



UNIVERSIDAD PONTIFICIA COMILLAS

ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

OFFICIAL MASTER'S DEGREE IN THE
ELECTRIC POWER INDUSTRY

Master's Thesis

**Cross-border interconnections:
influence in the Spanish market price**

Author: Óscar Miralles Pérez

Supervisor: Cristina González Ventosa

Madrid, July 2018

Master's Thesis Presentation Authorization

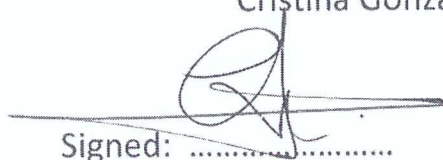
THE STUDENT:

Óscar Miralles Pérez



THE SUPERVISOR

Cristina González Ventosa



Signed:

Date: 02/ 07/2018

Authorization of the Master's Thesis Coordinator

Dr. Luis Olmos Camacho

Signed:

Date://

Preface

Cross-border interconnections: influence in the Spanish market price was developed between February 2018 and July 2018 by Óscar Miralles Pérez as a Master's thesis during the 2nd semester of the study program of "*Official Master's Degree in the Electric Power Industry*" conducted at Universidad Pontificia de Comillas (ICAI). The project has been developed during the internship at Red Eléctrica de España (REE), the TSO of the Spanish electric system.

The software's used for modelling and graphical data presentation has been Eviews and Excel. All the references used can be found in the bibliography.

Sections, figures, equations and tables are referenced by chapter# .index# , e.g. section 5.2, figure 5.2, equation (5.2) and table 5.2.

Reader Guidelines

Ahead of the report a nomenclature is given alphabetically. Throughout the report literary references are made using numbering style, so the sources are referred to as [x]. The used sources are listed by order of appearance at the back of the report. All sources are listed by author, year and title. Additionally, edition and publisher are given for books, journals for papers and URLs for web pages. Furthermore, lists of figures and tables are given after the bibliography.

Equations, tables and figures are numbered related to the current chapter and in order of appearance.

Acknowledgments

Acknowledgments are addressed to Red Eléctrica members for their support, specially to my supervisor, Cristina González Ventosa for her helpful supervision and advices.

Abstract

Cross-border interconnections represent a key infrastructure for the achievement of a common European energy market which ensures a fair price for consumers. Renewable sources also benefit from these infrastructures as enables the transmission of the locally generated energy to high demand areas. Additionally, new interconnections reinforce the security of supply of the system by the increase of the transmission capacity among regions.

This thesis analyses the effect of the interconnection capacity increase between Spain and France in the Spanish day-ahead market by an econometric model. It pays special attention to the recently established interconnection between Santa Llogaia and Baixas on October 5, 2015, which increased the interconnection capacity between both countries, from 1400MW up to values close to 2800MW. Therefore, the effect on the market price as well as the market coupling and congestion periods is also studied.

It has been observed a decrease in the Spanish market price of 3,54 €/MWh since the establishment of this infrastructure. The market coupling periods have increased from 10,08% to 26,36%. Regarding to the cross-border congestions, it has been observed a reduction by 24,24% in the importing direction. However, it has been increased the number of congestion hours in the exporting direction by 26,87%, probably due to the unavailability of several French nuclear power plants during 2016.

Based on the results depicted by the econometric model, it has been concluded that the new interconnection "Santa Llogaia-Baixas" could have contributed to increase the market coupling between France and Spain and reduced the cross-border congestions. Moreover, the Spanish prices has been reduced due to the increasing energy imports from France.

Nomenclature

<i>AC</i>	Alternating current
<i>ACER</i>	Agency for the Cooperation of Energy Regulators
<i>ATC</i>	Available Transfer Capacity
<i>CACM</i>	Capacity Allocation and Congestion Management
<i>CAPEX</i>	Capital expenditure
<i>CCGT</i>	Combined cycle gas turbine
<i>CfD</i>	Contracts for differences
<i>CWE</i>	Central-Western Europe
<i>DA</i>	Day ahead
<i>DC</i>	Direct current
<i>ENTSO – E</i>	European Network of Transmission System Operators
<i>EU</i>	European Union
<i>FCA</i>	Forward Capacity Allocation
<i>FTR</i>	Financial transmission rights
<i>IFE</i>	Interconnection France-Spain
<i>IPE</i>	Interconnection Portugal-Spain
<i>NTC</i>	Net transfer capacity
<i>REE</i>	Red Eléctrica de España
<i>RTE</i>	Réseau de Transport d'Électricité
<i>REN</i>	Redes Energéticas Nacionais
<i>SWE</i>	South-Western Europe
<i>UGH</i>	<i>Unidad de Gestión Hidráulica</i>
<i>OMIE</i>	Iberian Market Operator - Spanish Pole
<i>OMIP</i>	Iberian Market Operator - Portuguese Pole
<i>PCI</i>	Project of Common Interest
<i>PCR</i>	Price Coupling of Regions
<i>PDBC</i>	<i>Precio Base de Casación</i>
<i>PTR</i>	Physical transmission rights
<i>TYNDP</i>	Ten-Year Network Development Plan

Table of Contents

Nomenclature	ix
Chapter 1 Introduction	1
1.1 Motivation	1
1.1.1 Benefits of electricity exchange and interconnections	2
1.2 Problem statement	5
1.3 Methodology	6
1.4 Limitations	6
Chapter 2 Background	9
2.1 Interconnection capacity targets	9
2.1.1 Requirements and challenges	9
2.2 Interconnection Evaluation	10
2.2.1 <i>Expert Group</i> Recommendation	11
2.3 European energy market	13
2.3.1 Price convergence & Market coupling	15
2.4 Interconnection management	17
2.4.1 Capacity auctions	17
2.4.2 Congestion management	18
2.5 Spanish electric system	19
2.5.1 Installed capacity and generation mix	20
2.5.2 Spanish cross-border interconnection capacity	21
2.5.3 Spanish cross-border interconnection management	23
Chapter 3 Input data description	25
3.1 Period of analysis	25
3.2 Spanish demand	25
3.3 Generation Mix	27
3.3.1 Thermal-based technologies	28
3.3.2 Renewable-based technologies	29
3.3.3 Hydroelectric power	31
3.4 Cross-border congestions	33
3.5 Cross-border flows	34
3.6 Unavailability of French nuclear power plants	36
3.7 Interconnection capacity between Spain and France	37
Chapter 4 Econometric Analysis	39
4.1 Literature review	39
4.2 Model estimation: Equations specifications	41
4.2.1 Multiple regression models	41
4.2.2 Autoregressive (AR) model	42

4.2.3	Moving-Average (MA) model	42
4.2.4	ARMA model	42
4.2.5	Seasonal autoregressive (SAR) model	43
4.2.6	Intervention variable	43
4.3	Model Equation output	43
4.4	Model description	45
4.4.1	Model 1: Dichotomous variable	46
4.4.2	Model 2: Hourly maximum import capacity	49
4.4.3	Model 3: Hourly exchange flows	51
Chapter 5	Results and discussion	55
5.0.1	Cross-border interconnections	55
5.0.2	Marker impact	55
5.0.3	Model results	57
Chapter 6	Conclusions	59
Chapter 7	Future work	61
	Bibliography	63
	List of Figures	65
	List of Tables	67

1 Introduction

1.1 Motivation

The future of the global energy development takes place under the framework of the climate energy objectives of the European Union for 2020, 2030, and 2050, as stated in the Energy Union Framework strategy and the Paris Agreements [1]. The long-term objective aims to avoid a drastic and dangerous climate change by limiting the global warming below 2°C and presumably below 1.5°C [2].

It is recognized by the *Expert Group* that the electricity sector will be one of the main contributors to the decarbonisation of the European economy. At the present, time 27.5% of the electricity produced in the EU is generated by renewable sources, half of which are weather dependent. Forecasting models show that it is expected an increase of the renewable production share up to 50% by 2030. The present cost reduction of renewable technologies, and the electrification trends in sectors traditionally dominated by fossil fuels, such as transport, heating and cooling, may lead to even a higher relevance of renewable technologies [2].

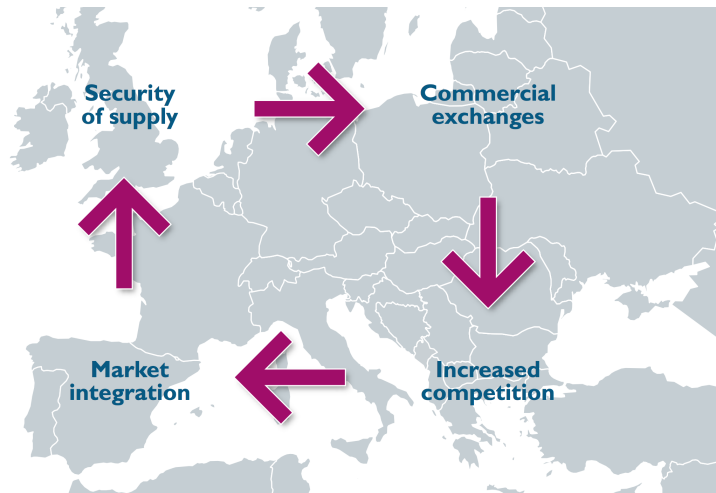


Figure 1.1. The role of international connections [3]

In order to meet the energy and climate objectives set by the EU, significant investments are required. Specially, investment is needed to remove infrastructure bottlenecks between and within Member States to improve the security of supply, competition and the integration of a growing share of renewable sources. This infrastructure development aims to achieve a trans-European robust electricity system. In order to perform a cost-efficient investment, a more competitive and interconnected internal energy market in Europe is required. This framework is particularly relevant for the integration of a a rising share of unpredictable technologies in a cost-efficient and secure manner [2].

The backbone of that system is constituted by the electric network and the cross-border interconnections, which at the present time are often used inefficiently either due to internal congestions or because of discrimination against cross border exchanges. Therefore, the development of the European electricity market should be developed under clear non-discriminatory rules and a stable regulatory framework. [2].

New technological developments, such as energy storage and demand response, could increase the system flexibility and offer complementary services. Despite that this technologies has not been implemented yet at large scale within the present European transmission network, expansion plans should take them into account for the future needs and roles of interconnections. Hence, the expansion plans should be dynamically developed and adjusted, based on technological development. Furthermore, the development of cross-border interconnections under a strict coordination among the different Member States is essential for an efficient performance [2].

The European Commission is encouraging Member States to increase electricity interconnections, in order to promote a more efficient single electricity market and to integrate renewable energy sources. Unfortunately, despite that the interconnection capacity between France and Spain has increased in the last years, it is still far from the goals established by the European Union. In the Barcelona Convention of 2002, the interconnection capacity threshold was set a 10% over the total installed capacity by 2020. Later, the European council of October 2014 endorsed to extend the current 10% target up to 15% by 2030, while considering the cost aspects and the potential of commercial exchanges in relevant regions. At that point, due to the lack of a clear methodology to establish the interconnection capacity, the European Commission decided to set up a Commission Experts Group. On March 2016, this committee was created to provide technical advice and examine the aimed interconnection targets.

1.1.1 Benefits of electricity exchange and interconnections

The energy transition opens the possibility to the development of new technologies, and an improvement of the transmission network. The challenges of the new energy model provides the possibility to improve the current system with the integration of new technologies that provides a higher system flexibility, a lower carbon emissions, and a higher efficiency level. Based on the Comission Expert Group, the increase of the interconnections within the European Union provide five main benefits [2]:

- **Market integration**

Cross-border interconnections enable the integration of the European electricity markets, whcih results in a more competitive, liquid, and homogeneous system with better prices for consumers. Market signs provide revealing information for generation capacity investment, assuming there is a high level of coordination between Member States. Hence, interconnections allow the complementary use of the different generation technologies across Europe, for the integration of renewable sources. Furthermore, a high interconnection level reinforces the system adequacy, lowering the needs for operational security margins and reducing grid losses [2].

The positive interconnection effect has been already proven in the existing Member

States. For instance, market coupling between Slovenia and Italy has already increased stability of prices in the SouthPool market. On the other hand, the interconnection between Norway and the Netherlands improved competition in both markets, in the Baltic countries, their interconnection with Sweden increased their access to the Northern European power resources and lead to significant savings [2].

Nevertheless, interconnections should be built only if they contribute to the European energy and climate goals, and if their contribution to socio-economic welfare outweighs their costs. In consequence, it leads to lower costs for end-consumers, enhances system stability and reduces price volatility.

In figure 1.2 it can be observed that there still exist notable price deviations within the different market regions, despite the efforts done to achieve a single European market. In general basis, Nordpool usually shows the lowest prices in the EU, whereas Italy leads the highest prices. It should be noticed that Spain shows a high price volatility, setting in some periods the lowest prices as in March 2013 and 2014, but with a high average price compared to the EU regions.

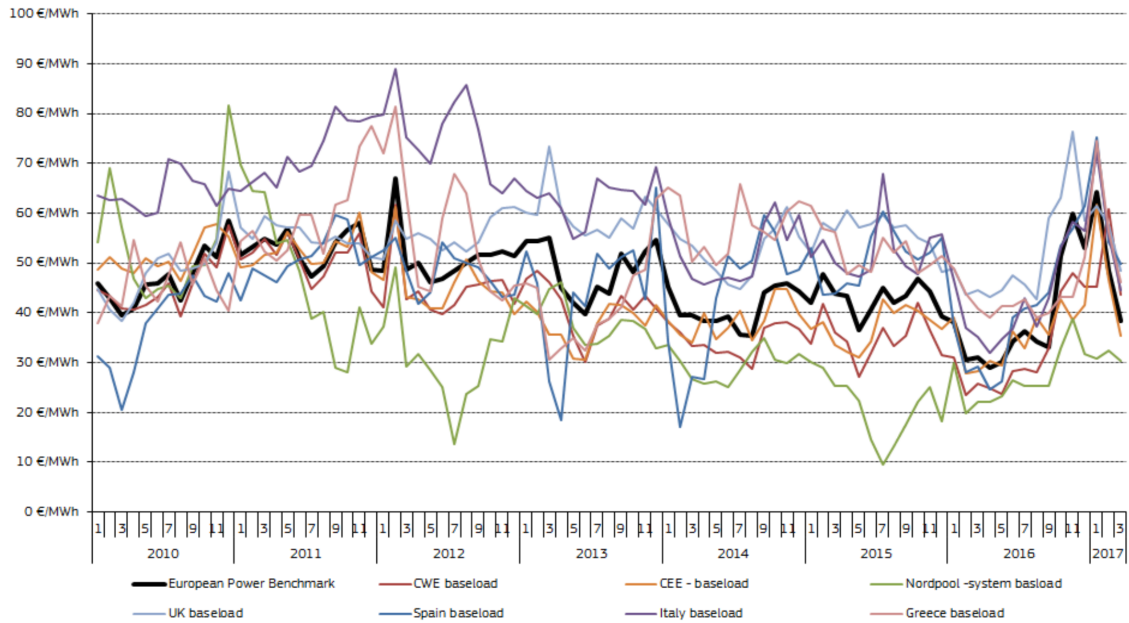


Figure 1.2. Comparisons of the European benchmark and the monthly baseload prices in regional electricity markets [4]

The relative standard deviation shown in figure 1.3 indicates that a higher interconnection capacity is required in order to achieve lower deviations among the electricity prices of the different European Markets. It is especially relevant taking into account that the fast introduction of variable sources would lead to more volatile prices specifically if a proper transmission system is not developed.

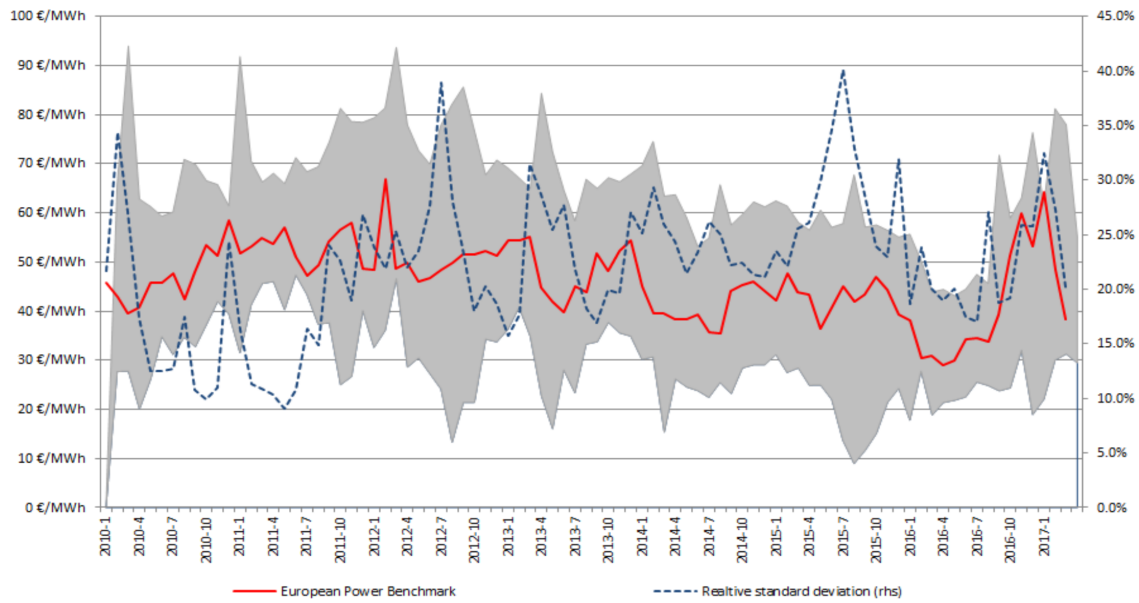


Figure 1.3. Evolution of the lowest and the highest regional wholesale electricity prices in the EU and the relative standard deviation of the regional prices [4]

- **Climate and environmental benefits**

The share of renewable energies is growing steadily, contributing to reach the 2020 target, in which interconnections contribute to facilitate the integration of renewable generation and thus enhance the potential for CO₂ emissions reduction [2].

The initial grid network was designed based on the location of traditional generation plants, leading to a network typology that was connecting large generation units with large consumers. However, the large share of today's renewable production does not correspond to this grid architecture. Interconnections, in addition to internal infrastructure, are key elements for the development of new electricity routes in order to connect areas with high renewable potential with main consumption areas. In this way, the transmission infrastructure would enable the grid to accommodate increasing levels of variable generation in a secure and cost effective way.

The increasing share of renewable generation represent a challenge in terms of grid management, price volatility and congestions. These variable sources can lead to unplanned flows of electricity which may put in risk the security of the system. Thus, more flexible and smarter energy grids are required, including distribution networks at local and trans-regional level.

In peripheral countries, interconnection capacity is limited due to the geographical constraints (electrical peninsulas), nevertheless, half of the operator's needs for flexibility could be provided by interconnections. Furthermore, due to the increasing share of renewable sources to the grid, interconnections are becoming an important tool for the management of unexpected flows and system unbalances .

For instance, cross-border interconnection between Denmark and Norway enables the energy storage of the excess of wind generation in the Norwegian hydro power stations. In the Iberian peninsula, the INELFE interconnection between France and Spain enabled the integration of a larger volume of renewable energy into the grid [2].

- **Security of supply**

Cross-border interconnections allow to import electricity when there is not enough generation in the local market and there is availability in the neighbouring regions. Additional interconnection capacity makes possible to share generation when scarcities occurs at different times at connected systems. Hence, it could provide additional system balancing tools such as frequency response, when it is not fully used for commercial purposes. It has been the case in BritNed (United Kingdom-Netherlands) and IFA (United Kingdom-France) [2].

However, it has been endorsed the importance of a legal framework to manage situations of simultaneous scarcity, in the case that interconnections are considered as a reliable alternative for domestic capacity.

- **Political relevance and European integration**

European interconnections are a key aspect for the development of a trans-European network for energy. The development of this networks is an important obligation set in the European Treaties to strengthen economic, social and territorial cohesion among the Member States. Particularly, the development and implementation of the Projects of Common Interest (PCI) are especially relevant to stimulate and strengthen regional cooperation and increase socio-economic welfare.

- **Industrial competitiveness and innovation**

The promotion a low-carbon economy and a more energy efficient industry lead to the modernization of the European Members and became the leaders in most advanced energy technologies and business models. The European transmission and distribution industry became a technological leader since the beginning of the electrification, therefore the energy transition is an opportunity to maintain and strengthen their position.

1.2 Problem statement

Cross-border interconnections represent a key infrastructure for the achievement of the European goals. This objective is the development of a super-grid at pan-European scale that allows the implementation of a single European market, the integration of renewable sources and the decarbonization of the electric industry.

The Iberian Peninsula is considered an "energy island" due to its low interconnection rate with France and the large share of installed renewable source. Therefore, Spain is unable to benefit completely from all the advantages of being part of the European network such a more competitive market, lower prices for consumers and security of supply.

Despite the low Spanish interconnection rate, a new cross-border line was set between Spain and France, October 5, 2015, which increased the capacity exchange from 1400MW up to values close to 2800MW. This new infrastructure, enabled larger energy trades between both countries and giving access to the Central European Network. Therefore, the objective of this study is to analyse the impact of cross-border interconnections in the Spanish Day Ahead price, paying special attention to the Spain-France border.

Nevertheless, the assessment of the capacity increase represents a challenge as is influenced by many other parameters such as the contribution of renewable sources, prices at the other European countries or the local demand. Therefore, it is developed an econometric explanatory model which aims to describe the evolution of the Spanish price by means of a set of explanatory variables. This model is based on historical data since the implementation of the Price Coupling Region in Spain, May 14, 2014, until the most recent available data, March 31, 2018. Additionally, it has been analysed the market behaviour before and after the introduction of the new cross-border line by means of the quantification of the market coupling and congestion periods.

