Nuno Miguel dos Santos Carvalho Figueiredo

ELECTRICITY MARKET INTEGRATION AND SPOT PRICE CONVERGENCE IN A CONTEXT OF HIGH PENETRATION OF RENEWABLES

PhD Thesis in Sustainable Energy Systems supervised by Professor Patrícia Pereira da Silva,
submitted to the Faculty of Sciences and Technology of the University of Coimbra

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ENERGY FOR SUSTAINABILITY
SUSTAINABLE ENERGY SYSTEMS
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This thesis is dedicated to my wife, Anabela, my son, Hugo, and my daughter,
Teresa, who encourage me to chase my dreams.

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Abstract

The interaction between the large-scale deployment of Renewable Energy Sources Electricity (RES-E) and spot electricity markets has sharply increased in the last decade. The high penetration of RES-E, which is now being achieved in some world regions, associated with the integration of electricity markets, creates new challenges requiring detailed study. The literature is scarce in addressing these issues simultaneously. Appropriate modelling can be developed to allow the evaluation of the key determinants of electricity market integration, considering the penetration of RES-E, by including adequate exogenous variables. The objective of this research is, therefore, to assess the influence of high penetration of RES-E on the level of electricity market integration. The spot electricity market price behaviour and the cost allocation mechanism of interconnections, through implicit auctioning, will be appraised. With this research we aim to provide robust quantitative analysis to stakeholders in both the public and private sectors, helping them to understand the wider picture. Statistical modelling is developed taking into account the objectives proposed. Vector Autoregressive (VAR) models or Vector Error Correction Models (VECM), depending on the analysis objectives, are considered. Additionally, non-parametric models are herein applied for the first time to our knowledge, in order to capture the level of price convergence, within already integrated electricity markets. Several exogenous variables are taken into account to express the behaviour of renewable generation and related influence on spot electricity markets. Results from the estimated models demonstrate a good integration level between the Portuguese and Spanish spot electricity markets. However, this is not the case between the Spanish and French spot electricity markets. The central west European spot electricity markets are found to be integrated at some level. Furthermore, smoothing of responses to innovations are also found after the introduction of market coupling mechanism in Germany. The high level RES-E generation, or moreover, the low marginal cost generation technologies are proven to have a decreasing effect on spot electricity prices. Additionally, this low marginal cost generation has an effect on market integration by increasing the probability of spot price divergence, or market splitting, as determined between both Iberian spot electricity markets. However, this behaviour can also be dependent of several other determinants, such as, the relative spot electricity market size, the available interconnections between bidding areas and the electricity generation mix.

Keywords: Electricity Market Integration, Electricity Price Convergence, Renewables, Non-parametric models

Resumo

A interacção entre o desenvolvimento de projetos com base em fontes de energias renováveis e o objetivo de interligar os mercados de electricidade europeus aumentou significativamente na década passada. A elevada e rápida penetração de electricidade gerada com base em energias renováveis atingida presentemente em algumas regiões do globo, associada à integração dos diversos mercados de electricidade, coloca novos desafios que carecem de estudo detalhado. A literatura tem sido escassa no que diz respeito ao tratamento destes problemas em simultâneo e de modo sistémico. Para possibilitar a avaliação dos principais determinantes da integração de tais mercados, atendendo à elevada penetração de electricidade gerada com base em energias renováveis, foram desenvolvidos modelos através da inclusão de apropriadas variáveis exógenas. O objectivo desta investigação é, na sua essência, propor novos modelos de modo a melhor aferir a influência da elevada penetração de electricidade gerada com base em energias renováveis no nível de integração dos mercados de electricidade. O comportamento dos preços do mercado grossista de electricidade e o mecanismo de alocação de custos das interligações através de leilão implícito será, por conseguinte, avaliado. Esta tese encontra-se delineada de modo a fornecer contribuições significativas a diversos agentes de decisão no âmbito dos mercados de electricidade Europeus atravessando processos de reestruturação similares. Os modelos estatísticos desenvolvidos tiveram em conta o tipo de dados adquiridos e os objectivos propostos. Foram considerados modelos VAR (Vectores Auto-regressivos) ou VECM (Modelo de Vector com Correção de Erros), dependendo dos objetivos específicos da análise em cada fase do projecto. Adicionalmente, modelos não paramétricos, nunca utilizados em estudos prévios, foram aplicados na análise do nível de convergência dos preços de mercados de electricidade, já considerados integrados. Variáveis exógenas foram incluídas de modo a expressar o comportamento da electricidade gerada com base em energias renováveis e correspondente influência na convergência de preços dos diversos mercados de electricidade. Os resultados dos diversos modelos estimados mostraram um bom nível de integração entre os mercados grossistas de electricidade Português e Espanhol. No entanto, não foram encontradas evidências que demonstrassem integração entre os mercados de electricidade Espanhol e Francês. Os mercados de electricidade da Europa central também demonstraram ter algum nível de integração, e adicionalmente, a inclusão do mercado eléctrico Alemão no mecanismo de acoplamento de mercados, suavizou as respostas a um eventual choque no mercado. A elevada penetração de renováveis na geração de electricidade, ou mais correctamente, a geração de electricidade com baixo custo marginal, foi comprovada ter um efeito decrescente no preço de electricidade. Este tipo de geração de electricidade foi demonstrado como tendo um efeito na integração de mercados eléctricos adjacentes, através do aumento da probabilidade da divergência de preços, tal como no mercado Ibérico. No entanto, foi também comprovado que este comportamento pode depender de vários outros factores, tais como, o tamanho relativo dos mercados, a capacidade de interligação disponível com os diversos mercados adjacentes e o ”mix” tecnológico de geração de electricidade.

List of Abbreviations and Acronyms

ACER Agency for the Cooperation of Energy Regulators.

ADF Augmented Dickey-Fuller.

AIC Akaike Information Criterion.

APX Amsterdam Power Exchange.

ATC Available Transfer Capacity.

BIC Schwarz Bayesian criterion.

BPX Belpex.

CAES Compressed Air Energy Storage.

CCGT Combined Cycle Gas Turbines.

CDD Cooling Degree-days.

CDF Cumulative Distribution Function.

CHP Combined Heat and Power.

CRE Commission de Régulation de L'énergie.

CWE Central-West European.

DE Germany.

DK1 West Denmark.

DK2 East Denmark.

EDF Électricité de France.

EDP Eletricidade de Portugal.

EEX European Energy Exchange.

ENTSO European Network of Transmission System Operators.

EPEX European Power Exchange.

ERGEG European Regulators Group for Electricity and Gas.

ERSE Entidade Reguladora dos Serviços Energéticos.

EU European Union.

EU ETS European Union Emissions Trading Scheme.

GARCH Generalized Autoregression Conditional Heteroskedasticity.

GHG Greenhouse Gas.

GME Gestore dei Servizi Energetici.

HDD Heating Degree-days.

HQC Hannan-Quinn criterion.

HV High Voltage.

IEA International Energy Agency.

IEM Internal Electricity Market.

ILR Institut Luxembourgeois de Régulation.

IRF Impulse-response Functions.

KPSS Kwiatkowski–Phillips–Schmidt–Shin.

LNG Liquefied Natural Gas.

LPX Leipzig Power Exchange.

MGARCH Multivariate Generalized Autoregression Conditional Heteroskedasticity.

MIBEL Mercado Ibérico de Eletricidade.

NEM Australian National Electricity Market.

NO2 Norway bidding area 2.

NREL National Renewable Energy Laboratory.

NTC Net Transfer Capacity.

