserve, with its amount of energy exported being the lowest. The Spanish TSO is the one who exports the most, with a considerable difference from their peers. After the analysis of the previous tables, it is possible to conclude that the French TSO sells low quantities, but when the selling occurs, it is cheaper when compared to the other sellers, on average.

Table A5: Statistical data of exportation quantities.

	Quantity – Portugal	**Quantity – Spain**	**Quantity – France**
Mean	2797	27925	1689
Standard Error	330	2594	410
Median	2600	22250	600
Standard Deviation	1979	15564	2461
Variance	3917992	242251357	6057730.2
Skewness	1.120	0.875	1.695
Range	8050	64250	8450
Minimum	200	7750	0
Maximum	8250	72000	8450
Sum	100700	1005300	60800

In Table A6 it is possible to observe the price of the TSO's in the importation scenario. Statistically, the Portuguese TSO is the one who bought tertiary reserve at the lowest price. The standard deviation in the Portuguese TSO is higher, indicating a less concentrated amount of transactions around the mean.

This indicates well-distributed prices of bought tertiary reserve. The slight negative skewness also indicates a good distribution regarding the bought tertiary. The minimum value of the Portuguese TSO importation is considerably lower than the other ones. In terms of the maximum value, the French is the TSO, on average, that bought replacement reserve at a higher price.

Table A6: Statistical data of importation prices.

	Price – Portugal	Price – Spain	Price – France
Mean	49.53	53.25	52.43
Standard Error	2.61	2.22	2.35
Median	48.95	53.12	51.60
Standard Deviation	15.65	13.32	14.08
Variance	245.03	177.32	198.24
Skewness	-0.11	0.68	0.51
Range	63.25	62.05	55.43
Minimum	18.19	30.97	27.23
Maximum	81.44	93.02	82.66

In table A7 it is possible to observe the quantity of import activation. The Spanish TSO is the player who imports less tertiary reserve, with a significant difference from both the French and the Portuguese. Another observation can be made: the Spanish TSO is the one who bought energy at a more expensive price. Analyzing the statistical tables, it is possible to conclude that the Spanish TSO is mostly an exporter and the other two TSO's use this market mainly to buy replacement reserve. It is important to remember that the conditions verified are different for Spain (it is possible to trade with Portugal and France) when compared to Portugal and France (both can only trade with Spain).

Table A7– Statistical data of importation quantities

	Quantity – Portugal	**Quantity – Spain**	**Quantity – France**
Mean	12261	4486	15664
Standard Error	1001	634	2001
Median	10850	3550	13225
Standard Deviation	6007	3802	12009
Variance	36089302	14454230	144206087
Skewness	1.525	1.406	0.932
Range	27250	16300	47400
Minimum	4050	400	550
Maximum	31300	16700	47950
Sum	441400	161500	563900

Appendix B

Appendix B.1 – Zero Sum mechanism

The Portuguese pricing scheme results in a zero-sum mechanism for the TSO. To see this formally, use definitions for V_i and R_i expressed in Chapter 7, and the fact that $\sum_i K_i = 1$, to verify that the total cash flow received from imbalanced BRPs, $\sum_i V_i$, equals the net cash outflow paid to reserve providers, $\overline{P}\,\overline{E} - \underline{P}\,\underline{E}$:

$$\sum_{i=1}^{I} \boldsymbol{V_i} + \sum_{i=1}^{I} (\boldsymbol{D_i P} + \boldsymbol{K_i R}) = \boldsymbol{P} \sum_{i=1}^{I} (\boldsymbol{D_i}) + \boldsymbol{P}(\underline{\boldsymbol{E}} - \overline{\boldsymbol{E}}) - \underline{\boldsymbol{P}}\,\underline{\boldsymbol{E}} + \overline{\boldsymbol{P}}\,\overline{\boldsymbol{E}} = \overline{\boldsymbol{P}}\,\overline{\boldsymbol{E}} - \underline{\boldsymbol{P}}\,\underline{\boldsymbol{E}} \tag{B.1}$$

where the last equality results from the fact that the amount of imbalances must equal the net amount of reserves used $\sum_{i=1}^{I} D_i = \overline{E} - \underline{E}$.

Appendix B.2 – Proof of Preposition 1

Proof. Consider first the case, from Chapter 7 which $D_i < 0, \forall\ i \in \{1 \ldots I\}$. Also, it thus has $\underline{E} = \sum_{j=1}^{I} |D_j|$ and $\overline{E} = 0$. From Chapter 7, i.e.:

$$V_i = D_i P + \frac{|D_i|}{\sum_{j=1}^{I} |D_j|} \left(P - \underline{P}\right) \sum_{j=1}^{I} |D_j| = D_i \underline{P}$$

which is negative for all i. The corresponding result obtains if all deviations are positive.

Appendix B.3 – Typical Imbalance Pricing Systems

Table B.1 compares typical single and dual prices systems, which shows the cash flows to the system operator (SO) per MWh of absolute imbalance ($|Di|$). A positive value means that cash is flowing from the balance responsible party (BRP) to the SO. P and P denote, respectively, the upward and downward reserve prices. In dual-price systems, P is day-ahead price. $\overline{P}$ is the upward reserve price aggravated by a penalty, that is, $\overline{P} > P$. Similarly, for the downward price, $\underline{P} < P$.