Electric networks and cross-border interconnections represents the backbone for the achievement of the single European market. Thus, the efficient development and use of the interconnections is of vital importance, especially for peripheral countries as Spain.

1.3 Methodology

The following study is divided in three main parts in order to assess the market impact of the increase of the interconnection capacity as well as, other identified parameters.

The first step to achieve the goals presented above is the analysis of the European recommendations for the interconnections rates as well as, the assessment of the *Experts group* for the indexes used in order to evaluate this threshold. Additionally, a review of the price convergence and the market coupling in the European context is performed. Regarding to the Spanish context, a brief analysis of the cross-border trades is introduced.

In the second part the different variables that could have an impact in the day-ahead Spanish market price are included in the econometric model. These variables includes the generations sources (thermal-based and renewables), as well as the cross-border flows and the interconnection capacity.

In the last part of the analysis an econometric model is developed. First, a state-of-the-art review is performed about the statistical methods used for the market analysis, followed by the equations applied in the developed model. In the last part of this chapter are presented the different model's approach to evaluate the impact of the explanatory variables.

1.4 Limitations

The development of the analysis is bounded by some technical constraints that sets a limit for the performance of the study. The first point is the challenged faced in order to model a complex market as is the electric system.

On the other hand, due to the introduction of the Price Coupling Region (PCR), it is not accurate to use data before that moment as the market operation rules were modified, and thus the system behaviour. Therefore, the effect for instance, of long term phenomena such as hiper-annual hydro reservoirs could not be included. Therefore, It would probably be required a larger data-set to completely assess the actual effect of the interconnection in the Spanish market.

Finally, the econometric model is not able to reflect all the phenomena due to the modelling limitations. Hence, the model does not accurately predict the price behaviour when spikes are present. Other type of models such as GARCH could be further analysed.

2 Background

2.1 Interconnection capacity targets

The required international exchange capacity has been a matter of discussion as there is not a clear methodology to determine the optimal value. The original interconnection target was set in 2020 by Member States in the Barcelona Convention of 2002. The threshold set was a 10% transfer capacity, measured as a ratio of net transfer capacity over installed generation capacity per Member State. Later on, the European council of October 2014 endorsed the proposal of the European Commission of May 2014 to extend the current 10% electricity interconnection target to 15% by 2030, *while considering the cost aspects and the potential of commercial exchange in the relevant regions* [2].

The initial electricity interconnection target was set when the process of creating the internal energy market to enhance competitiveness just started. Interconnections were an instrument to bring competitiveness to markets largely monopolistic, in that case bring competitors from abroad. At that time, the penetration of renewable sources was still marginal.

The electrical situation has drastically changed since 2002. The introduction of variable sources into the electric system, the cross-border coordination and the development of new technologies has changed the role of the interconnections. Nevertheless, the most important reasons behind the investments in exchange capacity is still the security of supply and the competitiveness.

At that point, due to the lack of a clear methodology to establish the required interconnection targets, the European Commission decided to set up a Commission Expert Group On March 2016. The objective of the group was to provide specific technical advice by analysing if the targets should be taken into account at regional, country and/or border levels, as well as other parameters that could impact the interconnections development [2].

2.1.1 Requirements and challenges

Some prerequisites should be fulfilled based on the *Expert Group*, to develop all its socio-economic potential, include:

- **Well functioning market:** Interconnection capacity is a fundamental part of the efficient capacity allocation in a well-functioning market. If the capacity is properly allocated in the market the outcome would maximize the system welfare. The *Expert Group* indicates that the current use of the interconnections is often inefficient. Hence, further developments of the operational processes that allow the efficient use of existing interconnections should be applied. In order to achieve a well operated system, the Agency for the Cooperation of Energy Regulators (ACER) proposed three principles [5]:

- Limitations on internal network elements should not be considered in the cross-zonal capacity calculation methods.
- The capacity calculated in cross-zonal networks should not be reduced to accommodate loop flows.
- The "*polluter-pays principle*" should be applied for the remedial actions costs sharing, where the unscheduled flows over overloaded networks should be considered as "*polluters*" and should contribute in the costs proportionally to the overload.

In the Continental Europe, on average only 31% of the thermal capacity of the Alternate Current (AC) interconnections, for meshed and non-meshed networks, is made available to the market. Otherwise, for the Direct Current (DC) interconnections the average capacity available is 80% of the thermal capacity [2].

- **Public involvement:** New transmission assets are required for the connection of isolated generation units to the consumption and storage sites. The development of transmission infrastructure has a large impact on the landscape, and on nature, due to its dimensions and the long lifespan of the assets. Therefore, the development of new infrastructures has important public acceptance problems that have led to significant delays and technological changes, such as undergrounding. Therefore, the involvement of the local communities is necessary when designing a project in order to overcome justified concerns.
- **Investment and cost challenge:** Developing cross-border interconnections implies significant capital costs (CAPEX) which requires long-payback periods. Specially, for non-regulated investments (e.g. merchant lines) this increases the financial uncertainty for investors. Even though nearly all interconnection projects can be financed on market terms, in some specific cases, the project could negatively impact in the tariff, which would require support from the Connecting Europe Facility to ensure the project viability.

Additionally, carbon pricing could collaborate in the economic viability of interconnections as it increases the price spread between areas with high renewable rates and others with high demand and fossil fuel generation. The use of interconnections for complementary services such as exchange of reserves could also improve its revenues.

- **National energy mix and energy profile:** Member States considerably differs in terms of their energy mix, size and geographical location. There is a need for cooperation among regions for the identifications of complementarity patterns that allow the coordination of variable sources with dispatchable renewables such as sustainable biomass. Furthermore, energy profiles could complement each other for the mutual benefit of the interconnected systems.

2.2 Interconnection Evaluation

There is not a unique valid index to evaluate the interconnection ratio between bidding regions. The initial definition set at the Barcelona Council of 2002, computed the ratio between net transfer capacity and the total installed generation, which was set up to 10%.

At that time, the penetration of renewables sources was only around 2%, hence the discrepancy between installed generation and peak load was negligible across Europe. At present, the estimations indicate that by 2030 solar and wind combined will account for more than 29% of electricity generation [6], increasing significantly the variability in the electric system.

ENTSO-E TYNDP 2016 scenarios foresee a continuous growth of renewables in Europe by 2030, which are expected to cover from 45% up to 60% of the overall demand [7]. This energy sources are characterized by a much lower load factor than the traditional thermal generators. Therefore, the ratio between interconnection capacity and installed generation further decreases.

The current formulation would offer certain continuity and consistency to the measurement of interconnectivity. Nevertheless, the *Expert Group* concludes that this criterion would not be suitable to the reality after 2020. This index would not adequately account for the identified benefits of and prerequisites for the development the interconnectors. It has been proposed an update for the numerator and denominator by the *Expert Group*. Anyway, two completely new criteria has been proposed by the *Expert Group* in order to take into account the imports and exports, as well as the penetration of renewables [2]. These criteria are further explained in the following subsection.

2.2.1 *Expert Group* Recommendation

The *Expert Group* concludes that at national level interconnection should consider both, the electricity demand (imports) and supply (exports). Therefore, it is proposed two different criteria in order to evaluate the level of interconnection. In order to evaluate the new criteria, two thresholds are set[2]:

- Countries below the **threshold of 30%** for any of the formulas, should urgently investigate possible interconnections and report annually results of the analysis to the High Level Regional Groups and the Infrastructure Forum. Any project helping member states to reach the 30% threshold must apply to be included in the TYNDP and future PCI lists.
- Countries **between 30% and 60% thresholds** for any of both formulas, should investigate new possible interconnectors regularly. Such projects should consider applying to the TYNDP and future PCI lists.

Each interconnector project must be subject to a cost-benefit analysis as part of the TYNDP analysis. Only projects that can assess a potential socio-economic welfare benefit by the investment should be developed. Additionally, a threshold recommendation is to reach a maximum Yearly average price difference of 2€/MWh between bidding zones. Additional price difference should be considered if the cost-benefit analysis is not fulfilled. In the following subsections are presented the two criteria proposed by the *Expert Group*.

Import Criteria (Demand)

The proposed criteria evaluate the ratio between the nominal capacity of interconnection over the peak load. Therefore, it evaluates the capacity to import energy from a neighbouring region when is needed. It should be noticed that nominal transmission should account for

all EU interconnections including Norway and Switzerland. This criteria aims to ensure the grid reliability and continuity of supply at all times [2].

The downside of this criteria is that the peak demand is strongly dependant on the weather conditions. Hence, it should be taken the 99th percentile of the yearly demand distribution [2]. Additionally, it should be analysed how the interconnections with non-EU countries are considered.

$$\text{Exchange capacity} \geq \frac{\text{Nominal Transmission Capacity}}{\text{Peak Load 2030}} \quad (2.1)$$

In Figure 2.1 the results of the exchange capacity based on two TYNDP 2016, the scenario 3 "*National green transition*" and the scenario 4 "*European green revolution*" are shown. Based on the mentioned thresholds, the peripheral areas have an interconnection level under the 30% (orange). Interconnection levels between 30% and 60% are presented in yellow, and in green those with an interconnection levels above 60%. Figure 2.1 suggests that the Spanish interconnection level is lower than the 30% set by the current criteria, therefore new infrastructures are required to achieve an optimal level.

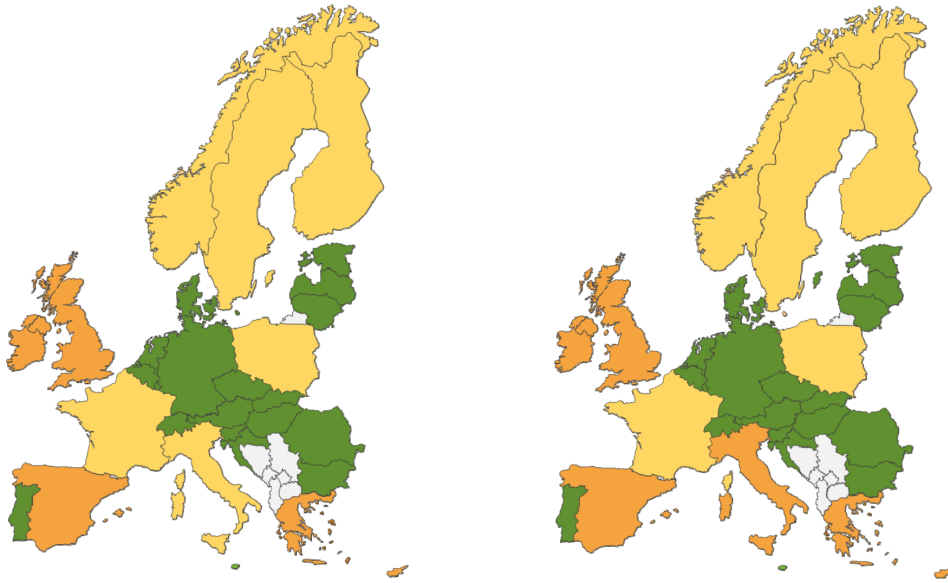


Figure 2.1. Member States by interconnection level as measured in relation to the peak load in vision 3 (left map) and vision 4 (right map) [2]

Export Criteria (Supply)

This formula is used to assess the contribution of interconnections to the renewable sources integration in the network. This second criteria is defined as the ratio between the nominal capacity of interconnection over the installed renewable capacity. The objective of this index is the evaluation of the cross-border capacity to evacuate the surpluses of energy

produced by renewable sources.

$$\text{Exchange capacity} \geq \frac{\text{Nominal Transmission Capacity}}{\text{Installed renewable generation capacity 2030}} \quad (2.2)$$

Analogously to the previous formula, the values of the *export criteria* based on the scenarios 3 and 4 of the TYNDP 2016 are shown in figure 2.2. It should be noticed that this parameter could indicate more reasonably the interconnection requirements for and efficient integration of renewable sources. Based on the mentioned thresholds, areas with an interconnection level under 30% are represented in orange. Interconnection levels between 30% and 60% are presented in yellow, and in green those with a interconnection levels above 60%.

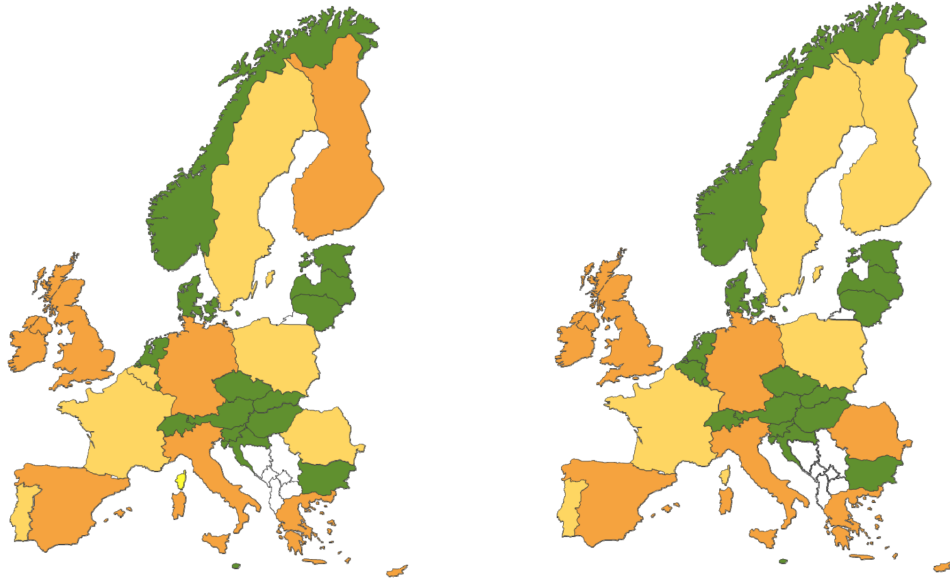


Figure 2.2. Member States by interconnection level as measured in relation to the installed renewable generation capacity in vision 3 (left map) and vision 4 (right map) [2]

Based on that second criteria, Spain is still classified in the group with the lowest interconnection capacity based on the installed renewable generation capacity. Therefore, this criterion indicates that between Spain and Central Europe are required more interconnection infrastructures.

2.3 European energy market

It is essential to achieve a well-functioning energy market in order to achieve a European competitive market with affordable energy prices.

To reach that goal, the European Union has done, a great effort in order to promote the development of a common platform for a single energy market. Physical constraints have been reduced by the reinforcement of cross-border interconnections, and the establishment of legal and coordination procedures. Therefore, the cross-border trades have increased

during the last decades, nevertheless, it has not fully completed the integration of all the Member States in the system.

The Framework Guidelines and Network Codes has been develop in order to set clear rules and procedures for the organization and operation of a European Energy system, which provides harmonized rules for cross-border exchanges of electricity. The drafting of those documents involves the European Commission, ACER and the European Network of Transmission System Operators of Electricity or ENTSO-E. Through that initiatives the different organisms aim to achieve an integrated system from the point of view of the wholesale market, but also from the operational and security perspectives.

Regarding to the market integration of the different Member States, the main achievement has been the development of the Price Coupling of Regions (PCR). This initiative involved seven European Power Exchanges for the development of a single price coupling algorithm, named Euphemia, used to calculate the electricity prices across Europe and allocate cross-border capacity on a day-ahead basis. The integrated European electricity market is expected to increase liquidity, efficiency and social welfare [8].

The map in figure 2.3 shows the seven different Power Exchanges regions participating in the PCR initiative, which includes: APX, Belpex, EPEX SPOT, GME, Nord Pool Spot, OMIE and OTE.

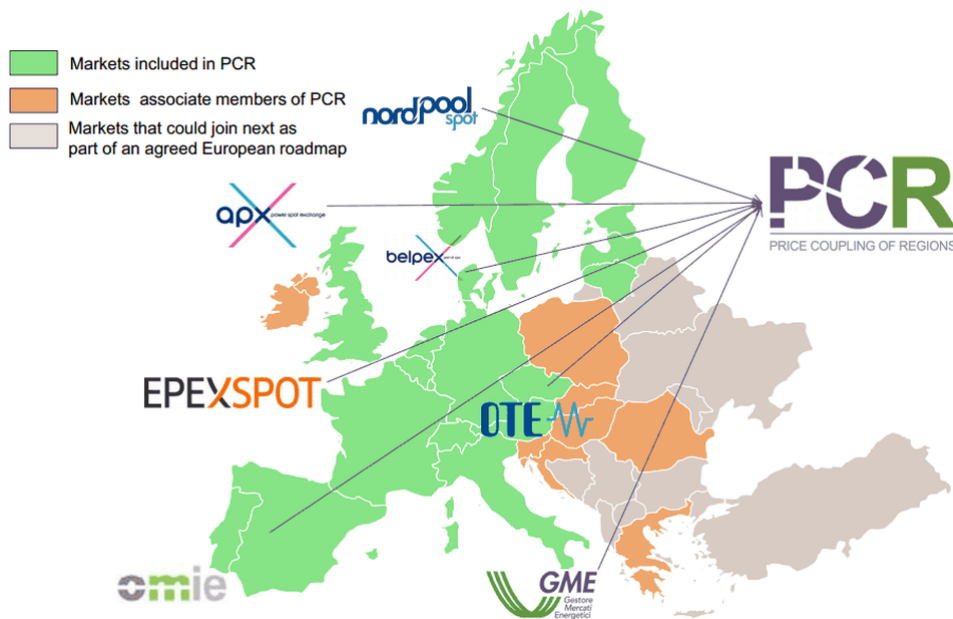


Figure 2.3. Price Coupling of Regions initiative

With respect to the cross-border interconnection, a market code has been developed in order to establish a set of rules to harmonize the system operation. The Framework Guideline on Capacity Allocation and Congestion Management is developed in two Network Codes: the CACM Guideline, which deals with bidding zones definition, cross zonal capacity calculations and day-ahead/ intraday capacity allocation. This document was published as a Commission Regulation (EU) 2015/2012 and entered into force the 15th August 2015 [5].

Additionally, the Forward Capacity Allocation (FCA) Guideline regulates cross-zonal capacity allocation in long-term time-frames (monthly and annual). The FCA GL was published as Commission Regulation (EU) 2016/1719, and entered into force the 17th October 2016, establishing a guideline on forward capacity allocation [9].

2.3.1 Price convergence & Market coupling

The convergence of the average electricity price over different regions provides an indicator of the market integration level, which depends both on the efficient use of interconnectors and on the existent infrastructure. In figure 2.4 the different average price regions as function of the depicted colours can be observed. In the Central-European region and Nordic countries, the lowest prices are reached, between 25-29 €/MWh. As we move away to the peripheral areas, the average price and the price spread increases up to 49 €/MWh. On some borders (Portugal-Spain, Czech Republic-Slovakia and Latvia-Lithuania), the absolute price spreads in 2016 were on average below 0.5 €/MWh. Others, as the British borders, Austria-Italy and Germany-Poland registered price spreads equal or higher than 10 €/MWh.

These values evidence the relevance of increasing the cross-border exchange capacity in order to reduce the price spread among the different regions, especially those with the highest values. This lack of infrastructure leads to a noticeable social welfare loss, however, reaching full price convergence is either the objective as it would require an over investment, which is in economic terms inefficient [10].

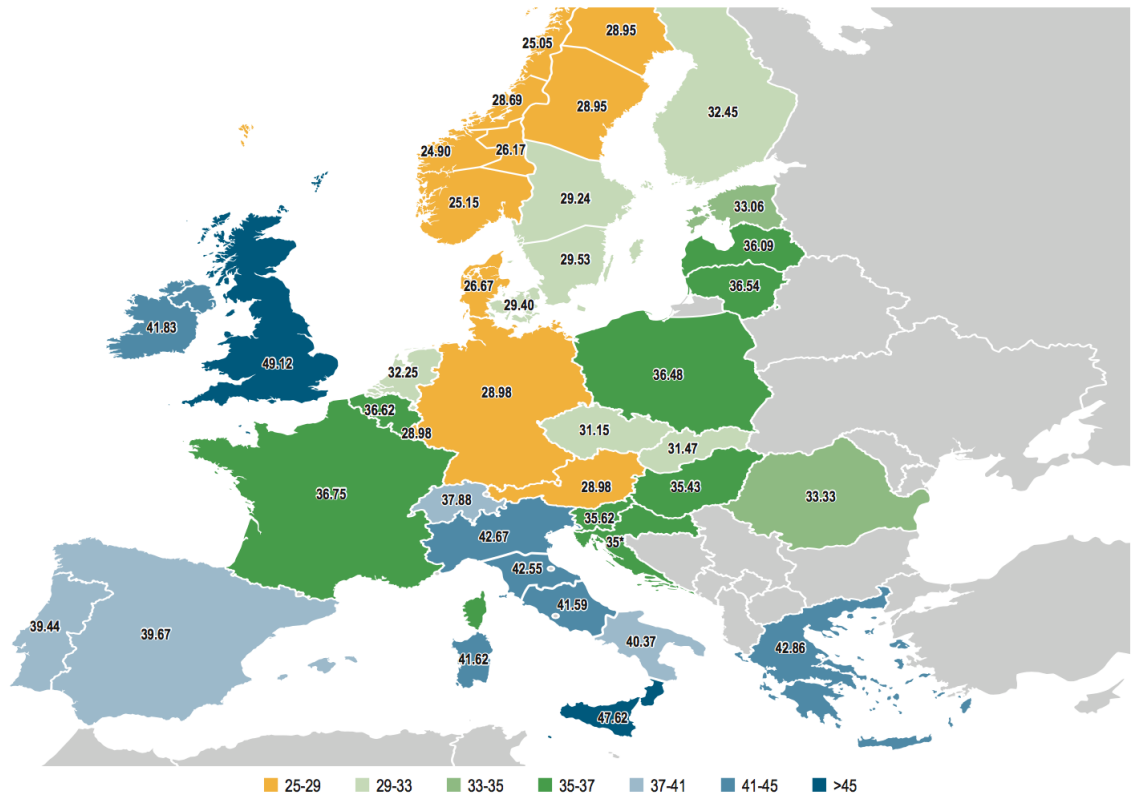


Figure 2.4. Average electricity wholesale day-ahead prices – 2016 (euros/MWh) [10]

Figure 2.5 provides an overview of the market coupling evolution within the different European regions between 2008 and 2016. The three regions with the highest frequency of full convergence rate in hourly prices have been the Baltic (71%), Central-West Europe (39%) and South-West Europe (30%). Additionally, all these three regions showed the highest increase in the frequency of full day-ahead price convergence between 2015 and 2016 [10].