OLS Ordinary Least Squares.

OMIE Operador do Mercado Ibérico de Eletricidade.

PCA Principal Component Analysis.

PCR Price Coupling of Regions.

PDF Probability Density Function.

PP Phillips-Perron.

PWNX Powernext.

R&D Research and Development.

REE Red Eléctrica de España.

REM Regional Electricity Market.

REN Redes Energéticas Nacionais.

RES Renewable Energy Sources.

RES-E Renewable Energy Sources Electricity.

RTE Réseaux de Transport d'Électricité.

SE3 Sweden bidding area 3.

SE4 Sweden bidding area 4.

SWE South-west European.

TLC Trilateral market coupling.

TSO Transmission System Operator.

UK United Kingdom.

USA United States of America.

VAR Vector Autoregressive.

VARX Vector Autoregressive with eXogenous variables.

VECM Vector Error Correction Model.

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Chapter 1

Introduction

Electricity can be viewed as a commodity, however with special characteristics due to its physical behaviour (Lucia & Schwartz, 2002)[1]. The need for real–time balancing of supply and demand derives from the absence of effective storage mechanisms for the electricity, therefore it needs to be produced and consumed simultaneously (Eydeland & Wolyniec, 2003). Additionally, physical restrictions in the transmission system can cause local constraints (Figueiredo & Silva, 2012).

Electricity markets involve three sets of activities, the main segments of the sector's value chain: production, transport and commercialization (Silva, 2007). Production of electricity can be based on several forms of technology[2], having different cost structures (capital *vs* variable costs). After being produced in a power generation facility, electricity has to be transported to consumption centres. This is done through electricity transport systems, comprised normally of a High Voltage Transmission system and local Medium/Low Voltage distribution systems. The Commercialization activity is carried out by buying (to producers) and selling (to consumers) block volumes of electricity (B. Murray, 2009).

Electricity market reform was firstly introduced in 1987 in Chile. Since then, electricity sector restructuring and markets were adopted in several regions of the world like the United States, Australia and Europe (Sioshansi, 2008). The usual

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[1] Citations throughout this thesis were made using the style APA 6th edition (American Psychological Association, 2010)

[2] Conventional power generation in the form of nuclear, coal fired, natural gas and hydro; Renewable power generation in the form of wind, solar, mini-hydro, tide, etc...

public electricity sectors were unbundled and privatised, introducing competition at the different market levels, with the exception of transmission system operators, which due to the nature of their business remain as natural monopolies.

Electricity trading is currently based on several types of markets:

- Exchanges or spot markets;
- Bilateral and over-the-counter markets;
- Ancillary services markets; and
- Retail markets.

In exchanges, volumes of electricity are traded at a clearing price. These exchanges can have day-ahead sessions for each of the day period (normally for each of the 24 hours) and intraday sessions, where market agents bid supply and demand offers. In this way, a clearing price is found for each transaction period by crossing the supply and demand curves. All market agents bidding at lower prices will trade their bidding volumes at the market clearing price. Generally in the bottom of the supply curve we can find agents bidding electricity produced with low marginal cost technologies, like nuclear or hydro. The so called *"merit order"* depends on the marginal costs of each generation technology and the marginal cost of generation for each electricity producer depends on the operational costs (Eydeland & Wolyniec, 2003). Each generating plant operational cost has several components like fuel, variable consumables, variable maintenance, emissions and transmission costs.

Interconnected spot markets can be joined through a market coupling/splitting mechanism where markets with lower prices export electricity to markets with higher prices through the interconnections. If the interconnection capacity is large enough to accommodate the exported electricity flows (without congestion) then the price is the same in both markets (Figure 1.1), otherwise market splitting occurs and two regional market prices are cleared (Figure 1.2). The congestion revenue is the price difference multiplied by the exchanged volume of electricity and can be used according to the European Community Regulation 1228/2003/EC of the European Parliament and of the Council of 26th June 2003 on conditions for access to the network for cross-border exchanges in electricity (European Union, 2003b). In bilateral markets two agents enter into an agreement for the transaction of pre-determined volumes of electricity or ancillary services at set prices. In the ancillary services markets, producers can sell to Transmission System Operators (TSOs) balancing services, allowing for the matching of the electricity supplied and demanded (spinning reserves, non-spinning reserves, operating reserve, energy imbalance, reactive energy regulation, black start, frequency response). Retail markets introduce competition at domestic and industrial level customers.

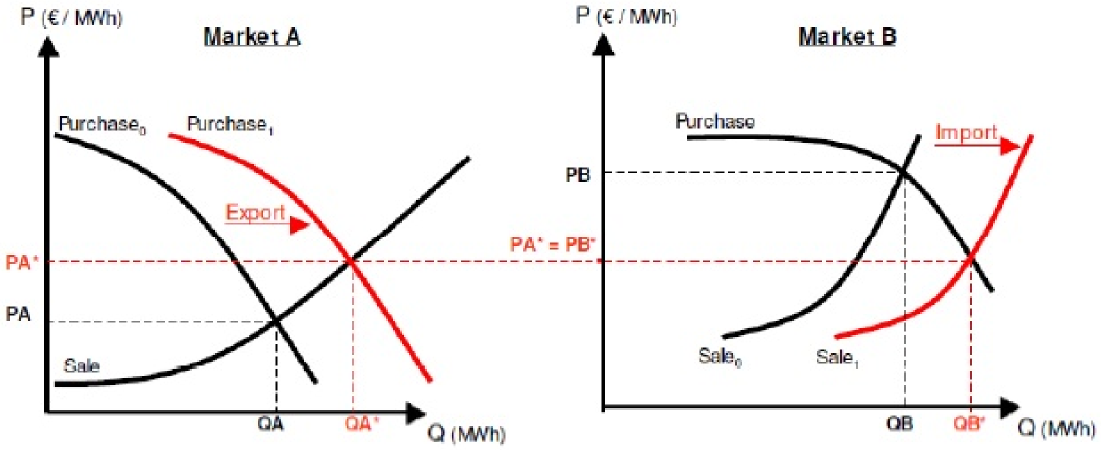

Figure 1.1: Market coupling without interconnections congestion (EPEX, Apx-endex, & BelPEX, 2010)

The Council Directive 90/547/EEC of 29th October 1990 on the transit of electricity through transmission grids (European Union, 1990b) and the Council Directive 90/377/EEC of 29th June 1990, concerning a procedure to improve the transparency of gas and electricity prices charged to industrial end-users (European Union, 1990a), provided the first steps for the creation of the European Internal Electricity Market (IEM). The European Directive 2003/54/EC (European Union, 2003a) and lately the European Directive 2009/72/EC (European Union, 2009b) reviewed the European Directive 96/92/EC (European Union, 1997), which for the first time established common rules for the various electricity markets in Europe, based on the liberalisation of the sector without prejudice of the public service