Single-price systems are zero-sum mechanisms for the system operator (SO) because negative deviations pay for positive deviations. In most markets, upward and downward reserve prices ($\overline{P}$ and $\underline{P}$ in table B.1) are marginal clearing prices. It is usually considered that single-price systems provide optimal incentives because a balance-responsible party (BRP):

(i) It pays exactly the marginal cost of its deviation when it aggravates the system imbalance ($\overline{P}$ or $\underline{P}$, depending on the net system state), and;

(ii) It receives exactly the marginal value of its deviation when it contributes to balance the system.

Dual-price systems are non-zero-sum mechanisms for the SO because there are different prices for long and short imbalances. For example, if the whole system is short (programmed generation is insufficient for the actual load), the SO has to dispatch upward reserves at some price $\overline{P}$.

However, for a BRP that is short, and thus aggravates the system imbalance, the SO charges a higher price $\overline{\overline{P}}$, which exceeds the marginal cost that the BRP is imposing on the system ($\overline{P}$ <$\overline{\overline{P}}$), that is, $\overline{\overline{P}}$ contains a penalty. On the other hand, a BRP that is long, and thus is helping the system, only receives a lower value (typically the day-ahead price, P), which does not compensate for the full value of the injected energy (P < $\overline{P}$). Hence, a dual-price system penalizes any deviation from the market program more strongly than a single-price system.

Table B.1-Typical imbalance price systems

BRP Imbalance	System Imbalance	
	Short ($Gen < Load$)	Long ($Gen > Load$)
Single-price system		
Short	$+\overline{P}$	$+\underline{P}$
Long	$-\overline{P}$	$-\underline{P}$
Dual-Price system		
Short	$+\overline{P}$	$+P$
Long	$-P$	$-\underline{P}$

Appendix B.4 – The Effect of an Asymmetric Secondary Band

As described in Chapter 7, there is an asymmetry in the use of downward and upward regulation reserves. To better illustrate this fact, Figure C1 shows the time series of secondary and tertiary reserves. Secondary and Tertiary reserves used per hour are rolling 30-day averages of hourly values, from 2012/01/01–2016/12/31.

Secondary reserve is typically small. However, there is a persistent difference between upward and downward secondary regulation: while downward secondary is typically a small value around 8 MWh, upward secondary fluctuates around 50 MWh. The fact that upward secondary is relatively stable around this higher value has a technical/economic explanation related to the design of the Portuguese balancing reserve market.

In the beginning of the market in 2007, when intermittent renewables were still small, the major risk for the system was insufficient generation due to, for example, a generator tripping offline or an unexpected increase in load. Additionally, tertiary suppliers had relatively long response times. Hence, market rules were set to require secondary reserve providers to offer a band of reserve split in the ratio of 2/3 for upward and 1/3 for downward regulation.

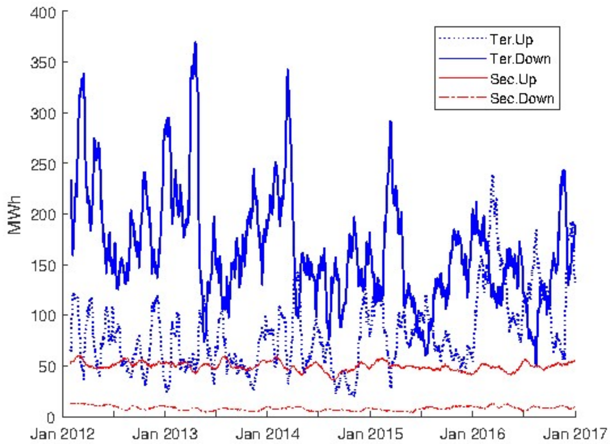

Figure B1 – Secondary and tertiary reserves.

For example, consider a thermal power plant that is able to vary its output between 200 and 400 MW, and suppose that it was dispatched at 300 MW in the day-ahead market. If this plant wants to sell the maximum possible band in the secondary reserve market, due to economic market rules, it must offer 100 MW for upward and only 50 MW for downward regulation.

More recently, as intermittent renewables increased, the risk became more symmetric, that is, the probability of too much generation also grew. Additionally, technological developments in some tertiary suppliers, like hydropower plants, now allow them to complement secondary reserves much faster than in the earlier period. Hence, the TSO now prefers to have the secondary band centered at the midpoint, with an equal amount of upward and downward availability.

However, the economic market rules in place are still the original ones, requiring generators to offer secondary reserves in the same 2/3 – 1/3 ratio. Since the secondary reserve is mobilized automatically by the Automatic Generation Control (AGC), the TSO indirectly controls the secondary band by manually dispatching tertiary reserve and thus forcing the AGC to adjust the secondary reserve in the intended direction. In the previous example, the TSO would dispatch 25 MW of downward tertiary reserve, forcing the AGC to automatically mobilize 25 MW of upward secondary (that is, to increase the generation of the thermal plant by 25 MW).

During 2012–2016 periods, the average secondary band offered in the market for upward regulation was 175MW and for downward regulation was 87.5 MW. The total band was thus, on average, 262.5 MW, with an equilibrium midpoint of 43.75 MW. As explained above, this requires the system to use, on average, approximately 44MW of downward tertiary reserve and another 44 MW of upward secondary reserve.

This mechanism induces a constant bias in secondary reserve, leading to the pattern observed in Figure B1. It also contributes to downward tertiary being, on average, higher than upward tertiary mobilization. In summary, the average bias of 44 MWh, in both secondary and tertiary reserves, results from what it might call the difference between “market equilibrium” and “technical equilibrium”.