Regarding to the SWE region, which includes Spain, France and Portugal, two main events had an impact in the regional price convergence. The upward trend observed between 2014 and 2015 is a consequence of the market coupling between French-Spanish border (14 May, 2014). The frequency of full price convergence in the SWE region increased from 14% in 2015 to 30% in 2016. This could be due to the increase of the exchange capacity between Spain and France, that approximately doubled from 1.400 MW to 2.800 MW the 5 October, 2015 [10].

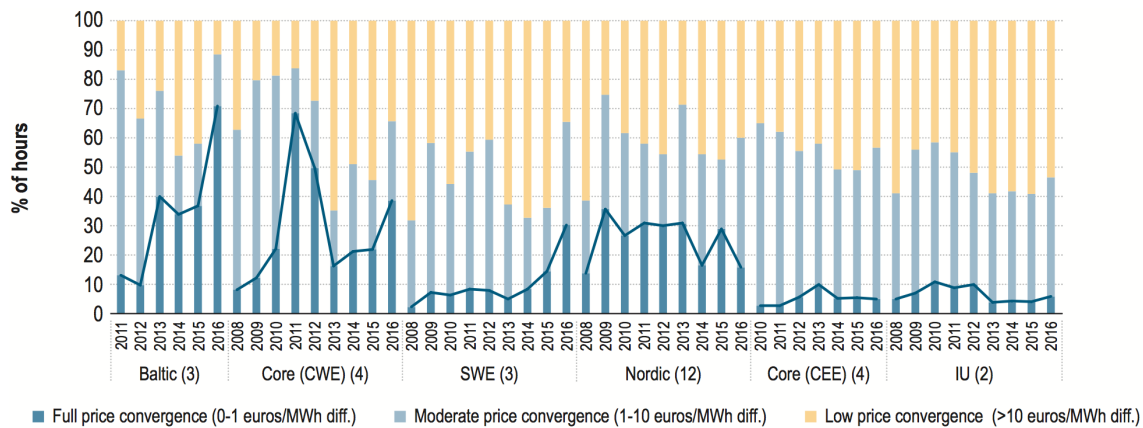


Figure 2.5. Day-ahead price convergence in Europe by region (% of hours) [10]

The efficient use of the cross-zonal capacity is an issue to be addressed. In general, the liquidity of forward markets in Europe remained low in 2016, with some exceptions as France, who recorded the highest growth. Due to the limited number of liquid forward markets in Europe, cross-zonal access to these markets becomes particularly important.

Regarding to the day-ahead timeframe, as a consequence of the coupling of two thirds of the European borders by 2016, the level of efficiency in the use of the interconnectors in this time-frame increased from approximately 60% in 2010 to 86% in 2016. Hence, during the last seven years, thanks to market coupling, a notably increase of the welfare gains and therefore a benefit for consumers have been achieved.

Figure 2.6 shows the level of efficiency in the use of the interconnectors within Europe by the different time-frames. Compared to the day-ahead (86%) the level of utilization in the intraday period is still low (50%), which implies a large potential for improvement in the use of the current infrastructure. Furthermore, it has been concluded that in 2016, cross-zonal capacity was used more efficiently in the intra-day time-frame on borders which applied implicit auctions (100%) compared to borders with implicit continuous trading (49%) or explicit capacity allocation methods (40%) [10].

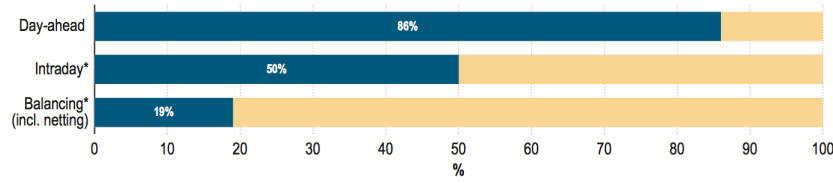


Figure 2.6. Level of efficiency in the use of interconnectors in Europe (% use of available commercial capacity in the *right economic direction*) in 2016 [10]

2.4 Interconnection management

The management of the cross-border lines require a special methodology for the operation and management of congestions. Nevertheless, it should be previously analysed the economic impact of the infrastructure.

The increase of the transmission capacity leads to a benefit of the involved regions, which can be evaluated by means of a cost-benefit analysis. The most common indicator to evaluate the benefits of transmission investments is the reduction in total costs. This analysis compares the total investment with the total cost reduction. The capacity increase between two bidding areas allows generators in the lower priced area to export power to the higher priced area as shown in figure 2.7. This leads to an increase of the social welfare as it reduces the fuel consumption and other variable costs. Additionally, capacity increase also has a positive impact such as enabling the use of generation capacity in a different location, which could avoid or postpone the need for construction of an additional generation unit in each area [11]. The capacity allocation and the congestion management are introduced in the following subsections.

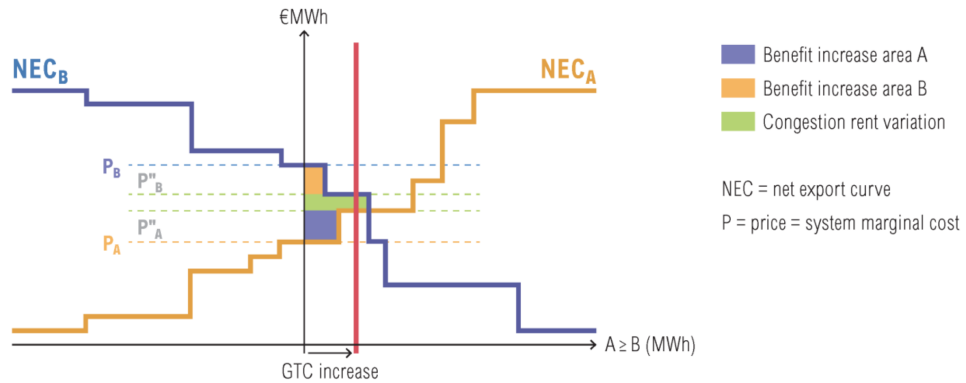


Figure 2.7. Benefits due to exchange capacity increase between two bidding areas [11]

2.4.1 Capacity auctions

The allocation of the transmission in the market is done by the System Operator by means of auctions. Two different ones are carried out, explicit and implicit auctions [12]:

- **Explicit auction:** It is a method that allows to manage and allocate the international exchange capacity in the different time-frames. This type of auction allocates the

exchange capacity independently to the auctioning of energy.

It is designed for long-term horizons. This is motivated by the prevalence of long-term bilateral contracts in which producers and consumers agree on a price and energy quantity for a time period which require the allocation of the transmission capacity. In this process, the System Operator determines the total capacity to be auctioned in the different periods. The different buying offers are collected and sorted according to decreasing price, the total volume of the offered capacity until is reached. Due to the fact that the capacity and the energy are not linked each other, they are sold independently.

- **Implicit auction:** By means of implicit auctions the cross-border capacity and the energy are sold simultaneously for the corresponding time-frame. Hence, both of them are allocated based on the most economically efficient buying and selling offers. This methodology implies that the interconnection allows the access to the market participants at each side of the border, hence the accepted offers would be allocated based on market rules.

The different assigned transmission rights can be classified in three different products:

- Physical transmission rights (PTR): Physical assignment of the interconnection use based on the principle of *use it or lose it* or *use it or sell it*, with the existence afterwards of a secondary market.
- Financial transmission rights (FTR): Financial rights for the use of the interconnection.
- Contracts for differences (CfD): These are financial products with the characteristics of a forward contract on the differential price over the systems. They are potentially offered by entities different to the Transport Operators and its implementation is easier than the PTR and FTR [13].

2.4.2 Congestion management

Cross-border interconnections allows the energy transmission of one bidding region to another. Nevertheless, this infrastructure have a physical limited capacity which can lead to the definition of two different market conditions:

- **Market Coupling**

Several bidding regions could be interconnected by exchange lines, which enables the energy transmission between the counter-parties. This infrastructure has several benefits such as a more efficient use of resources, higher system flexibility, reliability and integration of renewable sources among other.

The market participants of each region allocate their buying and selling offers in their corresponding markets. This system, makes use of the different interconnections in order to reduce the price differences among the regions. Hence, the areas with lower prices would export to those with higher ones until a single price is reached. It should be noticed that this situation is only possible if the cross-border interconnections allow the transfer of the required energy. Thus, the main objective of the market coupling is to maximize the social welfare.

- **Market Splitting**

This situation is reached when the exchange capacity between two interconnected regions is not enough to allocate all the desirable transactions. This leads to the congestion of the interconnectors and hence is not possible to exchange the required energy to reach the market coupling.

The algorithm used to operate the daily market ensures the optimal allocation of buying/selling offers in order to maximize the social welfare of the multi-regional areas.

Hence, when the interconnections are congested, the Market Operator Splits both regions and determines the electricity price of each isolated area. This price difference leads to an income for the System Operator, called *Congestion Rents*, that is calculated by the formula:

$$\text{Congestion Rent} = \text{Spread}_{A-B} \cdot \text{ATC}_{A-B} \quad (2.3)$$

where ATC is the *Available Transfer Capacity* and the *Spread* is the price difference.

This scarcity of capacity provokes that each market has to operate independently and thus, exists a loss of social welfare.

In figure 2.8 the market effect of the cross-border trade is depicted. When a country with a higher electricity price is interconnected with a lower one, the former imports energy at a lower cost from the second one. Hence, the prices tend to be equal (if the lines are not congested). Thus, it could be translated to a demand increase in the lower cost region and therefore, a reduction of generation in the higher cost area.

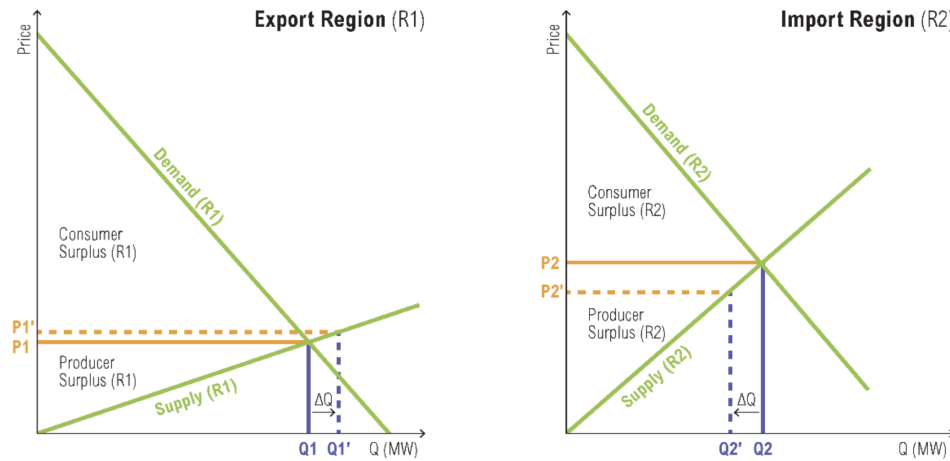


Figure 2.8. Market effect in the importing and exporting country [11]

2.5 Spanish electric system

The performance of the electric Spanish system is determined by its orography and generation mix. Due to the geography of the Iberian Peninsula, the interconnection within neighbouring countries is limited and therefore it is not possible to fully rely on the contribution on this connections for the energy supply and system reliability. Consequently,

the Iberian peninsula is considered an "energy island" as cross-border interconnections represents the bottleneck for its full integration in the European electrical grid.

Additionally, the penetration of renewable sources has increased during the last decade led by wind and photovoltaic energy. These variable sources depend on atmospheric conditions for the energy production, which introduce a certain degree of uncertainty in the demand supply. Thus, complementary technologies with fast response, such as hydro or combined cycles are necessary to provide energy when needed. Finally, low response technologies, such as coal and nuclear power, which operates as base-load plants with almost a constant generation in order to supply to the constant base demand.

2.5.1 Installed capacity and generation mix

The energy mix determines the system dynamics depending on the technology predominance and complementarity. As previously mentioned, the renewable energy share has increased during the last decades, with and installed wind and photovoltaic capacity of 22.863 MW, and 4.431 MW ,respectively in 2017, which jointly represents 27,5% of the total installed capacity.

Regarding to the installed capacity of thermal technologies, combined cycle, coal and nuclear represent 25% (24.948 MW), 9,6% (9.536 MW) and 7,2% (7.117 MW) ,respectively [14].

As shown in figure 2.9, the installed capacity in the Iberian Peninsula has grown since 2010 from 96.130 MW up to 99.311 MW in 2017. The installed capacity is largely dominated by renewable technologies, and combined cycle power plants. Additionally, the hydro power plays a significant role for the energy buffering due to, the notably storage capacity which enables a certain flexibility degree. Nevertheless, it has not been observed large variation in the installed capacity.

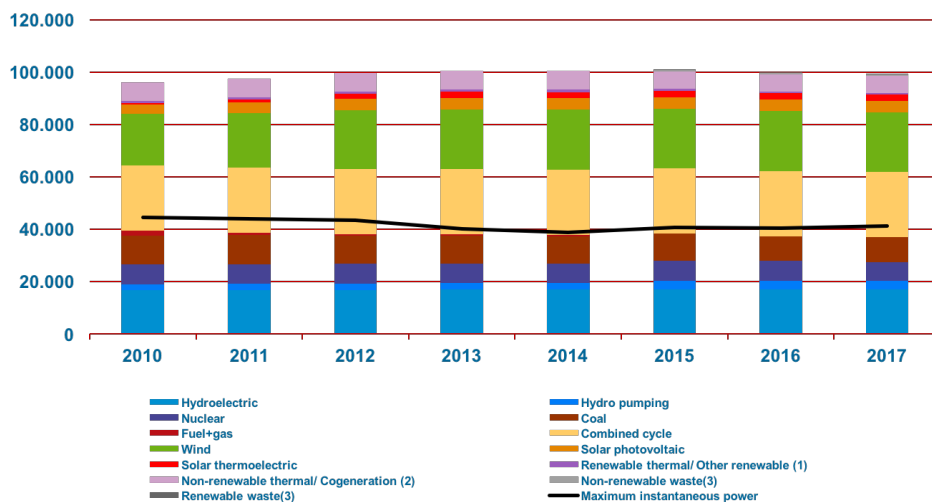


Figure 2.9. Evolution of the installed capacity in the Spanish peninsula [14]

The energy demand has decreased from 273.317 GWh to 248.424 GWh in the time-frame from 2010 to 2017. This reduction has been motivated due to the lower industrial activity

and technological developments in the area of energy efficiency.

From figure 2.10 an increase in the energy production from wind power and a reduction of combined cycles as can be observed. Additionally, it is remarkable the variation on the water production, which shows its dependency on the inflows for the electricity generation. Last but not least, the solar thermal and photovoltaic energy are contributing to, the energy share with a lower percentage.

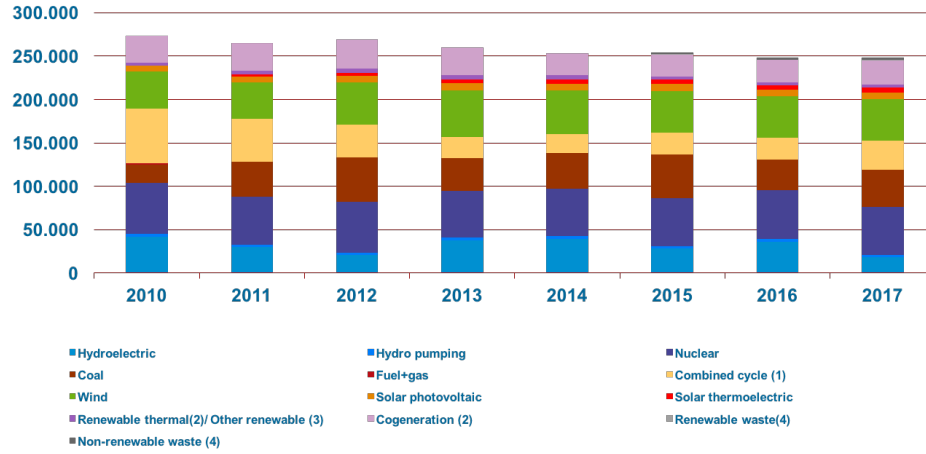


Figure 2.10. Evolution of the electricity generation in the Spanish peninsula [14]

2.5.2 Spanish cross-border interconnection capacity

The Spanish electric system is connected to the Portuguese one, creating the so called Iberian Electric System. Additionally, it is linked to the north of Africa throughout Morocco, to Andorra and to the Central-European System through the French border. Furthermore, the Central-European System is linked to the Nordic countries, Eastern Europe and the British Islands. Therefore the European network thus constituting the largest electric system worldwide [3].



Figure 2.11. Spanish cross-border interconnections [15]

As previously mentioned, Spain is considered an "energy island" due to its low interconnection levels. At the present time, the commercial exchange capacity only represents the 2,8% over the total installed generation capacity in Spain. Strengthening the interconnections to neighbouring countries is therefore essential to ensure the development of the uprising technologies and to benefit from being part of a pan-European grid. For that purpose, it is required to increase the interconnection capacity with France, as it represents the only way to access the European network. The actual interconnections capacities are presented in the following table 2.1:

Table 2.1. Spanish commercial cross-border exchange capacity

Connection	Minimum (MW)	Maximum (MW)
France - Spain	2.500	3.150
Spain - France	2.150	3.000
Portugal - Spain	3.000	3.700
Spain - Portugal	1.600	2.900
Morocco - Spain	600	600
Spain - Morocco	900	900

It should be taken into account that the October 5, 2015, a new DC line was set between Spain and France (Santa Llogaia- Baixas). This interconnection increased the exchange capacity from 1.400 MW up to approximately 2.800 MW. That infrastructure, set a break point by doubling the interconnection capacity. Nonetheless, the exchange rate is still far from the EU recommendations in order to achieve a well-functioning market and to benefit from a European Super-grid.

2.5.3 Spanish cross-border interconnection management

The Spanish interconnections management is divided in four temporal horizons as shown in figure 2.12. Therefore, transmission capacity is allocated in four stages according to different temporal horizons. The development of this section is based on the stated in source [12].

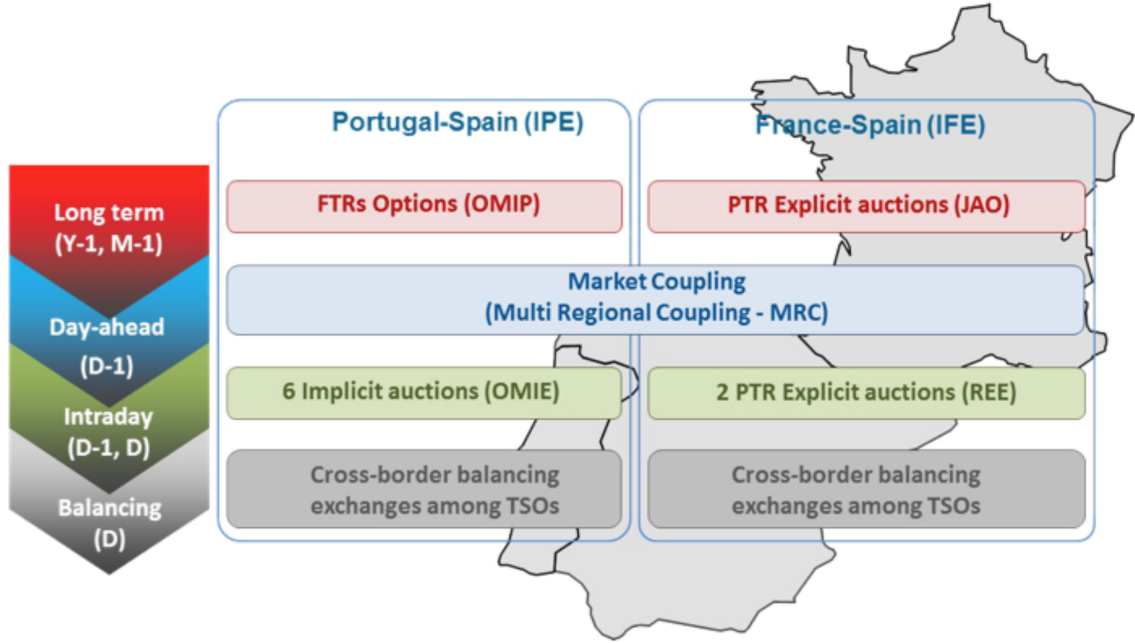


Figure 2.12. IPE and IFE interconnection scheme [14]

- **Long term:** The long-term capacity allocation between Spain-France and Spain-Portugal is done by means of explicit auctions. The Interconnection Portugal-Spain (IPE) is managed by OMIP (Iberia Market Operator- Portuguese Pole) and only auction physical rights (FTR) whose distribution of capacity in the horizons is decided at each auction by Resolution of the CNMC [16].

Regarding to the French interconnection (IFE), for annual and monthly time frames, it is carried out on the JAO *Joint Allocation Office* assignment platform. The capacity is distributed approximately in 1/3 between annual, monthly and daily. The product used is a physical right (PTR) under the condition of *Use It or Sell It*.