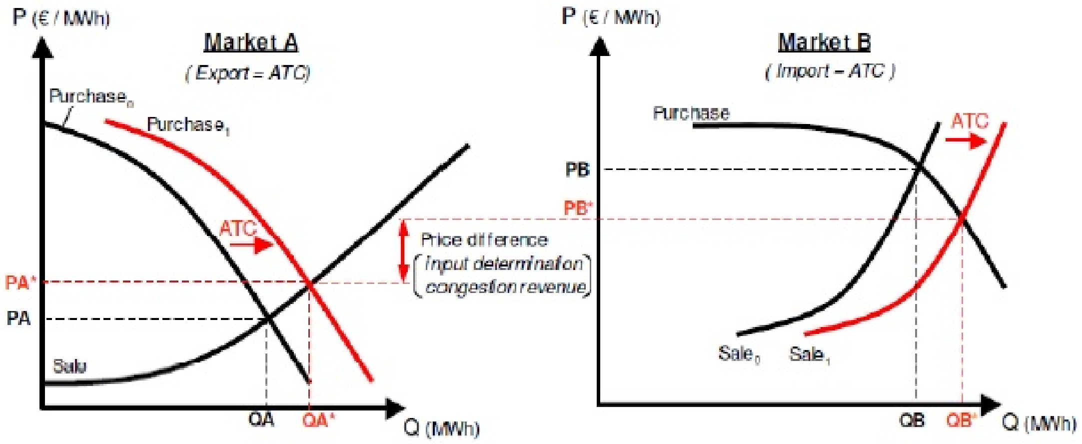

Figure 1.2: Market coupling with interconnections congestion (EPEX, Apx-endex, & BelPEX, 2010)

required and the access by the generators and consumers to the transmission and distribution grids (Jamasb & Pollitt, 2005; Vasconcelos, 2005). These requirements are guaranteed by regulating authorities established in each country (Silva & Soares, 2008; Silva, 2007). Guaranteeing the supply of electricity, reducing costs, fostering competition, ensuring security of supply and respecting the environment, were the objectives set for the European energy policies. However, different degrees of market opening and development of interconnectors between electricity transmission grids across European countries are observed. European member states took necessary measures to facilitate the transit of electricity between transmission grids, in accordance with the conditions laid down in the Directives. The adequate integration of national electricity transmission grids and associated increase of electricity cross-border transfers should ensure the optimization of the production infrastructure.

In 2006 the European Regulators Group for Electricity and Gas (ERGEG, currently the Agency for the Cooperation of Energy Regulators (ACER), established by European Commission Regulation 713/2009 of 13th July 2009 (European Union, 2009c)) launched seven Electricity Regional Initiatives (Karova, 2011; Meeus & Belmans, 2008) for the creation of Regional Electricity Markets (REMs):

- Baltic States (Estonia, Latvia, Lithuania);
- Central East (Austria, Czech Republic, Germany, Hungary, Poland, Slovakia, Slovenia);
- Central South (Austria, France, Germany, Greece, Italy, Slovenia);
- Central West (Belgium, France, Germany, Luxembourg, Netherlands);
- Northern Europe (Denmark, Finland, Germany, Norway, Poland, Sweden);
- South West (France, Portugal, Spain);
- UK and Ireland (France, Republic of Ireland, UK).

The objective for the creation of these REMs was to provide an intermediate step for the consolidated European Electricity Market (ERGEG, 2006).

The initiative denominated Price Coupling of Regions (PCR), aiming to join existing REMs through the market coupling mechanism, was launched at the Florence Regulatory Forum in 2009 by three power exchanges: Nordpool, EPEX and MIBEL (Europex, 2009). In the meantime additional members joined the initiative, APX-Endex, Belpex and GME, reaching 2860 $^{\mathrm{TWh}}/_{\mathrm{year}}$ of potential electricity trading (Europex, 2011), to be fully implemented by the end of 2014. In May 2014 market coupling between Iberia, Central West Europe and Nordpool was achieved, being one of the main objectives of the Price Coupling of Regions initiative. Finally, in February 2015 market coupling was implemented between Italy, Austria, France and Slovenia. Consequently, 19 countries are now linked, improving integration of the single European electricity market.

In April 2014, the former Polish prime minister introduced the idea for an Energy Union, driven by the Crimea crisis and the associated European fossil fuel security of supply. The ”non-paper” submitted to the European Commission suggested a set of measures covering infrastructures, solidarity, market power, endogenous energy sources, energy source diversification and the ultimate goal of energy community reinforcement (Tusk, 2014). The European Commission issued a communication shortly afterwards, with clear influences from the ”non-paper”,

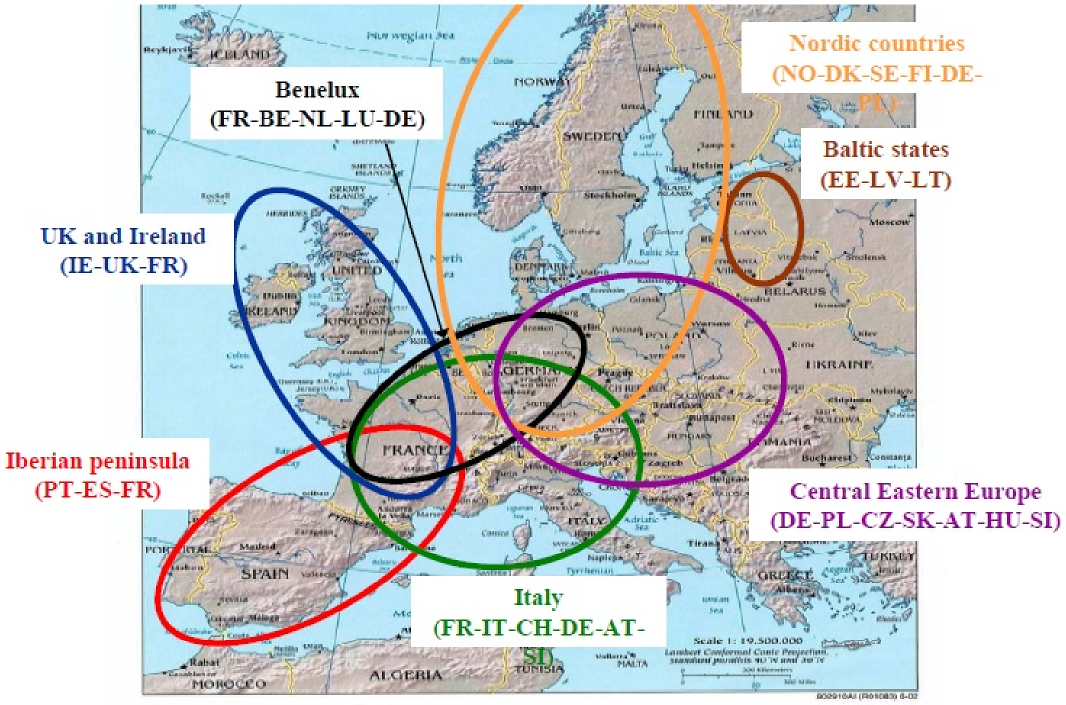

Figure 1.3: Regional Electricity Market (Everis & Mercados EMI, 2010)

entitled "European Energy Security Strategy", referring in particular the gas supply disruption in 2006 and 2009 (European Commission, 2014). This communication mentions strategies to improve energy security and namely addressing: gas storage capacities, gas reverse flows and Liquefied Natural Gas (LNG). Similar to the "non-paper", it also mentions solidarity mechanisms amongst Member States with respect to oil, gas and infrastructure, as well as reinforcement of the internal energy markets and increasing endogenous energy production (both renewable and nuclear power). In particular, it calls for the required increasing cross-border interconnection capacity and for the "Speedy implementation of all the measures to meet the target of achieving interconnection of at least 10% of their installed electricity production capacity for all Member States". Furthermore, an extension to 15% interconnection target is proposed by 2030. Overall, it calls for the coordination improvement of all Member States national energy policies, and as implicit in the "non-paper", jointly addressing external energy policy. Fifteen action points are then laid down in the Energy Union Package communication (European Commission, 2015a). Amongst these, we highlight the following: full implementation of the energy legislation, together with its compliance on intergovernmental agreements; develop infrastructure to achieve an integrated energy market through the proposal of a new European electricity market design for 2015 (European Commission, 2015b), integrate renewables and guarantee supply security; review the regulatory framework and the functioning of ACER and the European Network of Transmission System Operators (ENTSO); incentivise regional approaches to market integration; transparency on energy costs and prices; and a new target for 2030 of 27% of renewable energy.