The regulation for the operation of the IPE and IFE are collected in the *CNMC Circular 2/2014* [17] and in the *Harmonized Allocation Rules* annex SWE [18].

- **Day-ahead:** Both interconnections are based on the project *Multi Regional Coupling* (MRC) implemented on May 13 of 2014, in accordance with the European Guideline CACM [19]. The congestion management is based on implicit auctions (joint allocation of energy and capacity), managed by the Iberian Market Operator in a cooperative way with the operators of the coupled markets. This mechanism establishes the interconnection program leading to a single price if the interconnections are not congested, otherwise, the markets would split reaching different prices.

- **Intraday:** Regarding the IFE interconnection, the capacity would be allocated by means of two explicit auctions of physical rights (PTR) by the cooperation of both, the Spanish and French System operators (REE and RTE). In the case of the IPE interconnection, it would be performed six implicit auctions coordinated by both system operators (REE and REN) and by the Market Operators as well. In 2018 has started the operation of the continuous market under the name of XBID.
- **Balancing:** At the present time, the cross-border balancing mechanism applied is the BALIT for both IPE and IFE. The assignment mechanism is *First Come First Served*, being time products, with an activation time of 30 minutes.

The interconnection management procedures with Morocco and Andorra are set by the CNMC circular 2/2014 [16]. In that case, Andorra is considered as a price integrated area of the Spanish system. With respect to the Morocco connection, it is considered an area outside the frontier, hence with bilateral contracts and market transactions.

3 Input data description

3.1 Period of analysis

This chapter introduces the variables that will be included in the econometric model. Furthermore, the behaviour and effect of the different variables in the Spanish spot market is analysed. It should be mentioned that the developed analysis has been performed on a previous one carried out by *Red Eléctrica de España*.

The total sampled data consists of hourly values since January 2010 to March 2018. Within that time-window, three different periods have been identified. The named *period 0* includes data since the beginning of 2010 until the implementation of the PCR initiative the 14th October 2014. During that period the market was not coupled yet with France, and hence the cross-border rules were not set. Therefore, this data-set is not reliable for its use in the econometric model. Nevertheless, it is still helpful for the understanding of the relationship between the market price and the different variables. *Period 1* ranges between the beginning of the PCR (14/05/2014) and the start of the operation of the new cross border line between France and Spain, "Santa Llogaia-Baixas" (5/10/2018). During that period of time the exchange flows were established based on the market rules. This data-set would correspond to the first period of time of the econometric model. Finally, *period 2* includes information since the 5/10/2018 until the last data available (31/03/2018). During that period, the exchange capacity between Spain and France doubled up to more or less 2800 MW. Additionally, during the third quarter of 2016 it has been detected the unavailability of several nuclear power stations in France, which affected the electricity price in Spain. In figure 3.1 is depicted the timeline of the data used for the econometric model.

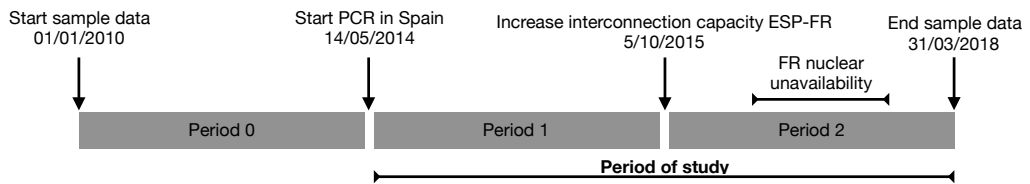


Figure 3.1. Time-line of the period of study

In the following sections are presented the main identified parameters included in the statistical analysis in order to analyse the Spanish market behaviour.

3.2 Spanish demand

The electricity demand is characterized by several seasonal components. At large scale annual seasons such as winter and summer have their own patterns due to environmental

conditions. In a shorter time-scale, weekly seasonal patterns could be appreciated due to working and non-working days with different demand profiles. Still in a shorter horizon, it could also be appreciated the daily demand pattern which reflects the Spanish society behaviour. It is characterized by two peak load periods corresponding to the peak production time at 12:00h and 20:00h, and a deeper valley period ranging from 2:00h to 4:00h.

In figure 3.2 are presented, the average Spanish demand and the average day-ahead price of the same period of time. As expected a relationship between both variables can be observed. During the low demand periods, the base load plants supply energy at a lower cost, and at peak loads, such as combined cycles, provide the energy demand.

It should be noticed that environmental parameters such as temperature or especial events as festivities are not included in the analysis, as they are already inherent to the demand values. That means, that it is not necessary to take into account these variables, as the demand already respond to them.

It have been represented, the box and whisker plot for the demand and the market price. Regarding to the price, it can be observed that the mean is close to 50€/MWh with an upper and lower quantile between 40 and 57 €/MWh. Regarding the demand, the average load is close to 27GW, with maximum and minimum values between 16GW and 40GW.

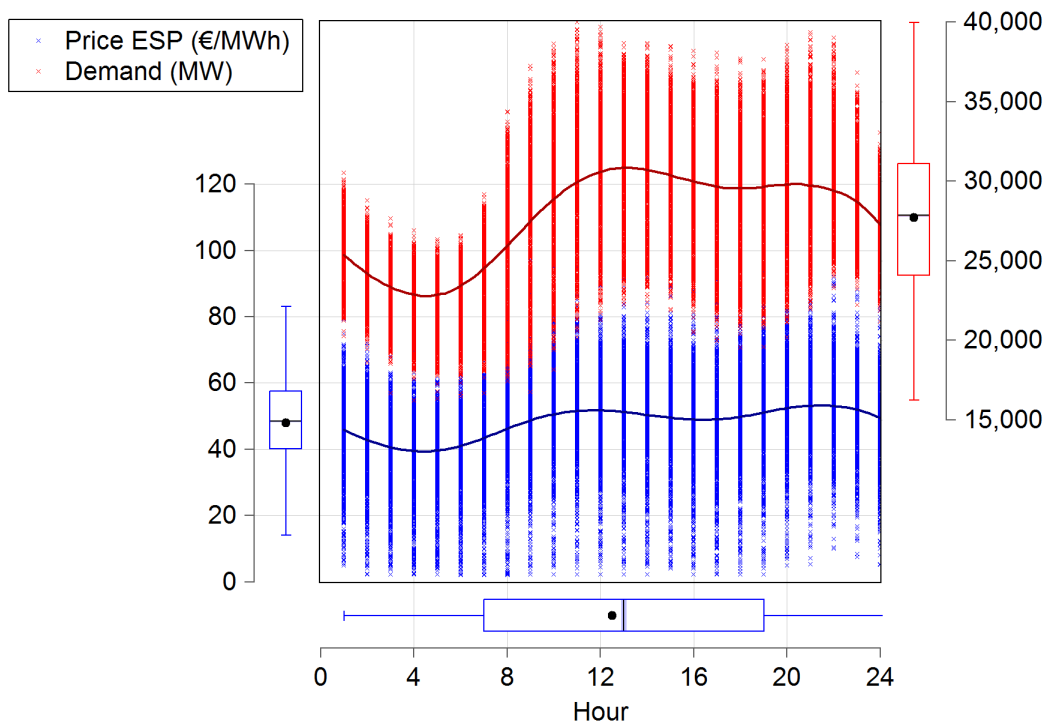


Figure 3.2. Relation between Spanish electricity demand and day-ahead market price

3.3 Generation Mix

The generation mix plotted in figure 3.3 determines the power plants that have been committed to supply the required energy to the demand, which can be classified based on their energy source. On one hand the thermal based plants depends on the combustion of a fossil fuel/ nuclear reaction in order to run a thermal cycle and generate electrical energy. These technologies are controllable as they do not depend on external factors in order to work. Nevertheless, its operation is based on the consumption of a fuel which has an associated cost.

On the other hand, renewable sources are based on technologies that make use of external sources, such as wind and solar ones. These technologies depends on atmospheric conditions in order to provide energy. Therefore, this are variable sources which cannot be easily predicted. Nevertheless, their generation does not depend on the consumption of any fuel, and thus, there is not a fuel cost associated with their operation.

Finally, hydro technology can be considered as a renewable source in the sense that it is not based on the consumption of a fossil fuel, nevertheless it has some particular properties. These power plants depend on the inflows in order to be able to turbine the water, hence depends on external factors. Nevertheless, the dams allow the storage of that energy allowing a certain generation flexibility. As it can be seen in figure 3.3 the hydro generation considerably varies from period to period as it depends on the actual inflows.

The data used is the day ahead "Programa Diario Base de Casación" PDBC which considers the offered generation capacity and the demand, which after a matching process, is set the marginal price for electricity. It should be noticed that the total volume offered in this market is lower than the final consumption as the bilateral contracts are excluded.

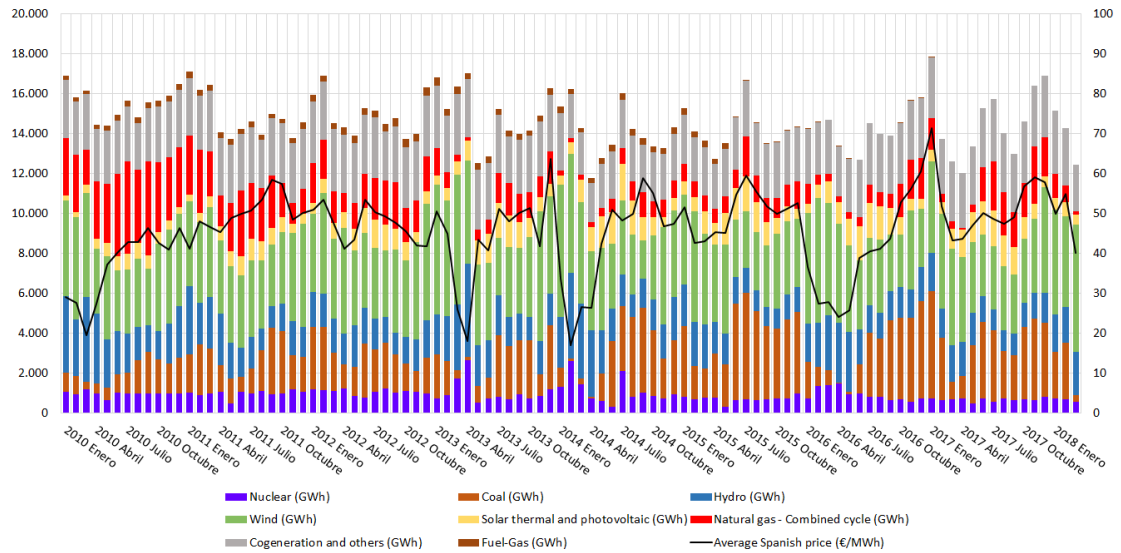


Figure 3.3. Generation mix of the sampled period

3.3.1 Thermal-based technologies

Thermal-based technologies are based on the consumption of a fuel for the energy production. Therefore, the variable cost of the plant is strongly related to the price of the fuel. The considered thermal units within that analysis are the following:

- Coal
- Nuclear
- Natural gas/ Combined cycle
- Fuel-Gas

From the mentioned technologies, natural gas/ combined cycle and fuel-Gas are characterized by a small capital cost and a high variable cost, due to, high costs of the fuel. These units are normally used to supply in peak load periods and at renewable generation scarcities. Nuclear and coal technology normally work as base load plants due to their low operational flexibility. They are characterized by the need of large investments with lower operational costs.

In graph 3.4 the evolution of the production of the different thermal-based technologies and the market price over time are presented. As it can be observed that the higher market prices correspond to higher productions of the mentioned technologies. That could be explained by the fact that in the market the bid is usually made at the variable production cost. It could also be observed the almost complete dismantle of the fuel-gas units since may 2015.

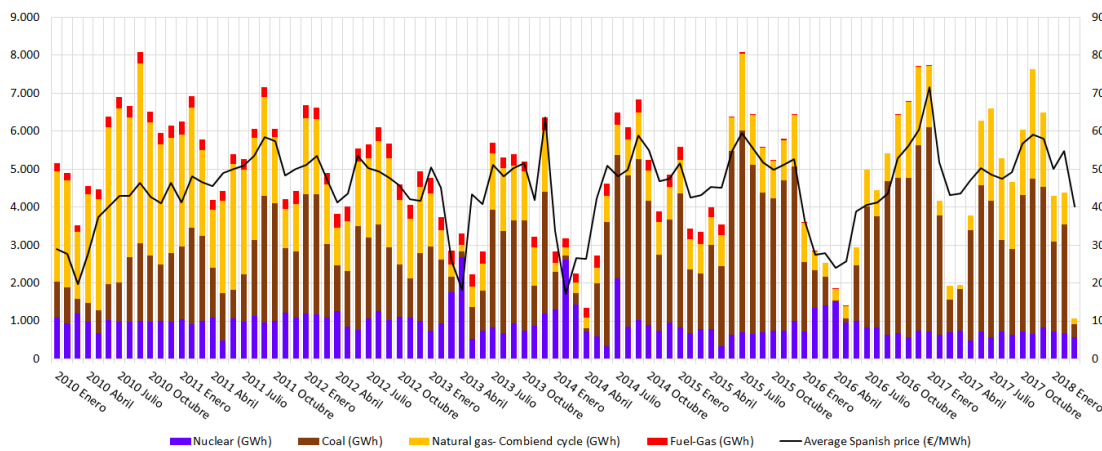


Figure 3.4. Thermal-based generation mix of the sampled period

In the scatter plot shown in figure 3.5 the hourly output of each technology as function of the day-ahead price is presented. It can be observed the behaviour of each technology with respect to the hourly price. From that, it can be noticed that the nuclear and fuel-gas technologies are not price dependent, therefore, its output does not change with price variations. Similarly, cogeneration slightly increases its production at higher prices.

Regarding the CCGT, it can be observed two particular behaviours, depending on the price range. From 0 to 78 €/ MWh the kernel fit line follows an exponential trend according to

the theoretical market behaviour, but from that point upwards seems to follow a different path. That could be caused by two different bidding strategies in which at lower loads the CCGTs are working as base load, and at peak loads are trying to increase the marginal price. This hypothesis should be further analysed in order to be confirmed.

Regarding the coal production, it can be observed a clear ascending trend in accordance to the price. This expected behaviour would have a significant impact in the price determination due to its clear pattern and the non-negligible installed power. It should be noticed that the presented data shown in figure 3.5 includes values since the start of the PCR to the end of the sampled data.

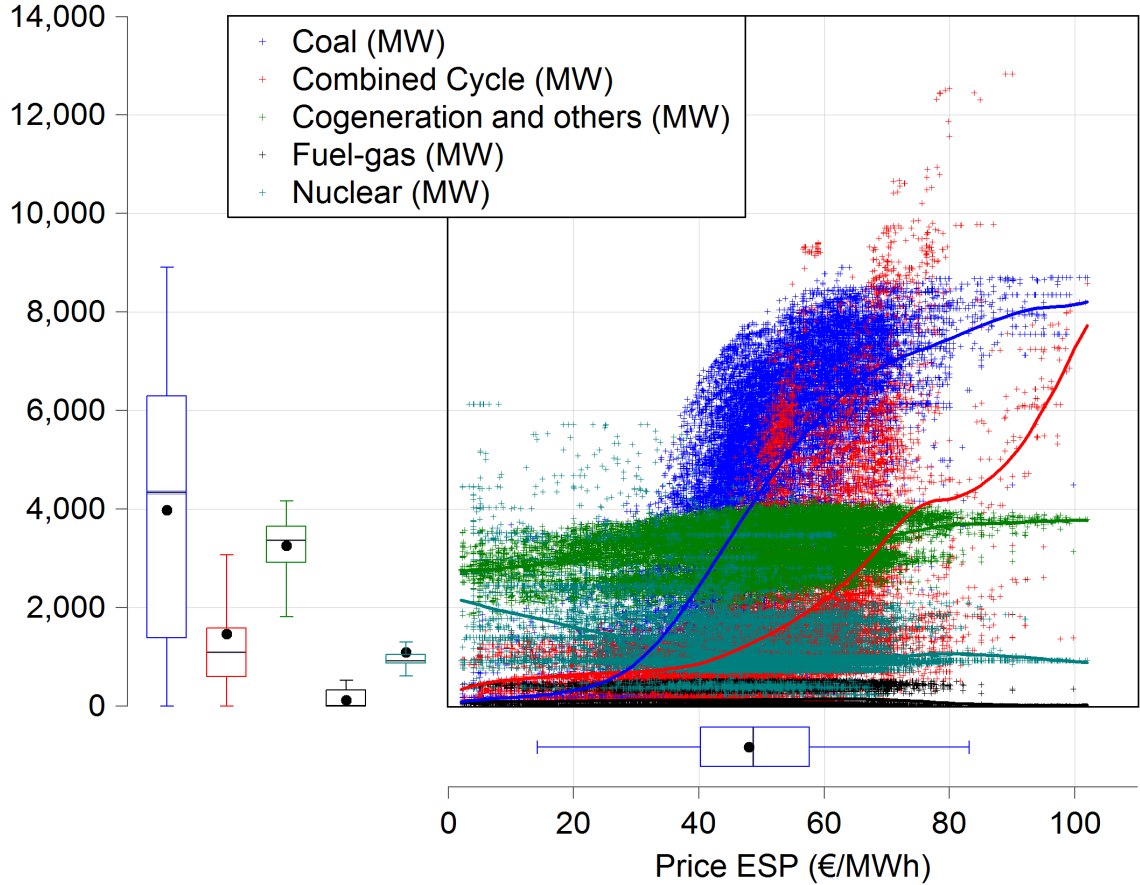


Figure 3.5. Thermal-based technology production as function of the day-ahead price

3.3.2 Renewable-based technologies

Renewable sources rely on external factors in order to supply energy. Therefore, these are unpredictable sources that tend to reduce the spot price with low bids as the variable cost of operation is close to 0. Thus, in periods with a large contribution of renewable energies the market price tends to reduce, as can be observed in figure 3.6. Therefore, especially in periods with huge productions of wind and hydro, these effect is enhanced.

It should also be considered that also exists certain dependency of these technologies to the seasons, which some of them are characterized by larger inflows and more constant wind generation. Regarding to solar technology, it could also be appreciated the increasing

contribution to the generation mix not only photovoltaic but also thermal. The analysed renewable technologies include:

- Wind power
- Photovoltaic solar power
- Solar thermal power
- Hydro UGH (unidad gestión hidráulica)
- Hydro non-UGH (unidad gestión hidráulica)
- Hydro pumping generation
- Hydro pumping consumption

Note that Hydro UGH (*unidad gestión hidráulica*) includes all the hydro power with storage capability, enabling generation flexibility. Hydro *non-UGH*, includes all the mini-hydro and run-of-river units, which are not able to decide when or when not to produce.

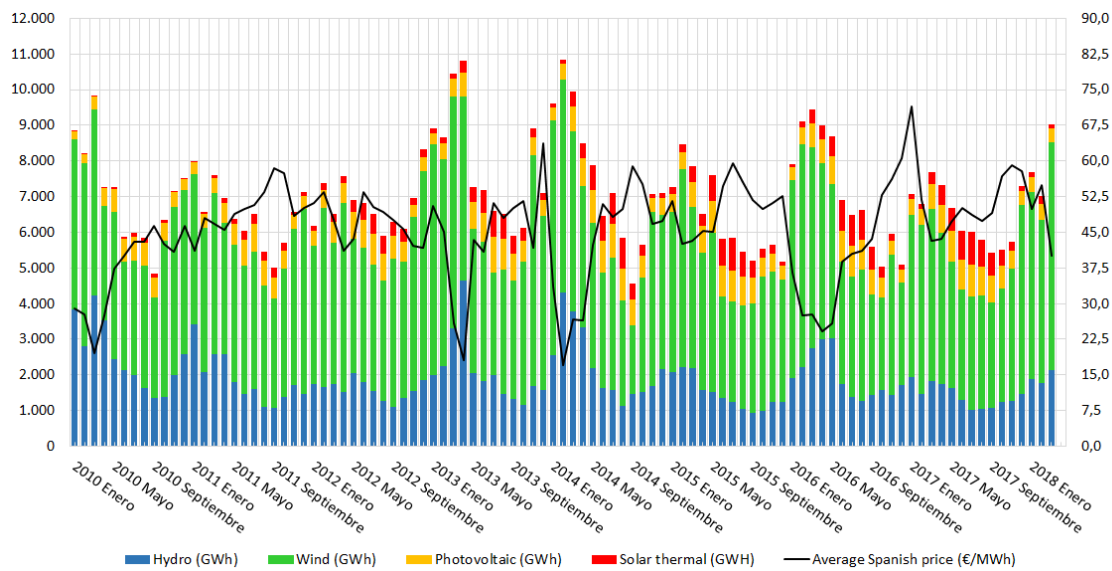


Figure 3.6. Renewable-based generation mix of the sampled period

In figure 3.7 the hourly production of wind and solar (thermal and photovoltaic) technologies as function of the day-ahead price is presented. It should be taken into account the larger amount of wind power installed with respect to solar, which leads to a lower market influence.

Regarding to the wind power, it can be clearly identified two different regions. High wind productions leads to low day-ahead prices, which is in accordance to the theoretical concepts as it avoids the consumption of fossil-fuels by thermal plants and thus reducing the spot price. This follows almost a linear behaviour until the day-ahead price reaches 78 €/MWh. At that point, the bidding strategy seems to follow a different strategy in order to increase the marginal price. Nevertheless, this hypothesis should be further studied

Regarding the solar thermal and photovoltaic, both of them follow a similar production pattern without a significant price influence. It should be noticed the lower production of solar thermal technology is due to its lower installed capacity.

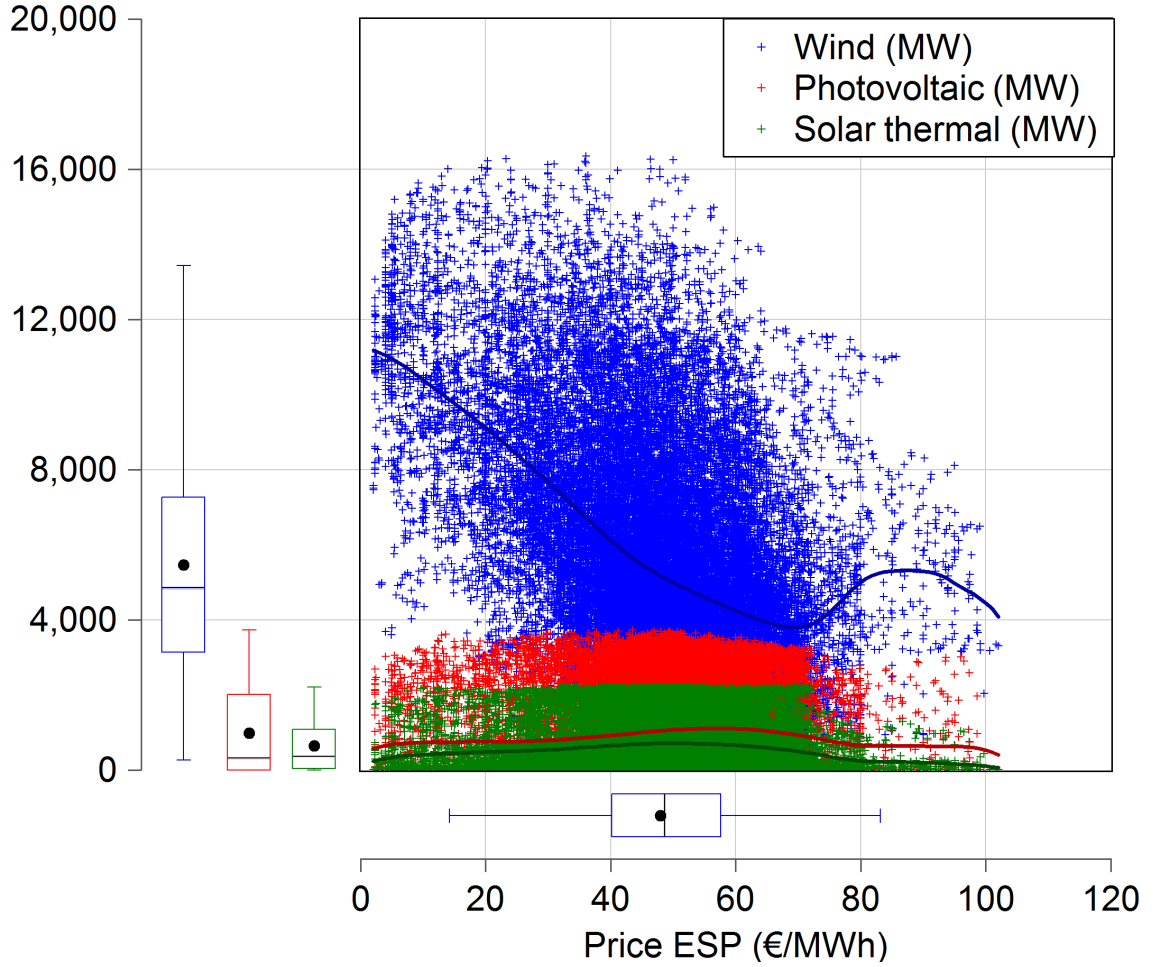


Figure 3.7. Renewable-based technology production as function of the day-ahead price

3.3.3 Hydroelectric power

As presented in figure 3.6 large hydro power production corresponds to lower market prices, in a similar manner to other renewable sources. This technology has a different behaviour compared to renewable sources such as wind and solar due to a storage capability and to the dependency of seasonal inflows. Therefore, these sources could induce to a price reduction when water surplus is expected, or to a price increase in scarcity periods.

Hydro power technologies can be classified in three different groups. The first, and most relevant group is constituted by the units named *Unidad de Gestión Hidráulica* (UGH). This power plants are equipped water storage facilities that allows a flexible generation. The second group is constituted by the *non-ugh*, which includes run-of-river and mini-hydro. These technologies are unable to manage its production as totally depends on the current water flows. Nonetheless, this units depend on the dams' management upstream of its hydrological basin. The last group included are the power stations which are able to pump water to the upper reservoir in order to generate in peak load periods. This technology takes advantage of the market price fluctuations to generate a profit.

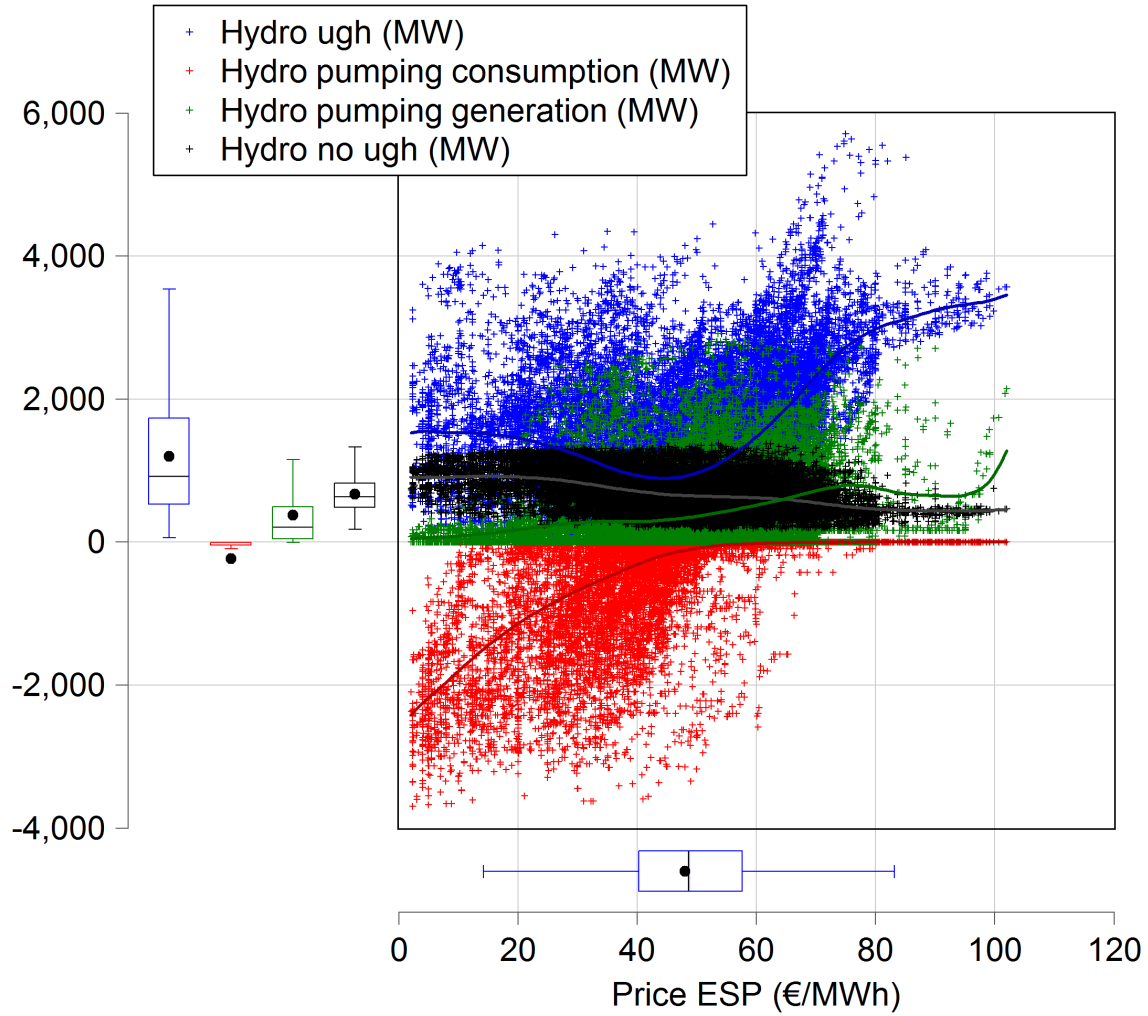


Figure 3.8. Hydro power production as function of the day-ahead price

Figure 3.8 shows the behaviour of each technology with respect to the market price, which includes data since the PCR start in Spain to the end of the sampled data in 2018. As previously mentioned, three technological groups can be clearly observed. A kernel fit line has been added in the scattered plot to represent the average value at each point.

Firstly, it should be noticed the small influence of the hydro pumping generation due to its low installed power. Therefore, it is not included in the econometric model due to its low market impact. Nevertheless, its behaviour is to increase its production with an increasing spot price. Regarding to the energy consumption of the pumping units, their behaviour to increase its power at lower prices in order to benefit from that lower energy cost. Regarding the *non-ugh* units, they have a low price response due to its inability to regulate its production. Nevertheless, it should be noticed a higher production at lower prices. It could be explained by its dependency to the upstream dams' operation, that in order to avoid spillages, are generating more than in normal conditions.

Regarding the *UGH* units, it could be observed two regions with a different behaviour. Firstly, at lower market prices, the *UGH* units increase its productions, probably, to avoid water spillages in the dams. At middle range market prices, the average production of the

units stall perhaps in order to store the water resources to be used at higher prices. At the higher price ranges, the production clearly increases in order to benefit from the higher market prices, so it is substituting expensive units.

In order to take into account the influence of the hydro units in the econometric model, it has been analysed the relationship between the percentage of the water reservoirs with respect to the spot market price as plotted in figure 3.9. From the figure could be observed that as the reserves level decrease, the market price increases, due to water scarcities. Therefore, the percentage of the reserve water would be used as an explanatory variable instead of the UGH.

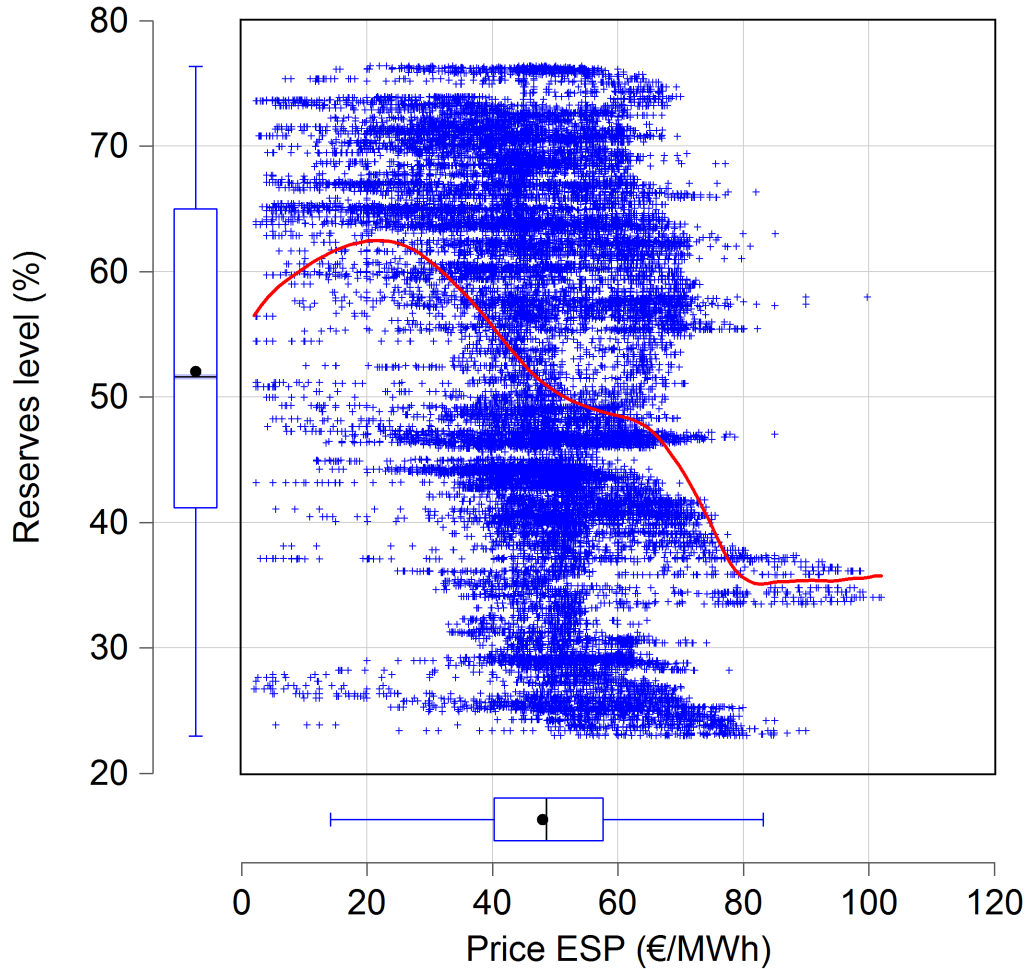


Figure 3.9. Hydro reserves as function of the day-ahead price

3.4 Cross-border congestions

Cross border interconnections enable the exchange of electricity until is reached the maximum capacity of the line and hence the markets are splitted. Therefore, the number of hours in which the markets are coupled, as well as the direction in which the cross-border congestions takes place is a good indicator of the system performance. From figure 3.10 could be observed the monthly historical evolution of the market congestions and market prices of Spain and France since 2010.

From 2010 until the PCR took place in Spain, the market was not coupled as the system operating rules were not clearly established. Therefore, this period would not be included in the econometric model due to the large operational rules differences between both periods. Since the PCR was established, the market started to be coupled, and thus the market prices at both sides of the border were the same at some periods. Until the new interconnection was established between Spain and France the October 5, 2015, the markets were coupled only 10% of the hours. After the new interconnection, the percentage market coupling raised up to 26,36% of the total time.

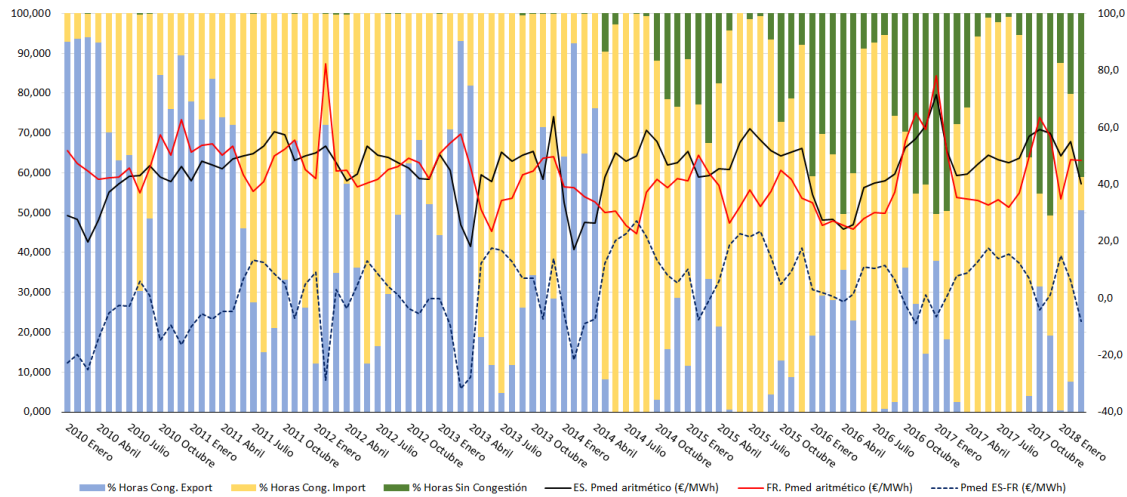


Figure 3.10. Market coupling and cross-border congestions between Spain and France

Comparing both periods of time, it could be noticed an increase in the number of hours in which the markets are coupled by 161,57%. Furthermore, it has been reduced by a 24,24% the number of hours in which there was a congestion when importing energy from France. Nevertheless, it has been detected an increase of 26,87% the number of hours in which the cross-border lines were congested in the exporting direction. That could be explained due to the unavailability of several nuclear power plants in the last quarter of 2016, which led to high prices in the French region and hence importing energy from Spain.

Table 3.1. Cross-border congestion between Spain and France

	Hours of congestion from ESP to FR	Hours of congestion from FR to ESP	Hours without congestion (Market coupled)
Period 1 (14/05/2014 to 05/10/2015)	10,79	79,13	10,08
Period 2 (06/10/2015 to 31/03/2018)	13,69	59,95	26,36
Increment %	26,87	-24,24	161,57

3.5 Cross-border flows

As previously mentioned, until the PCR was not established, the system management was different to the present one. Therefore, the developed econometric model would only

include data since that event. In figure 3.11 the exchanged cross-border flows between Spain and France can be observed, as well as the market prices of the corresponding countries. It should be noticed that the exchanged energy has significantly increased since the new interconnection was established between both countries was established. Thus, it contributed to reduce the price gap between both regions and increased the market coupling. Furthermore, from the presented figure it could be observed that Spain is an importing country due to an average higher price compared to France. One of the main periods at which Spain was a net exporter was during the unavailability of the nuclear power plants during the last quarter of 2016.

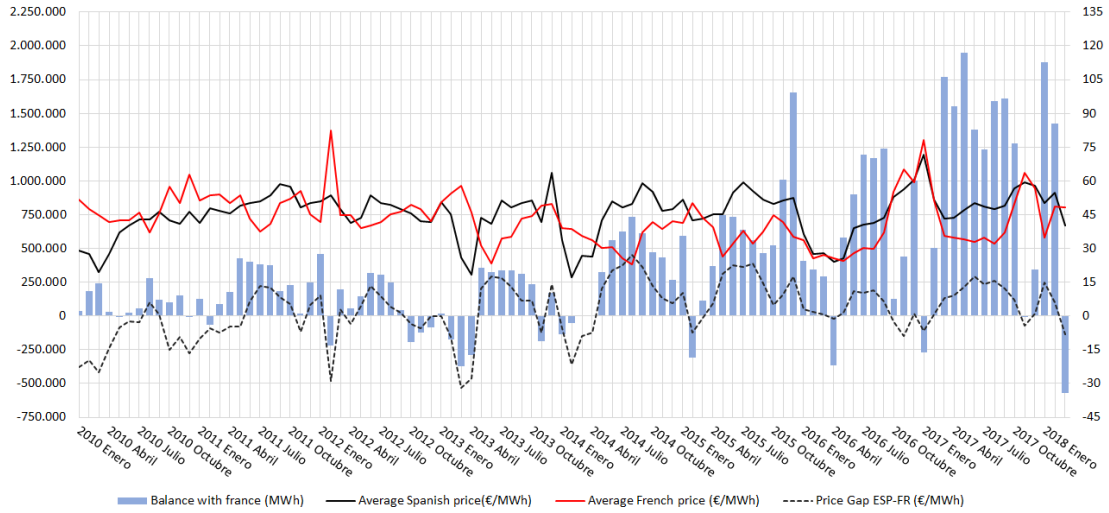


Figure 3.11. Cross border flows between Spain and France

To further depict the increase of the energy exchanged between Spain and France, figure 3.12 shows the cross-border flows in both periods since the PCR. In the positive side of the axis the imports from France before (green) and after (black) the new cross-border line are presented. It can be clearly seen that the additional infrastructure allowed to increase the exchanged energy from 1.400 MW to more than 3.000 MW.

At the other side of the axis, it can be seen the exported energy to France in the first period (blue), and in the second one (red). Equivalently to the importing case, the new cross-border line allowed a higher exchange capacity. It should be noticed that this clear separation between exports and imports are due to a proper system operation working according to the market rules. This phenomenon could not be observed before the establishment of the PCR, as energy exchange was not depending only on market rules.

Additionally, it should be noticed at the bottom of the figure that the mayor part of the price gap between Spain and France lays at the right side of the axis. That reaffirms the fact that the average price in Spain is higher than compared to France, hence the energy flow is usually in the importing direction.