The European Directive 2001/77/EC (European Union, 2001) repealed by the European Directive 2009/28/EC (European Union, 2009a) called for the promotion of electricity generation by Renewable Energy Sources (RES) in Europe, in order to reduce dependency on imported fossil fuels and to allow the reduction in (GHG) emissions. The RES-E generation in Europe was 467,7 TWh in 2013 consisting of 42.4% hydroelectric, 27.4% wind, 10.4% solar, 9,9% biomass and 10% of other renewable technologies (Eurostat, 2015). The RES-E generation technologies are in different stages of development, which explain the different shares of deployment achieved in each technology (Brown, Müller, & Dobrotková, 2011). The large deployment of RES-E generation in Europe was achieved by strong financial support mechanisms (Meyer, 2003), like feed-in tariffs, fiscal incentives, tax exemptions and other (de Jager et al., 2011). The achieved high level penetration of RES-E generation poses new challenges, both in the technical sense and in the market design. Electricity systems have to be restructured to accommodate intermittency and policy design has to reflect required market integration of these technologies (Benatia, Johnstone, & Haščič, 2013). RES-E is not competitive in general, suffering for a number of market failures, namely the CO_2 price in the European Union Emissions Trading Scheme (EU ETS), which does not provide a long-term price signal for RES-E investment (Ottmar Edenhofer et al., 2013). Additionally, the current financial crisis together with the high penetration of RES-E electricity led to huge incentive burdens on the states, creating the need to suddenly change incentive policies and causing distrust of investors (Baron, 2013). Therefore, the

2020 European targets are in jeopardy and policies have to be adjusted, namely by reducing the risk to investors while minimising RES-E incentive policy costs (Ragwitz et al., 2012).

The evolution of the installed generation capacity in some of the European countries demonstrates the trend towards renewable energies in Europe (Figures 1.4 to 1.8). Some successful countries in deploying renewables are: Denmark, Germany, Portugal and Spain with a high growth in wind power generation; France, Norway, Portugal, Spain and Sweden with their traditional hydro power generation; and Belgium, Germany and Spain in solar generation. Generally, it is seen in all considered countries a decrease in the share of installed thermal power generation, therefore, contributing to a lower share of fossil fuel based electricity generation. Nuclear power generation remained stable in the countries where it exists, with the exception of a small decrease seen in Germany. Furthermore, as part of the so called "Energiewende", Germany has the intention to proceed with the nuclear phase-out plan, closing all nuclear reactors by 2022 (World Nuclear Association, 2015b). The "Energiewende" in Germany is actually one of the most drastic plans in Europe to achieve a sustainable energy system. Initially, this term appeared through the opposition to nuclear power and the reduction of oil dependency. The view was that economic growth can be achieved through a sustainable energy system, paving the way to Germany's Renewable Energy Act. Further details on the "Energiewende" can be found in Morris and Pehnt (2015).

Cross-border interconnections offer numerous advantages under normal operating conditions, such as optimal power station production, increasing opportunities for operation with renewable energies, promotion of competition and enhancement of supply security. However, interconnectors are limited and have constraints due to the physical behaviour of electricity, which behaves like a fluid in a pipe; it flows through the easiest path. Therefore, high voltage grids interconnected through many cross-border interconnectors placed in different geographic positions originate unidentified flows, which are not necessarily related with cross-border trading. Consequently, a consumer that contracted with one generator across the border will probably receive electricity from different generators. All these properties of high voltage grids can create congestion of transmission lines and cross-border interconnectors causing the so called Loop Flow Problem (Coppens & Vivet, 2006). It is

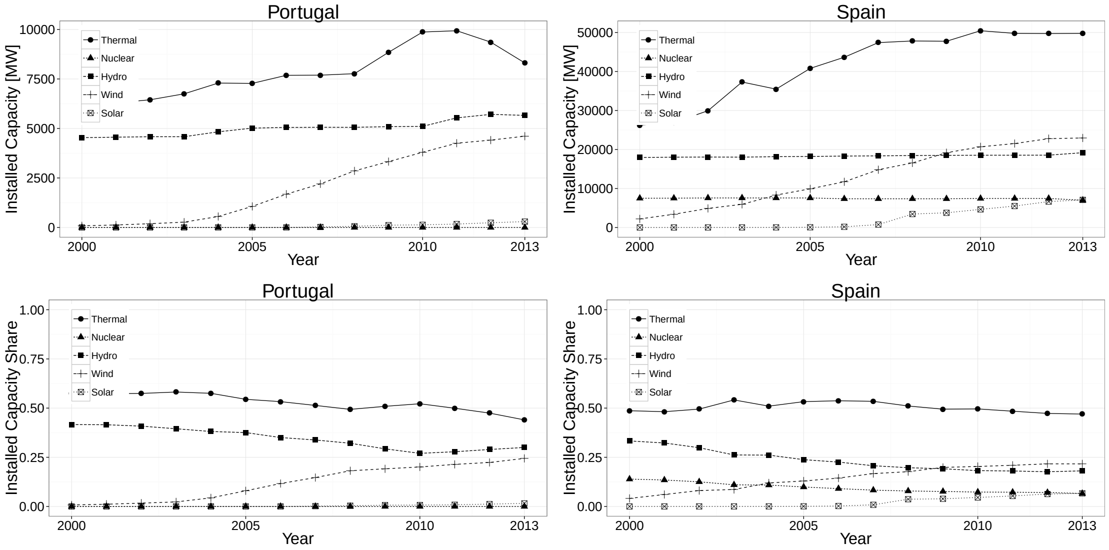

Figure 1.4: Installed generation capacities and shares in Iberia

the TSO responsibility to manage the above mentioned constraints (Turvey, 2006) and to deal specifically with cross-border exchanges in electricity, which in turn have to comply with the specific European Union Regulations 1228/2003/EC of 26th June 2003 and 714/2009 of 13th July 2009 (European Union, 2003b, 2009d). These regulations establish a set of rules for cross-border exchanges in electricity, in order to enhance competition, establish a compensation mechanism for cross-border flows of electricity, setting principles on cross-border transmission charges and allocating available capacities of interconnections (European Union, 2003b). The creation of ENTSO, the European Network of Transmission System Operators, was established aiming to prepare European wide network codes to guarantee an efficient transmission network management, together with allowing trade and supply of electricity across borders. In order to finance the development of cross-border interconnections, costs have to be allocated to the electricity systems stakeholders. Transmission costs allocation methods can be "Flat Rate" or "Flow-based". Flat rate methods calculation and implementation is straight-forward, however viewed as unfair to generators that use less capacity and extent of the transmission lines (Galiana, Conejo, & Gil, 2003). Flow-based cost allocation is most commonly used due to the dependence on the capacity and extent used of