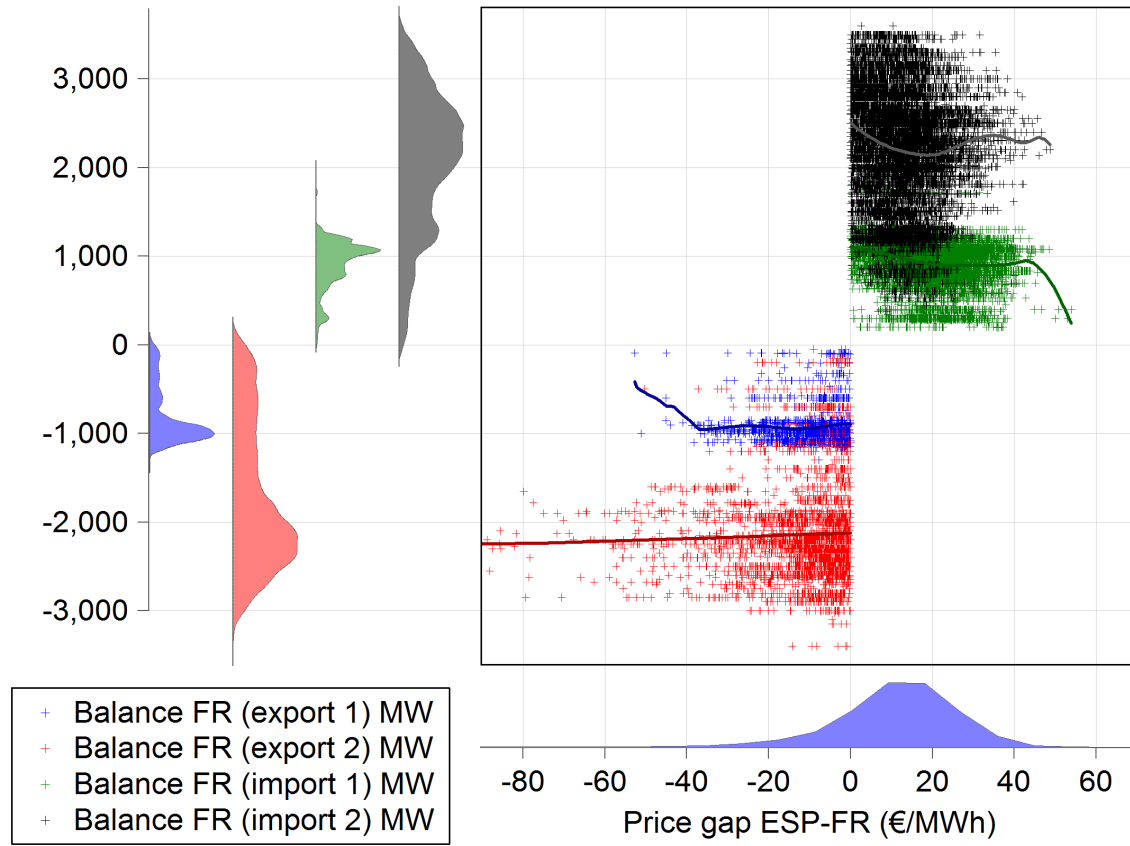


Figure 3.12. Energy imports and exports between France and Spain

3.6 Unavailability of French nuclear power plants

Figure 3.13 shows the monthly evolution of the day-ahead prices and the degree of full price convergence in the Core (CWE) region between 2014 and 2016. It illustrates that the frequency of full price convergence increased to 48% during the first three quarters of 2016. This trend was reversed in the last quarter of 2016, when the frequency of full price convergence dropped to 11%. The main reason that motivated the different behaviour between the first three quarters and the last one was the higher price in France and Belgium in the last quarter of 2016. These could be mainly caused by the unavailability of a significant number of nuclear reactors in France (and to a lower extent in Belgium), combined with a significant reduction in the amount of tradable cross-zonal capacity within the Core (CWE) region during the second half of 2016 [10].

Therefore, it has been introduced an intervention variable which take a of 1 during the duration of the event, otherwise, this variable would be equal to zero. It has been decided to apply this simplification due to the lack of precise information about this event.

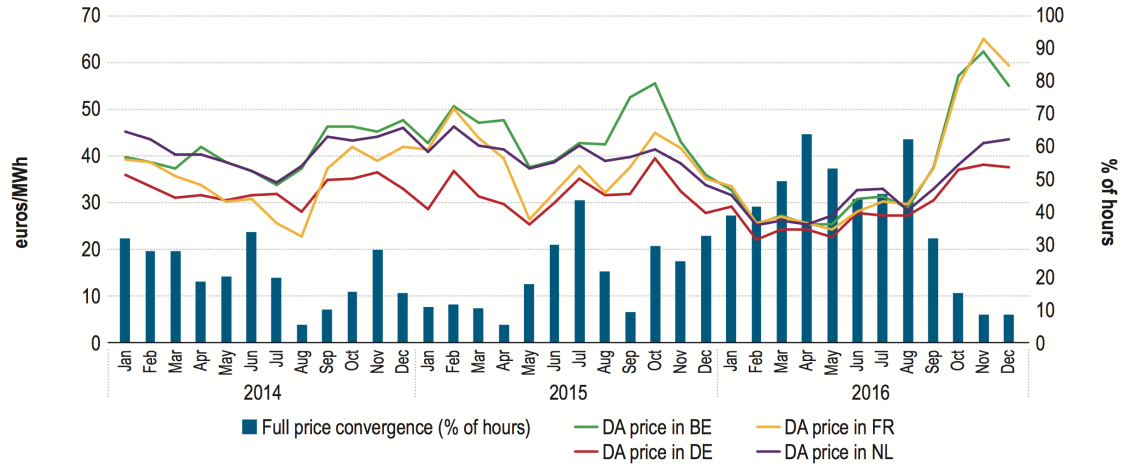


Figure 3.13. Monthly DA prices in Core (CWE) and the frequency of full price convergence – 2014–2016 (€/MWh and % of hours) [10]

3.7 Interconnection capacity between Spain and France

The capacity increase between Spain and France constitutes the major event of study of this analysis. Therefore, in order to study the effect of this event, two different approaches are followed in the econometric model:

In the first case, the capacity increase between Spain and France has been simplified and introduced in the econometric model as a intervention variable. Hence, this parameter has a value equal to zero until the 5/10/2015, (moment at which the new line started its operation) acquiring a value equal to one. This simplification allows the assessment of the explanatory variable.

In the second case, it has been used the real data of the available transfer capacity as shown in figure 3.14. Therefore, it could be observed a notable increase of capacity the 5/10/2015, day at which was settled the new interconnection. It should be noticed that the capacity exchanged made available to the market depends on other factors such as the ambient conditions, the security margins, maximum temperature, network flows, etc. Additionally, the available capacity is not symmetric even though it depends on the loads of adjacent lines at each side of the border.

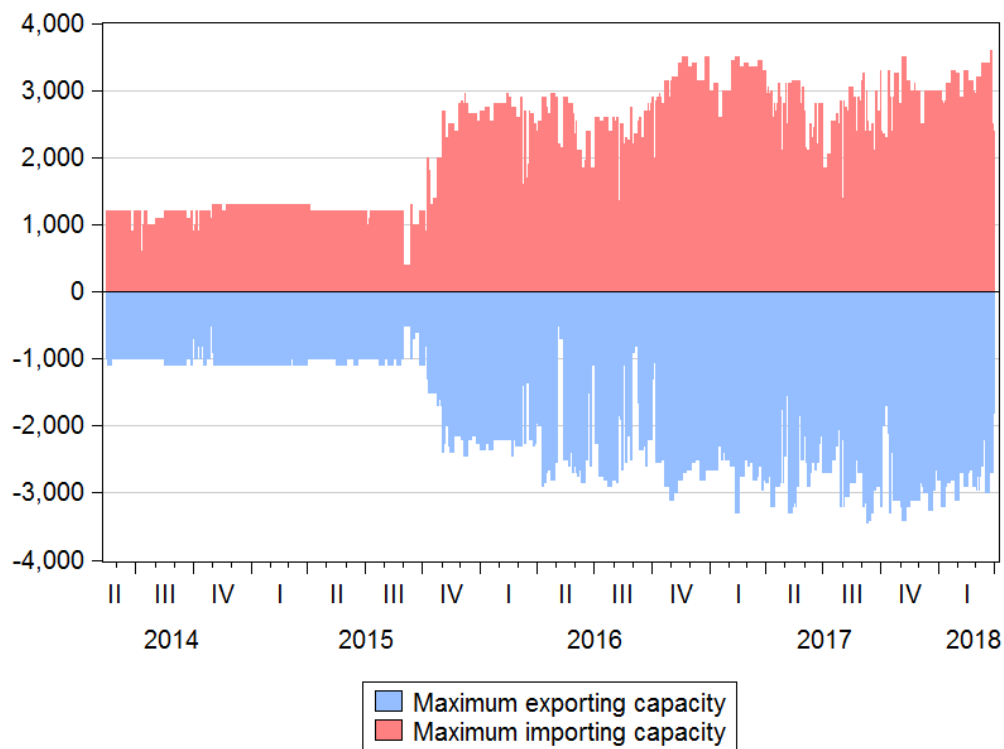


Figure 3.14. Hourly capacity exchange between Spain and France

From figure 3.14 can be observed that the available transmission capacity notably fluctuates, what represent a loss of the system efficiency due to the reduction of the traded energy. It should be noticed that the intervention variable would not be able to account for that capacity variations which represents a system limitation.

4 Econometric Analysis

4.1 Literature review

Electricity represent a characteristic commodity with special properties that makes it difficult to be predicted. Unlike most of the commodities or financial markets, the *Spot market* historically has not been a continuous market, hence it was not possible a continuous trading. In that system, the agents submit their bids for each hour of the next day. This implies that the system operators require information in advance in order to ensure the feasibility of the schedule production and demand. Therefore, system modelling and electricity forecasting represents a key issue for the system optimization [20].

Within that area of study, several methods and techniques have been developed for the modelling and forecast of the electricity demand, price, market integration, integration of renewable. Due to the complexity of electricity system, different techniques has been developed depending of the aimed objective, for instance: statistical models, multi-agent models, fundamental models, reduced-form models, computational intelligence models, etc. The present analysis focuses on the statistical models as is the main projects' object of study [20].

Statistical methods forecast the current price by making a combination of previous values of the electricity price and/or values of exogenous variables. The two most important categories are additive and multiplicative models. The attractiveness of the statistical models is their possible physical interpretation allowing to understand the system behaviour [20].

- **Similar-day and exponential smoothing methods:** It is based on searching for historical data with similar characteristics to the case of analysis, in order to be able to forecast future prices [21]. One of the most common implementation of the similar-day model was established by *Nogales et al.* [22], named as the *naïve model* which consists on specific correlations between different days of the week. The other simple benchmark is the *exponential smoothing* in which the prediction is developed on an exponential weighted average of past observations:

$$\hat{x}_t = s_t = \alpha x_t + (1 - \alpha)s_{t-1} \quad (4.1)$$

- **Regression models:** The general purpose of multiple regression models is to obtain the relationship between several independent variables and the dependent one. Multiple regression is obtained by least squares, hence the model is fitted in order that the sum-of-squares of the residual is minimized. In its classical form, it is assumed a linear relationship between the variables. Despite the large number of alternatives, these models are still among the most popular technique for the electricity price forecasting [20]. Furthermore, these models could include auto-regression approaches,

called regression models, which includes lagged electricity prices as regressors. Such models could be called auto-regressions with exogenous variables. For instance, *Conejo et al.* [23] applied a forecasting technique for the day-ahead price given by the previous day's low frequency and the predicted high frequency component for the PJM. *Koopman et al.* [24] consider general seasonal periodic regression models with ARIMA, ARFIMA and GARCH disturbances for the study of the daily spot prices.

- **AR-type time series models:** The standard time series analysis that takes into account the random nature and time correlation of the underlying phenomena of time correlation is the *Auto-Regressive Moving Average* model. The current value of the price X_t is expressed linearly in terms of its past price values (autoregressive part), and in terms of the previous values of the noise (moving average part). The ARMA modelling assumes that the series under study is weakly stationary, if not a previous transformation is required. For seasonal signals with extended lags, seasonal ARIMA models are adequate in order to account for that events. *Cuaresma et al.* [25] apply variants of AR(1) and general ARMA process to short-term electricity price forecasting in the German EEX market.
- **ARX-type time series models:** Electricity prices are also influenced by various exogenous factors such as generation capacity, load profile and ambient weather conditions. In order to account for the relationship between prices and these fundamental variables, time series analysis with exogenous input variables could be implemented. These models could also be named as *transfer function*, *dynamic regression*, *Box-Tiao*, *intervention* or *interrupted time series* models. Time series models with exogenous variables has been extensively implemented for short-term forecasting. *Nogales et al.* [26] used ARMAX and ARX models for prediction of hourly prices in California and Spain, with a significantly better performance than the ARIMA and ARIMA-E model.
- **Threshold autoregressive models:** These models can be classified in two regime-switching types: those where the regime can be determined by an observable variable and those where the regime is determined by an unobservable latent variable. The most popular member of the first class is the *Threshold AutoRegressive* model, in which is possible also to include exogenous variables [20]. This model has not extensively been applied in the electricity forecast, nevertheless, *Robinson et al.* [27] fits an LSTAR model to prices in the England and Wales wholesale electricity pool.
- **Heteroskedasticity and GARCH-type models:** These models does not assume *homoskedasticity*, hence not constant variance and covariance. The time series can show various forms of non-linear dynamics, with a strong dependence of the variability of the series on its own past. The *AutoRegressive Conditional Heteroskedastic* (ARCH) model of *Engle et al.* [28] was the first formal model which successfully addressed the problem of *heteroskedasticity*. In this model, the conditional variance of the time series is represented by an autoregressive process, named weighted sum of squared preceding observations [20]. Although heteroskedasticity is present in electricity prices, GARCH-type not always achieve better results, only under certain conditions this model is advantageous. *Contreras et al.* [29] studied ARIMA models with GARCH residuals, concluding that ARIMA-GARCH outperforms a generic ARIMA model only when high volatility and price spikes are present.

The performance of the forecasting model does not only depend on the numerical efficiency

of the algorithms employed, but also on the quality of the data analysed and the addition of fundamental factors such as historical demand, consumption, weather forecast or fuel prices. Nevertheless, due to the prevailing seasonality of power markets during normal processes, and non-spiky periods, statistical methods achieve an acceptable result. In the presence of spikes, however, statistical methods perform rather poorly.

Regarding to the analysis of market integration and transmission systems, some statistical models have been developed. *Ciarreta et al.* [30] applied a Multivariate Generalized Autoregressive Conditional Heteroscedastic model to asses the evidence of electricity market integration between Spain, Portugal, Austria, Germany, Switzerland and France between 2007 and 2012. In that case, spillovers and price convergence were used as indicators of market integration. It was detected a dynamic correlation between the pairs of Spain-Portugal, Germany-Austria and Switzerland-Austria. A lack of integration was detected between Spain-France and Germany-France since it was not estimated transmission cross volatility.

Pellini et al. [31] measured the impact of market coupling on the Italian electricity market employing the optimal dispatch model ELFO++. The result concluded that replacing the current explicit auction mechanism with market coupling maximizes the use of the cross-border interconnection leading to high integration levels, hence improving the social surplus. Additionally, the interconnection capacity is a key parameter for the integration of renewable sources. Thus, *Fernandes et al.* [32] analysed the expansion of the interconnection capacity that would be required for the integration of intermittent generation surplus. Hence it was concluded, that in order to be able to achieve that goal, a flexible system is required additionally to an adequate cross-border exchange capacity.

4.2 Model estimation: Equations specifications

In the following section would be introduced the equations applied in order to develop the econometric model of study. The developed analysis carries out an explanatory model for the analysis of a temporal series for the evaluation of Spanish day-ahead market price predicted by explanatory variables. Among the different explanatory variables, the most relevant for the developed analysis is the increase of the interconnection capacity.

4.2.1 Multiple regression models

Multiple linear regression analysis is a process that specifies the relationship between the dependent variable, with the independent explanatory variables. Multiple regression is based on least squares; thus the model is fitted such that the sum-of-squares of the differences between observed and predicted values is minimized. The general formulation is presented in the following expression [20]:

$$y[t] = Qx_t + \epsilon[t] = b_1x_1[t] + \dots + b_kx_k[t] + \epsilon[t] \quad (4.2)$$

Where Q is a $1 \times k$ vector of constant coefficients, $x[t]$ is the $1 \times k$ vector of regressors (some of all may be transformed beforehand), and $\epsilon[t]$ is an error term. The regressors selected are assumed to be correlated with the dependent variable $y[t]$ [20].

4.2.2 Autoregressive (AR) model

The autoregressive model of a random process specifies that the output variable depends linearly on its own previous values and on a stochastic term (white noise), thus the model is in the form of a stochastic difference equation. The process could be represented by the following expression [33]:

$$y[t] = \phi_1 y[t-1] + \phi_2 y[t-2] + \cdots + \phi_p y[t-p] + \epsilon[t] \quad (4.3)$$

or:

$$\phi(B)y[t] = \epsilon[t] \quad (4.4)$$

Where:

$$\phi(B) = 1 - \phi_1 B - \phi_2 B^2 - \cdots - \phi_p B^p \quad (4.5)$$

And B is the back-shift operator $By[t] = y[t-1]$

4.2.3 Moving-Average (MA) model

Equivalently to the AR, the moving average specifies that the output of the variable depends linearly on its own previous values and on an stochastic term (white noise). Together with the AR, the MA is a key component of the more general ARMA and ARIMA models of time series. The MA process is represented in the following expression [34]:

$$y[t] = \epsilon[t] - \theta_1 \epsilon[t-1] - \theta_2 \epsilon[t-2] - \cdots - \theta_q \epsilon[t-q] \quad (4.6)$$

or:

$$y[t] = \theta(B)\epsilon[t] \quad (4.7)$$

Where:

$$\theta(B) = 1 - \theta_1 B - \theta_2 B^2 - \cdots - \theta_q B^q \quad (4.8)$$

4.2.4 ARMA model

The ARMA model is a combination of the AR and MA models to describe a stochastic process. The general expression is presented in the following formula [35]:

$$y[t] - \phi_1 y[t-1] - \cdots - \phi_p y[t-p] = \epsilon[t] - \theta_1 \epsilon[t-1] - \cdots - \theta_q \epsilon[t-q] \quad (4.9)$$

or:

$$\phi(B)y[t] = \theta(B)\epsilon[t] \quad (4.10)$$

thus:

$$y[t] = \frac{\theta(B)}{\phi(B)}\epsilon[t] \quad (4.11)$$

4.2.5 Seasonal autoregressive (SAR) model

Occasionally, simple differencing at lag-1, even repeated many times, is not enough to make the series stationary. Specially, electricity loads or prices could correspond to seasonal signals of periods greater than one which require differencing at longer lags. Such processes are known as seasonal ARIMA (SARIMA) models [20]. The Seasonal autoregressive term (SAR) adds to an existing AR specification a polynomial with a lag of p :

$$1 - \phi_p L^p \quad (4.12)$$

4.2.6 Intervention variable

Deterministic inputs can be used to represent identified events, called *interventions*, which occurrence and timing is assumed to be known. Among the different types of interventions, we will focus on *step* interventions as is implemented in the developed model in order to account for specific events such as the change of interconnection capacity and the unavailability of the French nuclear power stations. Therefore, a *step* intervention represents a permanent change of $Y[t]$ for a defined period [36]:

$$\begin{aligned} X_t &= 0 & t < i \\ X_t &= 1 & t > i \end{aligned} \quad (4.13)$$

The step intervention has a permanent nature reflected in X , being "on" continuously starting at period i and thereafter. Notice that additional conditions could be added in order to for X to be "off" after a period of time in order to account the cessation of an event [36].

4.3 Model Equation output

The model output provides a series of coefficients assessing the impact of the different explanatory variables on the dependent variable. The following coefficients are provided by Eviews:

- **Regression coefficients:** Provides the least squares regression coefficients computed by the standard Ordinary Least Squares (OLS) formula:

$$b = (X'X)^{-1}X'y \quad (4.14)$$

The coefficient measures the marginal contribution of the independent variable to the dependent variable, maintaining all other variables fixed. The C variable of the list of regressors corresponds to the constant coefficient or intercept in the regression that is the base level of the prediction when all the other independent variables are zero. The other coefficients are interpreted as the slope of the relation between the corresponding independent variable and the dependent variable, assuming all other variables do not change [37].

- **Standard Errors:** Reports the estimated standard errors of the coefficient estimates. It measures the statistical reliability of the coefficient estimates. The larger the standard errors, the more statistical noise would be in the estimates.

- **T-Statistics:** Is computed as the ratio of an estimated coefficient to its standard error. It is used to test the hypothesis that a coefficient is equal to zero.
- **Probability:** This probability is also known as the p-value or the marginal significance level. Given a p-value, it indicates if you reject or accept the hypothesis that the true coefficient is zero against a two-sided alternative that it differs from zero.

For the evaluation of the model performance, several statistical indicators provides an estimation of the model behaviour and its data accuracy.

- **R-Squared:** Measures the success of the regression in predicting the values of the dependent variable within the sample. The statistic will equal one if the regression fits perfectly, and zero if it fits no better than the simple mean of the dependent variable. One problem with using R-Squared as a measure of goodness of fit is that it will never decrease as you add more regressors.
- **Adjusted R-Squared:** This statistics penalizes the addition of regressors which do not contribute to the explanatory power of the model. Adjusted R-Squared will never be larger than R-Squared.
- **Sum-Of-Squared Residuals:** Corresponds to the sum of the deviations predicted from actual empirical values of data. It is a measure of the discrepancy between the data and an estimation model. A small RSS indicates a tight fit of the model to the data. It is used as an optimality criterion in parameter selection and model selection.
- **Log Likelihood:** It reports the value of the log likelihood function evaluated at the estimated values of the coefficients.
- **Durbin-Watson Statistic:** It measures the serial correlation in the residuals.

$$d = \frac{\sum_{t=2}^T (e_t - e_{t-1})^2}{\sum_{t=2}^T e_t^2} \quad (4.15)$$

where T is the number of observations. Since d is approximately equal to $2(1 - r)$, where r is the sample autocorrelation of the residuals, $d = 2$ indicates no autocorrelation.

- **Akaike Information Criterion:** Is an estimator of the relative quality of statistical models for a given data set. It is founded on information theory, offering an estimation on the information lost when a given model is used to represent a process that generated the data. Note that l corresponds to the log likelihood.

$$AIC = \frac{-2l}{T} + \frac{2k}{T} \quad (4.16)$$

- **Schwarz Criterion:** It is an alternative to the AIC that imposes a larger penalty for additional coefficients, compared to the Akaike criterion:

$$SC = \frac{-2l}{T} + \frac{k \log T}{T} \quad (4.17)$$

- **Hannan Quinn Criterion:** It is an alternative to Akaike information criterion (AIC), which employs yet another penalty function:

$$HQ = -2\left(\frac{l}{T}\right) + \frac{2k \log(\log(T))}{T} \quad (4.18)$$

- **F-Statistic:** The F-statistic reported in the regression output is from a test of the hypothesis that all of the slope coefficients (excluding the constant, or intercept) in a regression are zero.
- **Variance Inflation Factors:** Are a technique to evaluate the level of collinearity between the regressors in an equation. VIFs show how much of the variance of a coefficient estimate of a regressor has been inflated due to collinearity with the other regressors. They are calculated by the division of the variance of a coefficient estimate by the variance of that coefficient had other regressors not been included in the equation.