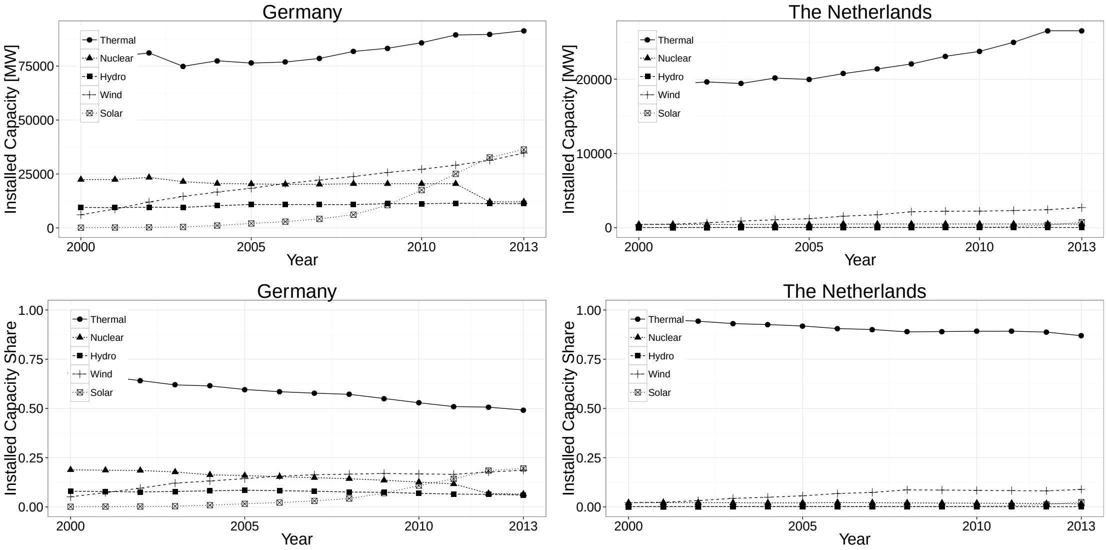

Figure 1.5: Installed generation capacities and shares in CWE (Germany and the Netherlands)

the transmission lines by each electricity market agent. Furthermore, flow-based cost allocation of cross-border interconnections can be made by ”Explicit auctioning”, where interconnector capacity is sold to the highest bidder, or ”Implicit auctioning” which integrates electricity and cross-border transmission electricity markets (Market Splitting and Price Coupling).

1.1 Motivation

The European Union is seeking to re-organize the electricity sector across Europe. The aim is to achieve efficiency gains, increase competitiveness and price reductions. Common rules for generation, transmission and distribution are laid down in European Directives since 1996. To ensure reduction of market dominance, access to the electrical grid, protection of small customers, clear market and environmental impact information, real choice for customers and additional cross-border trade, are all objectives traced by the European Union. Additionally, since 2001 the promotion of electricity produced from renewable sources became a priority since it would contribute to a sustainable development and security of

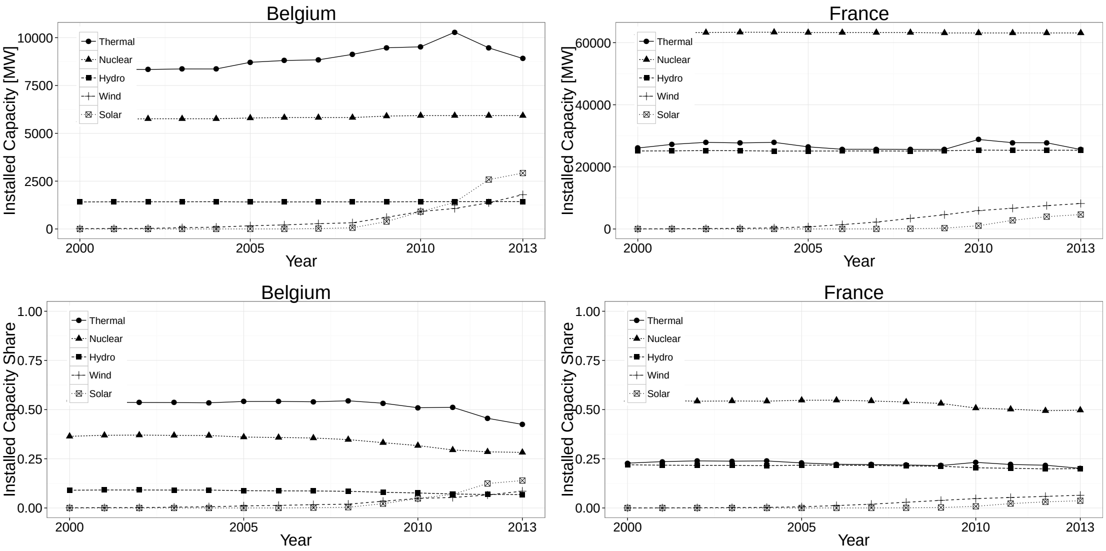

Figure 1.6: Installed generation capacities and shares in CWE (Belgium and France)

supply.

The motivation for this research is related with the paradigm shift towards a RES-E generation dominance and its influence on electricity markets. Furthermore, there is a need to assess, through the analysis of real markets, the RES-E generation effect on spot electricity price convergence and European market integration.

1.2 Research Questions

Growing concerns about climate change and energy dependence have driven specific policies to support renewable or more efficient energy sources in many regions, particularly in the production of electricity. These policies have non-negligible costs and still unknown impacts on the electricity markets evolution, therefore a careful assessment seems necessary. In this context, this research aims at performing an evaluation of the impacts of RES in the electricity markets and namely on their integration as required by European policies. The overall objective of this research is to assess electricity market integration, through the analysis of spot price behaviour and convergence, considering the influence of high penetration

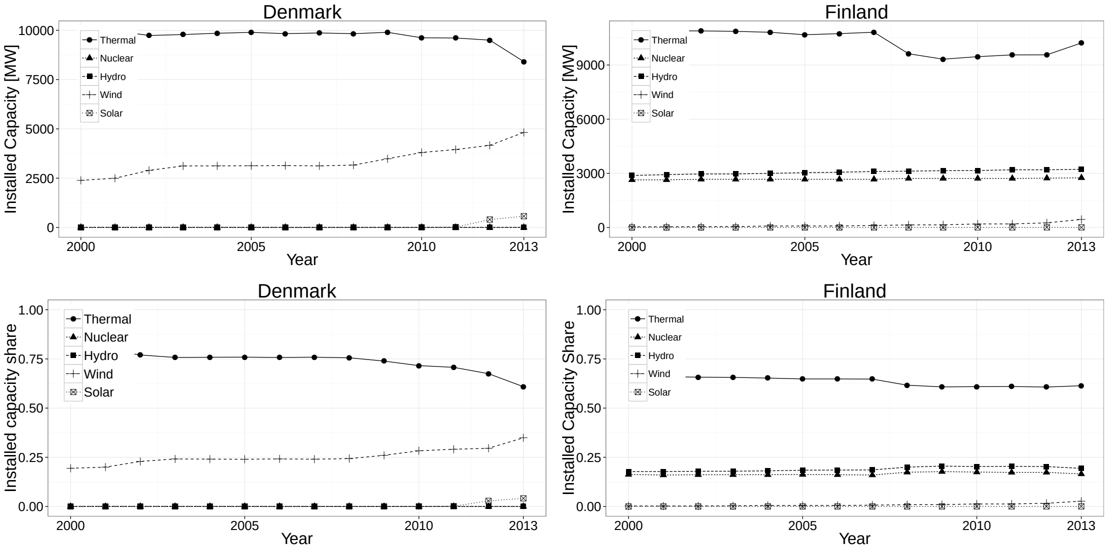

Figure 1.7: Installed generation capacities and shares in Nord Pool (Denmark and Finland)

of RES-E, and, by answering the following interrelated research questions:

- What is the current level of integration between electricity spot markets, under the influence of high penetration of RES-E?
- To what extent do climate conditions associated with high penetration of RES-E generation account for the Electricity spot price behaviour?
- Does an increasing RES-E generation increase the probability of market splitting occurrence?
- Do empirical data confirm the influence of available cross-border interconnection capacity on market splitting?
- How efficient have regulatory policies been so far in addressing the integration of large scale RES-E generation into the electricity markets?

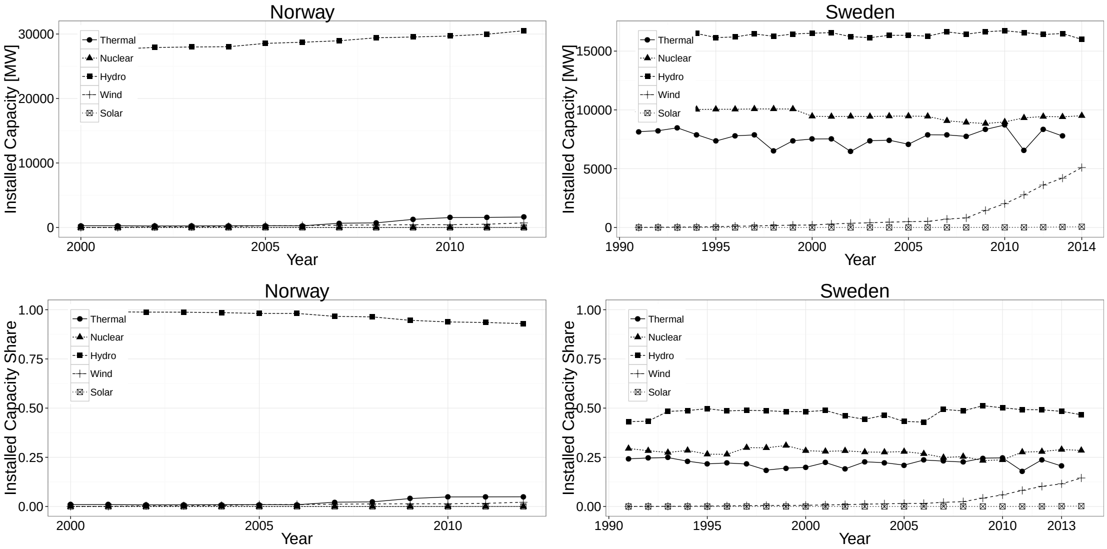

Figure 1.8: Installed generation capacities and shares in Nord Pool (Norway and Sweden)

1.3 Structure

The introduction of RES-E generation went through a global programme of incentives. This was seen mainly in Europe, but was also observed in Australia and the USA, with wind based generation having the highest growth, from 18 GW in 2000 to 373 GW in 2014, of global installed capacity (British Petroleum, 2015). Simultaneously, electricity markets and related liberalization of the electricity sector is also observed in some regions of the world. Regional electricity markets were created and then integrated in order to achieve the desirable objectives of efficient competition, security of supply, respect for the environment and reduction of costs. Policy makers aim to regulate the above effectively; however, difficulties come to light in face of the dynamics involved.

The high penetration of RES-E, which is now being achieved in some world regions, associated with the integration of electricity markets, creates new issues needing detailed study. The literature is still quite poor in addressing these issues simultaneously. Appropriate econometric modelling can be developed to allow the evaluation of the key determinants of electricity market integration, considering a high level penetration of RES-E.

Results extracted from the modelling carried out may provide essential information to generators, Transmission System Operators (TSOs), electricity retailers, consumers and policy makers, in order to guide investment priorities, establish and evaluate risks, and provide guidance in policy design and regulatory framework.

In this Chapter the reader was offered with an introduction, including a context outline, the motivation in Section 1.1, the research questions in Section 1.2 and this structure overview (Section 1.3). The reader can find the relevant literature review in Chapter 2, which is presented divided into sub-sections covering electricity market integration evaluation associated with cross-border interconnections, electricity market integration associated with the expansion of RES-E, and a review of the models used to evaluate these two aspects of electricity market integration.

In Chapter 3 the methodology and methods used in the studies carried out are described.

In Chapter 4 the research carried out concerning electricity market integration is described. The South-west European (SWE) and the Central-West European (CWE) electricity market integration was evaluated considering the existing high level RES-E in these regions. Based on this work, three conference papers were presented and one book chapter produced:

- Figueiredo, N. C. & Silva, P. P. d. (2012). Integration of South-West Spot Electricity Markets: An Update. In *12th IAEE - European Energy Conference* (pp. 1–14), presented at the International Association for Energy Economics European conference, held in Venice.

- Figueiredo, N. C. & Silva, P. P. d. (2015). Explanatory variables on south-west spot electricity markets integration. In P. Godinho & J. Dias (Eds.), *Assessment methodologies: Energy, mobility and other real world application* (pp. 65–88). Imprensa da Universidade de Coimbra. doi:10.14195/978-989-26-1039-9_3, presented at the International Conference on Energy & Environment, held in Porto in 2013 and later published as book chapter.

- Figueiredo, N. C. & Silva, P. P. d. (2013c). Integration of Central West Europe spot electricity markets: An update. In *10th International Conference* *on the European Energy Market (EEM)* (pp. 1–7). IEEE. doi:10.1109/EEM.2013.6607299, presented at the 10th International Conference on the European Energy Market, held in Stockholm and published in the peer reviewed IEEEXplore digital library.

- Figueiredo, N. C. & Silva, P. P. d. (2013a). Explanatory Variables on Central-West Spot Electricity Markets Integration. In *Energy for Sustainability 2013, Sustainable Cities: Designing for People and the Planet* (September, pp. 1–15), presented at the Energy for Sustainability Multidisciplinary Conference, held in Coimbra.

Additionally, in Chapter 5, weather influences and market specificities in RES-E price effects transmission, within a REM, were evaluated for the CWE. Based on this work, one journal article was published:

- Figueiredo, N. C., Silva, P. P. d., & Bunn, D. (2016). Weather and market specificities in the regional transmission of renewable energy price effects. *Energy*, *114*, 188–200. doi:10.1016/j.energy.2016.07.157

The research carried out concerning spot electricity market price convergence is described in Chapter 6. Due to the high level penetration of RES-E in both Iberia and Denmark, the determinants influencing spot electricity price convergence were investigated. This work originated two conference papers and two journal articles:

- Figueiredo, N. C., Silva, P. P. d., & Cerqueira, P. A. (2014). The Renewables Influence on Market Splitting : the Iberian Spot Electricity Market. In *14th IAEE - European Energy Conference*, presented at the International Association for Energy Economics European conference, held in Rome.

- Figueiredo, N. C., Silva, P. P. d., & Cerqueira, P. A. (2015b). Wind generation influence on market splitting: The Iberian spot electricity market. In *12th International Conference on the European Energy Market (EEM)* (pp. 1–5). IEEE. doi:10.1109/EEM.2015.7216649, presented at the 12th International Conference on the European Energy Market, held in Lisbon and published in the peer reviewed IEEEXplore digital library.

- Figueiredo, N. C., Silva, P. P. d., & Cerqueira, P. A. (2015a). Evaluating the market splitting determinants: evidence from the Iberian spot electricity prices. *Energy Policy*, *85*, 218–234. doi:10.1016/j.enpol.2015.06.013,
- Figueiredo, N. C., Silva, P. P. d., & Cerqueira, P. A. (2016). It is windy in Denmark: Does market integration suffer? *Energy*. doi:10.1016/j.energy.2016.05.038.