Two type of Variance Inflation Factor are calculated by Eviews: centered and uncentered. The centered VIF is the ratio of the variance of the coefficient estimate from the original equation divided by the variance from a coefficient estimate from an equation with only that regressor and a constant. The uncentered VIF is the ratio of the variance of the coefficient estimate from the original equation divided by the variance from a coefficient estimate from an equation with only one regressor (and no constant) [38]. In the analysis of multicollinearity, a $VIF > 10$ indicates a high multicollinearity [39].

4.4 Model description

The current study develops an explanatory model in order to explain the effect of the interconnection capacity increase on the Spanish price. It is developed based on the day-ahead values from the 14/05/2014 to the 31/03/2018. Therefore the this model has not been designed to be used for forecasting purposes.

The data used is the "Programa Diario Base de Casación" PDBC which takes into account the offered generation capacity and demand in the previous day. It should be noticed that the total volume offered in this market is lower than the final consumption as it is excluded the bilateral contracts. It has been used the PDBC instead of the PDBF as the bilateral contracts does not affect the market price, therefore it would introduce noise to the market analysis.

As previously mentioned in section 3.1 the period of study is divided in two different stages separated by the date in which took place the capacity increase between Spain and France (05/10/2015). This new interconnection increased the exchange capacity from 1400 MW up to approximately 2800 MW. The starting point of the analysis is determined by the beginning of the *PCR*, 14/05/2014, moment at which the markets between France and Spain were coupled. The end of the sampled data is the 13/03/2018, which corresponds to the up-to-date values. Additionally, it has been identified a particular event between 01/09/2016 and 01/02/2017, in which a large number of nuclear power stations remained unavailable due to technical reasons. In the following figure is presented the timeline of the analysis:

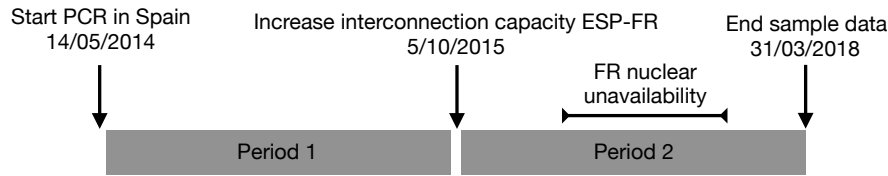


Figure 4.1. Time-line of the period of study

In order to analyse the effect of the capacity increase, it would be developed three different models. These models have been developed based on a previous analysis developed by *Red Eléctrica de España*. In all of them the parameters concerning the generation technologies, Spanish demand and French day-ahead price would remain unaltered. Nevertheless, interconnection capacity increase would be included following different strategies. In the first case, it would be introduced by its simplification as an intervention variable. That means that the analysed event would be evaluated by a dichotomous variable (taking a value of 0 or 1). In the second case, it would be introduced the real importing capacity splitted in two variables (for the first and second period) to account for the capacity increase. In the last case, as the capacity does not influence directly the price but it allows a larger energy exchange, it would be included the exchanged flows between France and Spain during both periods. In the following subsections would be further explained the different analysis.

4.4.1 Model 1: Dichotomous variable

Within the model development, it has been identified different parameters that could influence the day-ahead Spanish price. The first one is the French day-ahead price which directly influences the Spanish price due to the interconnection of both markets. Thus, when the French price increases, they import energy from Spain (assuming lower prices) and increases the price until they converge, otherwise, the markets split. Another relevant parameter is the Spanish demand, which directly influences the market price as it requires more expensive power plants to supply the demand peaks.

Regarding to the different energy sources, it has been included three different explanatory variables. In order to take into account the thermal-based technologies, it has been selected the coal production due to its clear market behaviour previously analysed in section 3.3.1. Thus, its effect is to increase the market price due to its higher variable cost. Renewable technologies (excluding hydro) has been included by the sum of the wind and solar (thermal and photovoltaic). This has been done due to its similar market effect trend to reduce the market price and its inability to manage their production.

Regarding to the hydro generation, it represents a tricky technology due to its different behaviour depending on external variables. Therefore, as previously analysed it could contribute to reduce the market price at high expected inflows, and on the contrary, could increase the price if there are water scarcities. Hence, its production is mainly based on the water availability.

An additional intervention parameter has been introduced in order to take into account the unavailabilities of the nuclear power stations during the last quarter of 2016, which led to

an increase of the market prices in Spain.

As previously mentioned, in this model has been included the increase of the interconnection capacity as a dichotomous variable (taking a value of 0 or 1). Hence, from the start of the operation of the new infrastructure (5/10/2015) the variable would be equal to 1.

Finally, it has been introduced an AR(1) and MA(1) in order to account for the effect of the previous hour price in the actual value. Finally, three seasonal autoregressive terms has been added due to a detected autocorrelation value every 24 hours with two satellite adjacent residual values. This adequacy of these parameters have been established based on the interpretation of the autocorrelation and the partial autocorrelation function. These parameters have been maintained unaltered in the three developed models.

Table 4.1. Results of the econometric model 1

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	30,7396	1,1579	26,5480	0,0000
Price FR (€/MWh)	0,0638	0,0027	23,6372	0,0000
Spanish demand (MW)	0,0017	0,0000	102,6049	0,0000
Coal production (MW)	0,0009	0,0000	24,3886	0,0000
Renewable non-hydro production (MW)	-0,0017	0,0000	-61,8298	0,0000
Hydro reserves (%)	-0,3536	0,0161	-21,9675	0,0000
Capacity increase (Spain-France)	-11,3367	0,4887	-23,1960	0,0000
Unavailabilities of French Nuclear power	4,5865	0,5982	7,6673	0,0000
AR(1)	0,8646	0,0031	276,6788	0,0000
SAR(23)	0,1098	0,0052	21,1177	0,0000
SAR(24)	0,2543	0,0052	48,6732	0,0000
SAR(25)	0,1063	0,0052	20,4663	0,0000
MA(1)	0,1129	0,0061	18,5210	0,0000

From table 4.1 should be taken special attention to coefficients of the explanatory variables. First of all, it should be noticed that the sign indicates if the variable increases the price (positive sign) or decreases it, and the units of each variable. Thus, the only parameters that has a negative sign are the renewable sources, the water reserves and the capacity increase. The remaining variables tend to increase the price with their own increase.

The variable *Hydro reserves* has a large coefficient as its values are in percentage, leading to a larger coefficient compared to the other ones. Nevertheless, it should be paid special attention to the standard error which indicated the reliability of the coefficient. That could be caused, as previously mentioned, to the double effect that it could have to increase or decrease the market price.

From the obtained model, it has been possible to reach a high level of data fitting, with a high *R-squared* and *Adjusted R-squared*. Additionally, the residue could be considered white noise with a mean value close to 0 and could be considered normally distributed.

Table 4.2. Model 1 validation parameters

R-squared	0,977148	Mean dependent var	47,95256
Adjusted R-squared	0,977136	S.D. dependent var	14,1463
S.E. of regression	2,139056	Akaike info criterion	4,359165
Sum squared residue	155.509,6	Schwarz criterion	4,363878
Log likelihood	-74.099,89	Hannan-Quinn criter.	4,360668
F-statistic	80.736,81	Durbin-Watson stat	2,00552
Prob(F-statistic)	0		

In the following table 4.3 are represented the Variance Inflation Factors corresponding to the variables of model 1. As previously mentioned, if the VIF value is larger than 10 indicates high collinearity between the variables. In that case could be observed that the hydro reserves (%) reaches a value of 20, thus it reveals a high collinearity. This issue should be further studied in future analysis to ensure that the variables are not collinear.

Table 4.3. Variance Inflation Factors of Model 1

Variable	Variance Coefficient	Uncentered VIF	Centered VIF
C	1,3407	37,14817	NA
Price FR (\euro /MWh)	7,28E-06	1,436824	1,126288
Spanish demand (MW)	2,90E-10	7,511763	1,336371
Coal production (MW)	1,35E-09	1,927897	1,335708
Renewable non-hydro production (MW)	7,90E-10	2,228558	1,162309
Hydro reserves (%)	0,000259	20,98787	1,583115
Capacity increase	0,238861	4,303142	1,572576
Unavailabilities of French Nuclear power	0,357828	1,212204	1,099666
AR(1)	9,76E-06	1,31349	1,31349
SAR(23)	2,70E-05	1,016763	1,016762
SAR(24)	2,73E-05	1,026657	1,026656
SAR(25)	2,70E-05	1,015333	1,015333
MA(1)	3,72E-05	1,279538	1,279538

Regarding the obtained residue, it can be assumed to be white noise with mean close to zero and normally distributed. Nevertheless, it can be appreciated large spikes in the presented graph due to the inability of the model to fit high volatility phenomena. Nevertheless, the maximum and minimum residue value are 21,71 and -28,25 respectively.

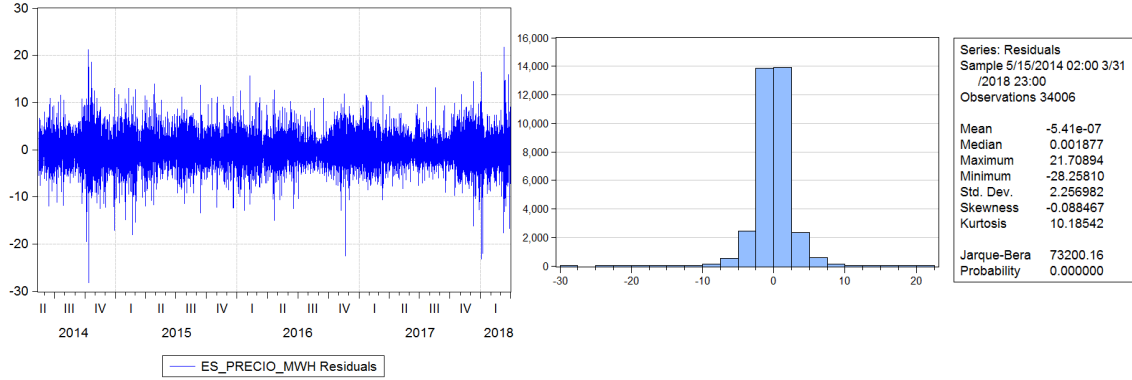


Figure 4.2. Residue plot and histogram of model 1

4.4.2 Model 2: Hourly maximum import capacity

As previously mentioned, in this second approach the effect of the capacity increase has been depicted by the hourly maximum import capacity from France, as Spain is most of the time an importing country. Therefore, the variable has been splitted between both periods in order to extract the effect of the capacity increase on the market. The rest of the variables has been maintained unaltered.

Table 4.4. Results of the econometric model 2

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	17,2051	1,0613	16,2120	0,0000
Price FR (€/MWh)	0,0648	0,0027	23,9445	0,0000
Spanish demand (MW)	0,0017	0,0000	100,5456	0,0000
Coal production (MW)	0,0009	0,0000	25,2676	0,0000
Renewable non-hydro production (MW)	-0,0017	0,0000	-59,1043	0,0000
Hydro reserves (%)	-0,1878	0,0172	-10,9287	0,0000
Maximum available capacity in period 1(MW)	-0,0012	0,0003	-4,4863	0,0000
Maximum available capacity in period 2(MW)	-0,0013	0,0001	-15,4505	0,0000
Unavailabilities of French Nuclear power	3,4837	0,6954	5,0100	0,0000
AR(1)	0,8835	0,0029	300,1939	0,0000
SAR(23)	0,1183	0,0052	22,6721	0,0000
SAR(24)	0,2594	0,0052	49,5272	0,0000
SAR(25)	0,1150	0,0052	22,0891	0,0000
MA(1)	0,1035	0,0060	17,1839	0,0000

From table 4.4 it could be observed lower values for the maximum available capacity compared to the previous case, as in that case the variables are expressed in the actual units (*MW*). Nevertheless, it could be observed that the price reduction effect is slightly larger in the second period, which is in accordance to the previous model. Nevertheless, it does not represent a huge gain. This could be explained as the capacity increase does not influence the market directly, nevertheless, it allows larger energy volume trades.

From table 4.5 could be observed a high model fit with a lower sum of the squared residuals. Additionally, the Durbin-Watson statistic is close to 2, hence it could be considered that there is not serial correlation in the residuals.

Table 4.5. Model 2 validation parameters

R-squared	0,974415	Mean dependent var	47,95256
Adjusted R-squared	0,974405	S.D. dependent var	14,1463
S.E. of regression	2,263196	Akaike info criterion	4,471845
Sum squared resid	174.108,9	Schwarz criterion	4,475317
Log likelihood	-76.020,77	Hannan-Quinn criter.	4,472952
F-statistic	99.582,82	Durbin-Watson stat	2,005699
Prob(F-statistic)	0		

As previously mentioned, Variance Inflation Factors indicated the collinearity between the variables. From the values presented in 4.6 it could be observed that hydro reserves (%) reach a value of 16,44 which is above the threshold of 10 set by [39]. Thus, it indicates the possible existence of collinearity which should be further studied in future models.

Table 4.6. Variance Inflation Factors of Model 2

Variable	Variance Coefficient	Uncentered VIF	Centered VIF
C	1,126271	21,45415	NA
Price FR (€/MWh)	7,33E-06	1,328636	1,113587
Spanish demand (MW)	3,03E-10	5,735809	1,307951
Coal production (MW)	1,40E-09	1,699981	1,277418
Renewable non-hydro production (MW)	8,61E-10	1,93375	1,135007
Hydro reserves (%)	0,000295	16,44356	1,24164
Maximum available capacity in period 1(MW)	6,87E-08	1,380409	1,187107
Maximum available capacity in period 2(MW)	7,39E-09	1,493841	1,141654
Unavailabilities of French Nuclear power	0,483522	1,188695	1,084149
AR(1)	8,66E-06	1,341118	1,341117
SAR(23)	2,72E-05	1,033327	1,033326
SAR(24)	2,74E-05	1,041431	1,04143
SAR(25)	2,71E-05	1,02856	1,028559
MA(1)	3,63E-05	1,246652	1,246652

In this second model, the obtained residues are very similar to the values obtained in model 1. Therefore, it could also be assumed to be white noise with an average value close to zero and normally distributed. Furthermore, similar spikes could be seen in the plot of residuals due to high volatility processes.

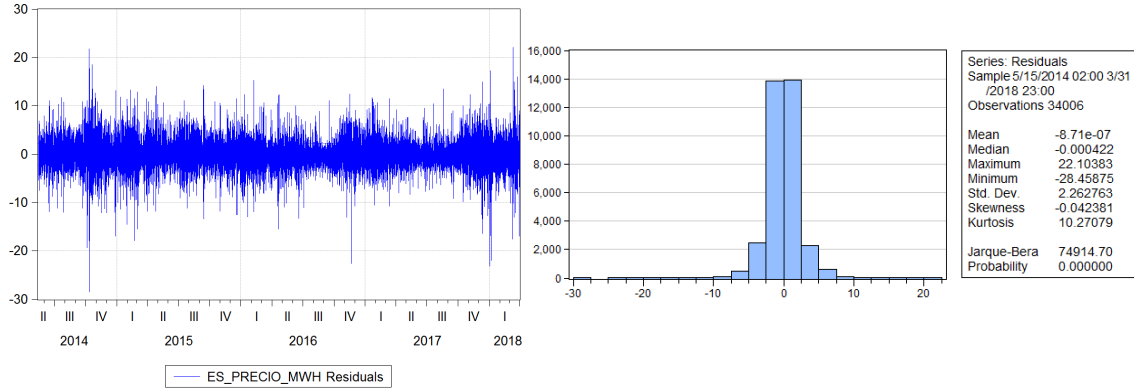


Figure 4.3. Residue plot and histogram of model 2

4.4.3 Model 3: Hourly exchange flows

In the last model approach, instead of the hourly maximum import capacity, it has been included the actual exchanged flows with France in both periods. The aim of this variable is to take into account the increase in the exchanged flows as a consequence of the capacity increase. Therefore, this parameter reflects the the actual use of the interconnection and the system operation.

Table 4.7. Results of the econometric model 3

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	14,5803	1,1375	12,8177	0,0000
Price FR (€/MWh)	0,0420	0,0026	16,0937	0,0000
Spanish demand (MW)	0,0020	0,0000	113,9539	0,0000
Coal production (MW)	0,0006	0,0000	17,1034	0,0000
Renewable non-hydro production (MW)	-0,0020	0,0000	-66,8999	0,0000
Hydro reserves (%)	-0,1947	0,0188	-10,3296	0,0000
Exchanged energy with France in period 1 (MW)	-0,0012	0,0001	-16,3931	0,0000
Exchanged energy with France in period 2 (MW)	-0,0015	0,0000	-55,8521	0,0000
Unavailabilities of French Nuclear power	1,9792	0,7783	2,5431	0,0110
AR(1)	0,9049	0,0026	346,1142	0,0000
SAR(23)	0,1180	0,0052	22,7173	0,0000
SAR(24)	0,2662	0,0052	50,9777	0,0000
SAR(25)	0,1153	0,0052	22,2433	0,0000
MA(1)	0,0977	0,0059	16,5523	0,0000

From table 4.7 it could be observed that the variable *Exchanged energy with France* has a larger impact in the second period compared to the first one. In that case, the coefficient variation is larger than in mdoel 2, nevertheless it is still a moderate change. Therefore, the coefficients indicate that the interconnection has a general price reduction effect, with a larger impact since the capacity has been increased.

From table 4.8 could be observed a high R-squared and adjusted R-squared value, which

indicates a good data fit. Additionally, the sum of the squared residuals is lower than the previous case. The remaining statistical parameters indicates a correct model adjustment.

Table 4.8. Model 3 validation parameters

R-squared	0,976508	Mean dependent var	47,95256
Adjusted R-squared	0,976499	S.D. dependent var	14,1463
S.E. of regression	2,168654	Akaike info criterion	4,386502
Sum squared resid	159.866,4	Schwarz criterion	4,389974
Log likelihood	-74.569,69	Hannan-Quinn criter.	4,387609
F-statistic	108.687,6	Durbin-Watson stat	2,004341
Prob(F-statistic)	0		

The Variance Inflation Factors indicates the level of collinearity between the regressors in the equation. In table 4.9 are presented the VIFs for the third evaluated approach, from which can be observed a high collinearity of the variable hydro reserves (%), with a value of 14,11, which is higher than the threshold equal to 10 set by [39]. Therefore, this high collinearity factor should be further studied in future analysis.

Table 4.9. Variance Inflation Factors of Model 3

Variable	Variance Coefficient	Uncentered VIF	Centered VIF
C	1,293929	17,59121	NA
Price FR (\euro /MWh)	6,80E-06	1,262404	1,119981
Spanish demand (MW)	2,97E-10	4,448519	1,346449
Coal production (MW)	1,36E-09	1,559177	1,265042
Renewable non-hydro production (MW)	8,86E-10	1,73742	1,151002
Hydro reserves (%)	0,000355	14,11733	1,06792
Energy exch. with FR in period 1 (MW)	5,66E-09	1,032197	1,027986
Energy exch. with FR in period 1 (MW)	7,15E-10	1,07641	1,070731
Unavailabilities of French Nuclear power	0,60572	1,156164	1,062693
AR(1)	6,84E-06	1,282176	1,282176
SAR(23)	2,70E-05	1,030323	1,030322
SAR(24)	2,73E-05	1,04066	1,040659
SAR(25)	2,69E-05	1,025131	1,02513
MA(1)	3,48E-05	1,194455	1,194455

In this third model, the obtained residuals could be assumed to be white noise with an average value close to zero and normal distribution. This residual patten is similar to the values obtained in the previous two approaches, thus it can be concluded a similar model behaviour in all three cases. As previously mentioned, similar spikes could be observed in the plot of residuals due to high volatility processes that the econometric model is not able to reproduce.

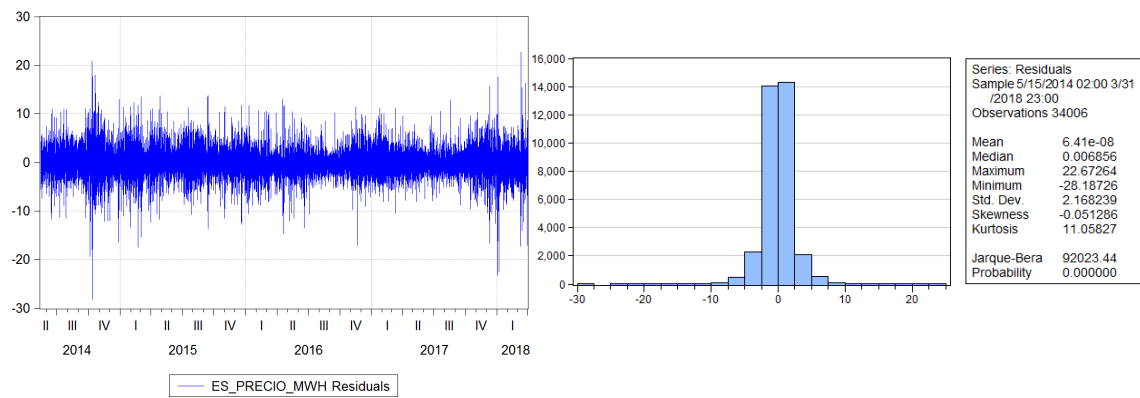


Figure 4.4. Residue plot and histogram of model 3

5 Results and discussion

The analysis of the market evolution and cross-border interconnections has provided information about the dynamics and behaviour of the electric system. The results are going to be classified in the three section according to the different parts of the study.