An overall discussion of RES-E integration in the existing electricity markets and policy implications is then provided in Chapter 7 and forms the basis of a book chapter:

- Figueiredo, N. C. & Silva, P. P. d. (2016b). Renewables Optimization in Energy-Only Markets. In V. Blanco (Ed.), *Analysis of energy systems. management, planning and policy* (Chap. 6). Taylor & Francis

Research conclusions are presented in Chapter 8, which includes further research suggestions.

Chapter 2

Literature Review

The behaviour of spot electricity market prices provides information to electricity generators, electricity retailers, consumers and policy makers, signalling investment and establishing risks. Some authors claim that electricity can almost be considered a commodity, which creates markets with singular behaviour characteristics. The electricity storage capacity is limited and is merely 125 GW worldwide (Beaudin, Zareipour, Schellenberglabe, & Rosehart, 2010), from which the most used technology is the Pumped Hydroelectric Storage with 97% of the total storage capacity available (Beaudin et al., 2010; Chen et al., 2009). This storage capacity is equivalent to 3% of the globally installed generation capacity (Chen et al., 2009), which means that in practice electricity supply needs to be permanently matched with demand, giving electricity demand a high inelastic, seasonal and volatile behaviour (Bourbonnais & Méritet, 2007). High price volatility and spikes are mentioned by Bower (2002), whilst Park, Mjelde, and Bessler (2006) describes volatility in electricity spot markets as a result of *"limited storability"*, transmission constraints and demand-supply imbalances. Higgs and Worthington (2008) and Lucia and Schwartz (2002) describe electricity spot price behaviour has having high volatility, mean reversion and jumps or spikes.

2.1 Interconnections and electricity market integration

Several studies addressed the interaction between interconnections with respective management and electricity markets. Coppens and Vivet (2006) described the physical behaviour of electricity in high voltage grids, the related congestion of transmission lines and the interconnectors *"Loop Flow Problem"*. Interconnectors can be managed through explicit or implicit auctioning mechanisms. In explicit auctioning, interconnector capacity is sold to the highest bidder, whilst in implicit auctioning, electricity and transmission markets are integrated, the so called *"Market Splitting"/"Market Coupling"* mechanisms. Galiana et al. (2003) suggested the use of *"Equivalent Bilateral Exchanges"* (a flow-based transmission cost allocation method) to allocate the costs of transmission through interconnectors, which was compared with the *"Postage Stamp"* method (a flat-rate transmission cost allocation method), and the *"Power Sharing Principle"* (also a flow-based method). Later, Perez-Arriaga and Olmos (2005) explored the possibility of explicit auctioning in the European IEM, however referring that an implicit auctioning scheme would be ideal. Turvey (2006) presented a comprehensive explanation of the interconnections management issues and economics surrounding their use in electricity markets. The methods for inter-TSO payments related with cross-border interconnections are then analysed in Camacho and Pérez-Arriaga (2007). The optimisation of market coupling and splitting mechanisms are discussed by Meeus, Vandezande, Cole, and Belmans (2009), whereas Jacottet (2012) provided a useful survey on the status of EU interconnections problematic.

Implicit auctioning was implemented in the Nord Pool in the form of market splitting, therefore, under a single power exchange, addressing interconnection congestion through the calculation of separate prices for the considered bidding areas (Lucia & Schwartz, 2002). The implicit auctioning method was found to increase economic efficiency, with the coordination between TSOs being suggested in Meeus, Purchala, Van Hertem, and Belmans (2006), taking into account interconnections and existing congestions for future development of renewables and security of supply. The first successful region created where different power exchanges were coordinated through an implicit auctioning method, included Belgium, France and the Netherlands, the so called *"Trilateral market coupling"* (TLC) (Meeus, Belmans, & Glachant, 2006). After the addition of Germany to the TLC, Weber, Graeber, and Semmig (2010) explained the setup of Market Coupling in the CWE region and its objective function for welfare maximisation, with the identification of practical and technical implementation issues.

The efficiency of implicit and explicit auctioning methods was evaluated in a vast number of studies. Through an experimental setup Jullien, Pignon, Robin, and Staropoli (2012) assessed the efficiency of implicit and explicit auction mechanisms and concluded that the former is more efficient for the allocation of transmission capacity. Multilateral market coupling is proven effective in Genesi, Marannino, Montagna, Siviero, and Zanellini (2008) and Genesi, Rossi, et al. (2008) and demonstrated by Polgari, Raisz, and Sores (2014), with increased social welfare. In Pellini (2012a) welfare gains were demonstrated when the introduction of market coupling between Italy and its neighbouring countries is simulated. Furthermore, the centralised market splitting outperforms the decentralised market coupling, in terms of both price convergence and social welfare, as reported by Biskas, Chatzigiannis, and Bakirtzis (2013). Market coupling associated with different versions of counter-trading is also analysed in a simulation study by Oggioni and Smeers (2013), where nodal pricing is set as a reference of a perfect implicit auctioning for congestion management and is compared with market coupling implemented mainly in CWE. It is also shown in this study that appropriate transmission capacities and an internal counter-trading resource market can approximate the horizontal integration of counter-trading operations. Moreover, it is suggested that a complete line capacity market would improve the TSOs counter-trading coordination. Market coupling is estimated to improve gains from cross-border trading as described by Newbery, Strbac, and Ivan (2015) in an assessment study of its benefits.

Since it became an objective of the European energy policies, the level of integration across electricity markets is being studied. However electricity market integration was not only an issue to Europe and one can find studies about different areas of the globe. De Vany and Walls (1999) started by evaluating the market integration across eleven regional electricity markets in the western United States of America (USA) using spot market electricity prices from 1994 to 1996, aggregated by peak and off-peak values. All time-series data analysed, except for the Northern California, were found to be serially correlated (Ljung and Box Q-statistic) with unit root (Augmented Dickey-Fuller test - ADF), however no unit root was found when integration of order one was performed. A Cointegration Analysis on the daily electricity spot market prices was also executed. Likewise, Park et al. (2006) studied the integration of eleven USA regional markets spread across the nation, through the use of a two-lag Vector Autoregression (VAR) model with direct acyclic graphs, for logarithmic levels of the daily peak spot market electricity prices and two exogenous variables at levels expressing aggregated daily weather effects for cooling and heating. Time-series data for the daily peak spot market electricity prices were found to be highly volatile, but stationary with mean reversion characteristics.

In Australia Worthington, Kay-Spratley, and Higgs (2005) examined the transmission of spot electricity prices and price volatility of the Australian National Electricity Market (NEM), through the use of a Multivariate Generalized Autoregression Conditional Heteroskedasticity (MGARCH) model, finding poor integration amongst the corresponding regional electricity markets. A review for the models used in spot market electricity price modelling was provided by Higgs (2008). Subsequently, Higgs (2009) assessed NEM by examining the inter-relationships of wholesale spot electricity prices among four regional markets and the impact of inter-connectivity on the electricity price dynamics. This was done through MGARCH models to examine dynamics of price volatility with the following variants: Constant Conditional Correlation MGARCH, Dynamic Conditional Correlation MGARCH (Tse & Tsui, 2002) and Dynamic Conditional Correlation MGARCH (R. Engle, 2002). After considering the Akaike Information and Shwartz Criteria, it was concluded that the Dynamic Conditional Correlation MGARCH (Tse & Tsui, 2002) model was the best variant to analyse the four Australian markets considered, having the ability to include the time-varying conditional correlation spillovers across markets and additionally better describing the price and price volatility inter-relationships. It was concluded that highly interconnected markets have higher conditional correlations, therefore, interconnectivity and/or geographic arbitrage between the Australian regional markets have developed an integrated electricity spot market.