5.0.1 Cross-border interconnections

The cross-border interconnection effect has been evaluated by means of its influence in the cross-border trades and the market coupling with the neighbouring countries. Regarding to the exchange behaviour, it has been observed a clear difference between the cross-border flows before and after the application of the PCR. Before that initiative, the cross-border flows were not obeying the market rules. After the PCR, it could be observed that the flows were exclusively determined by the price differences between both regions, leading to a better system operation.

Regarding the market coupling, an increase of the percentage of hours in which the markets were coupled, increasing from 10,08% to 26,36% has been observed. That increase represents a step forward to the achievement of a single European market and a pan-European super-grid. Nevertheless, the cross-border interconnection capacity still represents a bottleneck for the market coupling.

The analysis of the cross-border congestions should be differentiated according to the direction of the flow. In the importing direction, it has been identified a decrease from 79,13% to 59,95% of the number of hours in which the lines are congested. This reduction could have a large impact in the Spanish market behaviour due to its importing nature. Regarding the congestions in the exporting direction, it has been increased from 10,79% to 13,69% of the hours probably due to the issues occurred in the third quarter of 2016 in which many French nuclear power plants were unavailable.

Although the low interconnection capacity with France, the new interconnection have enabled to increase the energy traded between both countries contributing the achievement of the European recommendations for an integrated network and a higher market coupling rate.

5.0.2 Marker impact

Due to the geographical location and orography of Spain, its interconnection with central Europe represents a challenge. Compared to European countries, Spain, as well as the peripheral countries, has higher electricity prices in the range of 10-15 €/MWh when compared to Germany or the Nordic countries. The electricity price gap between France and Spain is lower due to its direct physical interconnection. Hereafter are presented the price differences between Spain and France before and after the introduction of the new cross-border line.

Spanish day-ahead price

It has been observed a price decrease in the Spanish day-ahead market price of 3,54 €/MWh after the increase of the exchange capacity. This price reduction is partly due to the possibility to import energy from France at a lower cost.

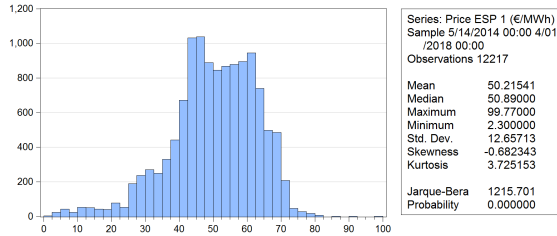


Figure 5.1. Spanish day-ahead price during the first period

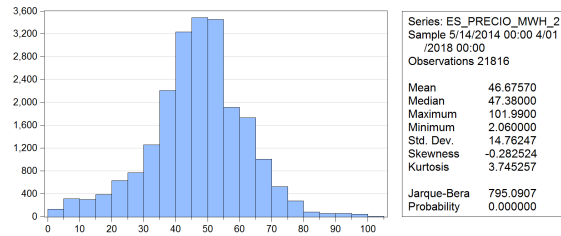


Figure 5.2. Spanish day-ahead price during the second period

French day-ahead price

The French day-ahead price has increased from 36,07 €/MWh in the first period to 41,018 €/MWh in the second one. That price increase could be mainly motivated due to the unavailability of many nuclear power stations, which lead the French prices to reach a maximum price of 283,36 €/MWh in the third quarter of 2016. This price increase could have partially neutralized the price reduction in Spain due to the transmission of electricity from Spain to France during that period. Nevertheless, the average price during both periods is lower than the corresponding average prices.

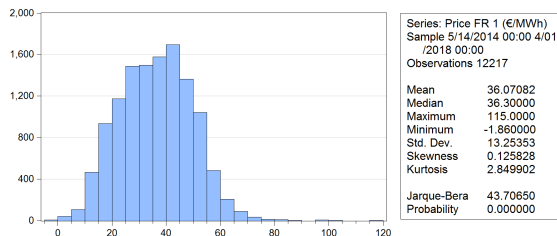


Figure 5.3. French day-ahead price during the first period

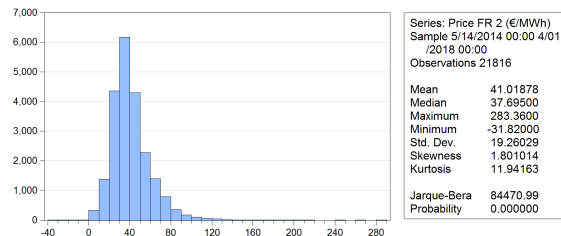


Figure 5.4. French day-ahead price during the second period

Price gap

It has been presented in the following figure the price gap between Spain and France for both periods. It could be observed that the average price gap has been reduced from 5,08 €/MWh in the first period to 3,62 €/MWh in the second one. As previously mentioned, the increase of the exchange capacity may have contributed to the reduction of the price gap as corroborated by the increase of the market coupling.

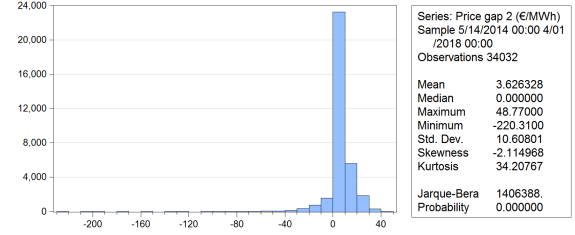
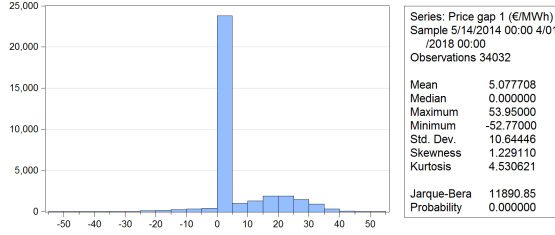


Figure 5.5. Price gap during the first period **Figure 5.6.** Price gap during the second period

Nevertheless, the average price gap calculated in monthly basis depicts larger price gaps. Therefore, in table 5.1 are calculated the average prices Spanish and French prices in monthly basis. In that case, the price difference is decreased from 14,1 €/MWh down to 5,6 €/MWh. Additionally, the maximum monthly price difference has been reduced from 19,6 €/MWh to 8,5 €/MWh. The large observed difference between the hourly prices and monthly values could be due to the neutralization of the positive and negative values.

Table 5.1. Monthly average price gap

	Average Spanish price (€/MWh)	Average French price (€/MWh)	Average price gap ESP-FR(€/MWh)	Maximum price gap (€/MWh)
Period 1 (14/05/2014 to 5/10/2015)	49,96	35,87	14,08	19,57
Period 2 (5/10/2015 to 31/03/2018)	46,69	41,13	5,56	8,50

5.0.3 Model results

By the development of the different econometric models, it has been analysed the effect of the main parameters affecting the day-ahead Spanish price. Especial focused has been paid to the analysis of the impact of the interconnection increase in the Spanish price.

Throughout the models, it could be concluded that exists a positive effect in the price reduction in the Spanish day-ahead price due to the higher transaction volumes of energy between Spain and France. Additionally, a clear market price increase produced by the unavailability of the French nuclear power stations has been observed. Regarding the generation sources, the price rising effect of the traditional fossil fuel power plants and especially the coal technology has been noticed. In contrast, renewable sources clearly reduce the market price as quantified in the different models. From the different generating technologies, hydro power has not been possible to determine its effect on the price due to its dual behaviour according to the water scarcity or surplus. In has been achieve a high-level data fit (over 97%) in all three models with a reduced residue. In the following figure 5.7 is presented the actual price values, the fitted model and residues only of *model 3* (in order to avoid repetition due to the similarity of the results).

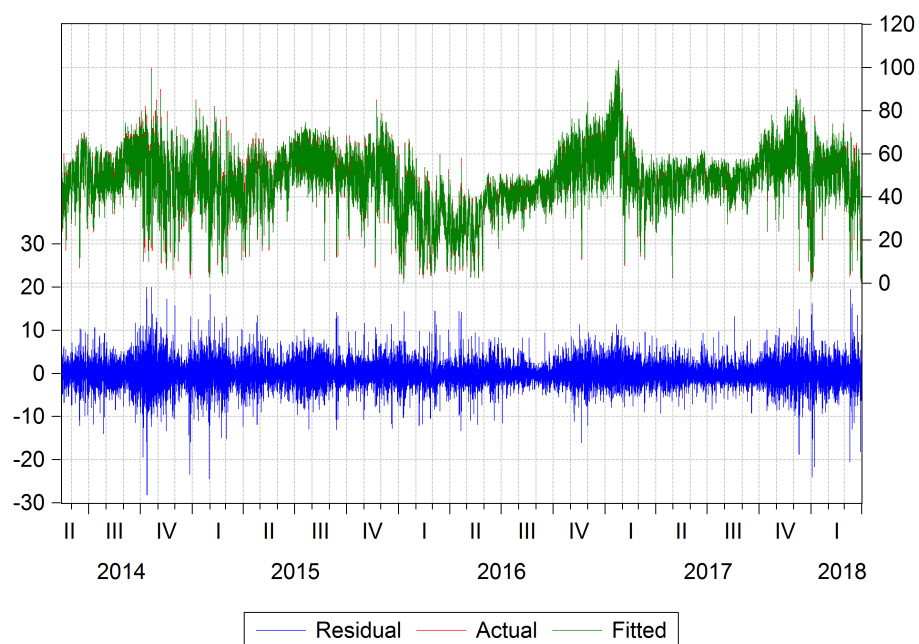


Figure 5.7. Fitted, actual and residue values of model 3

6 Conclusions

The European Union aims to achieve a super-grid at a pan-European scale to set the infrastructure for a decarbonized electric system with a fair price for consumers, and maintaining the system reliability. The actual network infrastructure requires upgrades in order to face the upcoming challenges imposed by the introduction of new generation sources and consumption patterns. Therefore, system flexibility and security of supply has become essential for the present and future network.

Based on the results depicted by the econometric models, it has been concluded that the new interconnection "Santa Llogaia-Baixas" has enabled an increase in the market coupling between France and Spain and reduced the number of hours in which the cross-border lines are congested. Therefore, between both periods, it has been observed an increase from 10,08% to 26,36% in which both markets are coupled.

The congestion periods in the importing direction has been reduced from 79,13% down to 59,95%. On the contrary, the congestions in the exporting direction has increased from 10,79% to 13,69% due to the unavailability of several nuclear power stations during 2016. Regarding to the market price, it has been observed a reduction in the Spanish day-ahead price of 3,54 €/MWh in hourly basis.

Another benefit provided by a larger interconnection capacity has been the increase of the system reliability and security of supply. This fact has been observed during the event occurred in 2016 in which many nuclear power stations in France were unavailable due to technical reasons. During that period, Spain became an exporter, supplying energy to France as the electricity price in this region was higher.

Taking everything into account, cross-border interconnections represent a key infrastructure for the achievement of a pan-European super-grid to enable the development and implementation of renewable sources to reach a decarbonized network.

7 Future work

Throughout the development of this thesis, multiple ideas for further analysis have been found. Due to the limited time frame of this thesis, it has not been possible to investigate all the different options that could yield interesting results. This chapter presents an overview about the possibilities for future work that could be implemented in order to extend and improve the findings.

In the current developed analysis it has not been possible to include data previous to the introduction of the PCR, due to the change in the market behaviour. Therefore, some long period phenomena could not be fully reflected in the conducted model. It would be recommended to develop a model able to include this data for a better system modelling.

Additionally, it would be interesting to analyse other modelling techniques able to reflect more accurately the high volatility of the electricity price. Therefore, it would be recommended to further study the GARCH model, as would be suitable to assess data with large fluctuations.

Finally, an interesting study would be to develop a forecasting model based on the presented historical data, in order to assess the impact of future interconnections in the market price. Therefore, it could be predicted the required interconnection capacity to lower down the average price gap to an optimum value.

Bibliography

- [1] United Nations. Paris agreement, 2015.
- [2] Commission Expert Group. Towards a sustainable and integrated europe, report of the commission expert group on electricity interconnection targets, 2017.
- [3] Red Eléctrica de España, Department of Communication and Corporate Responsibility. Electricity interconnections: a step forward towards a single integrated european energy market, September 2012.
- [4] European Commission, Directorate-General for Energy, Market Observatory for Energy. Quarterly report on european electricity markets, 2015.
- [5] Agency for the cooperation of Energy regulators. Recommendation of the Agency for the cooperation of Energy regulators, On the Common Capacity Calculation and Redispatching Countertrading Cost Sharing Methodologies, 11 November 2016. No 02/2016.
- [6] E3MLab & IIASA. Technical report on member state results of the euco policy scenarios. Technical report, 2017.
- [7] European Network of transmission System Operators for Electricity (ENTSO-E). TYNDP 2016 Scenario Development Report, 2015. - Final after public consultation -.
- [8] Operador del Mercado Ibérico de Energía - Polo Español. Price coupling of regions, what is PCR. Online. Retrieved May 15, 2018.
- [9] ENTSO-E. COMMISSION REGULATION (EU) 2016/1719 of 26 September 2016 establishing a guideline on forward capacity allocation, 2016.
- [10] Agency for the Cooperation of Energy Regulators and the Council of European Energy Regulators. Annual Report on the Results of Monitoring the Internal Electricity and Gas Markets in 2016. Technical report, ACER/CEER, 2016.
- [11] ENTSO-E Guideline for Cost Benefit Analysis of Grid Development Projects, Version for ACER official opinion. Technical report, ENTSO-E, 2016.
- [12] Santos José Díaz Pastor. Análisis del impacto de la congestión en las redes de transmisión Eléctrica y posibles soluciones. Aplicación al caso de España y Alemania . Master's thesis, UPM, 2018.
- [13] MIBEL Regulatory Council. Long-Term joint management mechanism for the Spain-Portugal interconnection, May 2010.
- [14] Department of access to the information of the electric system Red Eléctrica de España. Unpublished, 2018.

- [15] Red Eléctrica de España. Interconexión eléctrica España-Francia, por el golfo de Bizkaia, 2017.
- [16] Joint Term Management Mechanism for the Spanish-Portuguese interconnection Work done by the Board of Regulators of MIBEL. Technical report, May 2010.
- [17] *Circular 2/2014, de 12 de marzo, de la Comisión Nacional de los Mercados y la Competencia, por la que se establece la metodología relativa al acceso a las infraestructuras transfronterizas, incluidos los procedimientos para asignar capacidad y gestionar la congestión, así como la metodología relativa a la prestación de servicios de equilibrio entre sistemas gestionados por distintos operadores del sistema.* Retrieved May 5, 2018.
- [18] Agency for the Cooperation of Energy Regulators. Harmonised allocation rules for long-term transmission rights in accordance with article 51 of commission regulation (eu) 2016/1719 of 26 september 2016 establishing a guideline on forward capacity allocation. Technical report, 2016.
- [19] ENTSO-E, ACER and European Commission, Guideline Capacity Allocation and Congestion Management, 2015.
- [20] Rafal Weron. Electricity price forecasting: A review of the state-of-the-art with a look into the future. *International Journal of Forecasting*, 30:1030–1081, 2014.
- [21] Shahidehpour, M., Yamin, H., & Li, Z. *Market operations in electric power systems: forecasting, scheduling, and risk managemen.* Wiley, 2002.
- [22] Nogales, F. J., Contreras, J., Conejo, A. J., & Espinola, R. Forecasting next-day electricity prices by time series models. *IEEE Transactions on Power Systems*, 17, 342–348, 2002.
- [23] Conejo, A. J., Contreras, J., Espinola, R., & Plazas, M. A. Forecasting electricity prices for a day-ahead pool-based electric energy market. *International Journal of Forecasting*, 21(3), 435–46, 2005.
- [24] Koopman, S. J., Ooms, M., & Carnero, M. A. Periodic seasonal reg- ARFIMA-GARCH models for daily electricity spot prices. *Journal of the American Statistical Association*, 102(477), 16–27, 2007.
- [25] Cuaresma, J. C., Hlouskova, J., Kossmeier, S. and Obersteiner, M. Forecasting electricity spot prices using linear univariate time-series models. *Applied Energy*, 77, 87–106, 2004.
- [26] Nogales, F. J., Contreras, J., Conejo, A. J., and Espinola, R. Forecasting next-day electricity prices by time series models. *IEEE Transactions on Power Systems*, 17, 342–348, 2002.
- [27] Robinson, T. A. Electricity pool prices: a case study in nonlinear time-series modelling. *Applied Economics*, 32(5), 527–532, 2000.
- [28] Engle, R. F. Autoregressive conditional heteroscedasticity with estimates of the variance of United Kingdom inflation. *Econometrica*, 50, 987–1007, 1982.

- [29] Contreras J. van Akkeren M. & Garcia J. B Garcia, R. C. A GARCH forecasting model to predict day-ahead electricity prices. *IEEE Transactions on Power Systems*, 20(2), 867–874, 2005.
- [30] A. Ciarreta, A. Zarraga. Analysis of Mean Volatility Price Transmission in the MIBEL and EPEX Electricity Spot Markets. *The Energy Journal*, Vol. 36, No 4, 2015.
- [31] E. Pellini. Measuring the impact of market coupling on the Italian electricity market. *Energy Policy* 48, 322–333, 2012.
- [32] C. Fernandes, P. Frías, L. Olmos. Expanding interconnection capacity to integrate intermittent generation in the Iberian Peninsula. *IET Renewable Power Generation*, 7:45–54, 2012.
- [33] G. Udny Yule. On a method of investigating periodicities disturbed series, with special reference to wolfer’s sunspot numbers. *Philosophical Transactions of the Royal Society of London. Series A, Containing Papers of a Mathematical or Physical Character*, Volume 226, pp. 267-298, 1927.
- [34] G. Udny Yule. On the time-correlation problem, with especial reference to the variate-difference correlation method. *Journal of the Royal Statistical Society Vol. 84, No. 4*, pp. 497-537, 1921.
- [35] Herman Wold. *A Study In The Analysis Of Stationary Time Series*. 1938.
- [36] Alan Pankratz. *Forecasting with Dynamic Regression Models*. JOHN WILEY & SONS INC., 1991.
- [37] User’s guide : Basic single equation analysis : Basic regression analysis : Equation output, 2017.
- [38] User’s guide : Basic single equation analysis : Specification and diagnostic tests : Coefficient diagnostics, 2017.
- [39] Nachtsheim C. J Neter J Kutner, M. H. *Applied Linear Regression Models (4th edition)*. McGraw-Hill Irwin, 2004.

List of Figures

1.1	The role of international connections [3]	1
1.2	Comparisons of the European benchmark and the monthly baseload prices in regional electricity markets [4]	3
1.3	Evolution of the lowest and the highest regional wholesale electricity prices in the EU and the relative standard deviation of the regional prices [4]	4
2.1	Member States by interconnection level as measured in relation to the peak load in vision 3 (left map) and vision 4 (right map) [2]	12

2.2	Member States by interconnection level as measured in relation to the installed renewable generation capacity in vision 3 (left map) and vision 4 (right map) [2]	13
2.3	Price Coupling of Regions initiative	14
2.4	Average electricity wholesale day-ahead prices – 2016 (euros/MWh) [10]	15
2.5	Day-ahead price convergence in Europe by region (% of hours) [10]	16
2.6	Level of efficiency in the use of interconnectors in Europe (% use of available commercial capacity in the <i>right economic direction</i>) in 2016 [10]	17
2.7	Benefits due to exchange capacity increase between two bidding areas [11]	17
2.8	Market effect in the importing and exporting country [11]	19
2.9	Evolution of the installed capacity in the Spanish peninsula [14]	20
2.10	Evolution of the electricity generation in the Spanish peninsula [14]	21
2.11	Spanish cross-border interconnections [15]	22
2.12	IPE and IFE interconnection scheme [14]	23
3.1	Time-line of the period of study	25
3.2	Relation between Spanish electricity demand and day-ahead market price	26
3.3	Generation mix of the sampled period	27
3.4	Thermal-based generation mix of the sampled period	28
3.5	Thermal-based technology production as function of the day-ahead price	29
3.6	Renewable-based generation mix of the sampled period	30
3.7	Renewable-based technology production as function of the day-ahead price	31
3.8	Hydro power production as function of the day-ahead price	32
3.9	Hydro reserves as function of the day-ahead price	33
3.10	Market coupling and cross-border congestions between Spain and France	34
3.11	Cross border flows between Spain and France	35
3.12	Energy imports and exports between France and Spain	36
3.13	Monthly DA prices in Core (CWE) and the frequency of full price convergence – 2014–2016 (€/MWh and % of hours) [10]	37
3.14	Hourly capacity exchange between Spain and France	38
4.1	Time-line of the period of study	46
4.2	Residue plot and histogram of model 1	49
4.3	Residue plot and histogram of model 2	51
4.4	Residue plot and histogram of model 3	53
5.1	Spanish day-ahead price during the first period	56
5.2	Spanish day-ahead price during the second period	56
5.3	French day-ahead price during the first period	56
5.4	French day-ahead price during the second period	56
5.5	Price gap during the first period	57
5.6	Price gap during the second period	57
5.7	Fitted, actual and residue values of model 3	58

List of Tables

2.1	Spanish commercial cross-border exchange capacity	22
3.1	Cross-border congestion between Spain and France	34
4.1	Results of the econometric model 1	47
4.2	Model 1 validation parameters	48
4.3	Variance Inflation Factors of Model 1	48
4.4	Results of the econometric model 2	49
4.5	Model 2 validation parameters	50
4.6	Variance Inflation Factors of Model 2	50
4.7	Results of the econometric model 3	51
4.8	Model 3 validation parameters	52
4.9	Variance Inflation Factors of Model 3	52
5.1	Monthly average price gap	57