For Europe, Bower (2002) evaluated electricity market integration between fifteen European wholesale markets (Nordic countries, Germany, Spain, the United Kingdom, and the Netherlands) using mean day-ahead electricity prices observed in 2001. By taking the first differences, a correlation analysis to each pair of locations was made, revealing only good integration within Nord Pool. Additionally, using a Cointegrating regression by R. F. Engle and Granger (1987), the long-run equilibrium between mean day-ahead electricity price time-series was specified and the residual errors estimated, which in turn were tested for stationarity (ADF test). If these were to be found non-stationary, then there would be no cointegration between time-series. It was found that Nord Pool markets were well integrated, however, a significant but weaker integration relationship existed between Nord Pool and most of the remaining markets. The exception was Spain which was found not to be integrated. A good introduction to the European Union electricity market legislation can also be found, describing some of the development history of the wholesale electricity markets, and European Commission proposals, to further develop their integration. Galli and Armstrong (2007) assessed, through an exploratory data approach, the differences between four electricity markets: France, Germany, the Netherlands and Spain. A converging behaviour was reported between all electricity markets as price differences were decreasing on average. Newbery (2005) presented a comprehensive summary of the internal European market design at the date, bringing some insights from the USA experience and establishing as a success the case of the Nord Pool cross-border trading arrangements (the market splitting). The integration of the European electricity markets was also the subject of the analysis made in J.-m. Glachant and Lévêque (2005), where it was established that interconnection management is the main issue to be addressed in market design. This includes the harmonisation of rules and methods for congestion management, as well as data monitoring. Furthermore, in Coppens and Vivet (2006) the development of the unified European electricity market and related ongoing deregulation processes in each Member State electricity sector were analysed. Difficulties found throughout this process were reported and it was concluded that additional steps on European Commission policies and financial support were required from 2006 onwards. Using Markov switching fractional cointegration, Haldrup and Nielsen (2006) found that cointegration exists only when interconnections between bidding areas are not congested, by performing a detailed analysis to the electricity price pairs West Denmark – Norway and East Denmark – Sweden.

Domanico (2007) assessed the results of the European electricity policies on the liberalization of the sector and raises concerns about market concentration from utility companies' mergers & acquisitions. The contribution of interconnection capacity, between Member States, on electricity markets is investigated and it is stated that cross-border interconnection development is the key to enhance competition, avoiding market power abuse by national incumbents, increasing security of supply and allowing the reduction of spare generation capacity. Amundsen and Bergman (2007) studied Nord Pool's integration level, which was found to be quite highly integrated at wholesale level, diluting previously existing market power, but with low integration at the retail level where market power could still be felt. It was detected that hydropower had a major influence on market splitting. The implementation of market coupling on the Kontek cable, interconnecting East Denmark and Germany, is described by Kristiansen (2007), paving the way for further coupling between Nord Pool and the CWE region, in preparation for a full European electricity market integration. Silva (2007) and Silva and Soares (2008) evaluated the integration between four European electricity markets (Spain, France, Netherlands and Germany) with correlation and Ordinary Least Squares (OLS)/cointegration, using daily peak and baseload spot market electricity prices from 2002 until the 3$^{\text{rd}}$ quarter 2004. Furthermore, Dickey-Fuller, ADF and Phillips-Perron (PP) test for stationarity were performed and found to be stationary for the considered electricity price time-series. Low levels of integration between the evaluated markets were found. A Generalized Autoregression Conditional Heteroskedasticity (GARCH) model was also used to estimate spot price volatility.

de Jonghe, Meeus, and Belmans (2008) made an early assessment of the TLC, finding a decrease in wholesale electricity price differences and a reduction of volatility in the Amsterdam Power Exchange (APX). Meeus and Belmans (2008) reports the developments concerning Nord Pool, the TLC and the Iberian electricity market (Mercado Ibérico de Eletricidade - MIBEL). Moreover, the seven regional initiatives launched by ERGEG are described as the vehicle for a desired increasing European electricity market integration. Cross-border transmission capacities and related explicit capacity auctions were also found to be insufficient by Zachmann (2008), indicating that infrastructure development had to be pursued in order to achieve a common European electricity market. He based his study of European market integration on a Principal Component Analysis (PCA) of wholesale electricity prices (Austria, France, Germany, Netherlands, Spain, United Kingdom, Poland, Czech Republic, East Denmark, West Denmark and Sweden), concluding that full market integration had still not been achieved. Stationarity of data was tested with the ADF test (null hypothesis rejection of a unit root means convergence) and the Kwiatkowski–Phillips–Schmidt–Shin (KPSS) test (null hypothesis rejection of stationarity means divergence). The weaker hypothesis of (bilateral) convergence was accepted for pairs of markets based on unit root tests (KPSS and ADF) and a convergence test based on filtered pairwise price relations was also made. These price relations were based on the gross integration measure, or the logged ratio of the prices between two markets, modelled then by an autoregressive function. Congestion charges were then included in the formulation. For Italy, Gianfreda and Grossi (2009) analysed the existing zonal price differences as an indication of interconnection congestion and used this information, together with generation sources, in a model to express price dynamics. Price coordination importance is argued by Meeus et al. (2009) as it can give adequate signals to the electricity system stakeholders. Waniek, Rehtanz, and Handschin (2009) simulated market coupling based on the CWE electricity regional market, whilst Tersteegen, Schröders, Stein, and Haubrich (2009) assessed problems arising from market coupling algorithms and proposed solutions in a form of an extension to the existing algorithms used in the TLC. The South East European electricity markets are characterised by Hooper and Medvedev (2009) by describing the challenges towards the desired integration and in some cases the restructure of the electricity sector. Wholesale electricity prices relations were evaluated by Bosco, Parisio, Pelagatti, and Baldi (2010), through the use of cointegration and unit root analysis, for the European markets of Austria, France, Germany, the Netherlands, the Nordic countries and Spain. France and Germany were found to be strongly integrated, followed by Austria and the Netherlands with a high integration with the former. The Spanish and the Nordic electricity markets were found not to be integrated with the remaining assessed electricity markets.

An analysis of the efficiency of European electricity spot and forward prices (Germany, France, Spain, Netherlands and the United Kingdom) was performed by Bunn and Gianfreda (2010) by looking at properties of the regional markets linked by capacity constrained interconnections, through Correlation Analysis, Granger Causality tests and Cointegration Analysis. Dynamics of shocks for prices and squared logarithmic returns (as proxy of volatility) were investigated using Impulse-response Functions (IRF) in VAR for spot prices and VECM for forward prices. Some inefficiency of forward and spot price convergence was observed, with a positive relation in base and peak periods, even in the absence of adjacent physical connections. J.-M. Glachant (2010) described the efforts to achieve the European IEM and the two opposing models to achieve it: a central matching unit dealing with all demands, offers, cross-border capacities, price and volume calculation; or the PCR where existing power exchanges and TSOs can cooperate. In Oggioni and Smeers (2010) and Oggioni, Smeers, Allevi, and Schaible (2012) it is argued that counter-trading integration through the creation of an internal market, after energy market clearing, is fundamental to achieve high levels of electricity market integration and efficient calculation of Available Transfer Capacity (ATC). Creti, Fumagalli, and Fumagalli (2010) analysed the Italian electricity market structure and suggest that its differences would favour a volume coupling solution, when integration with neighbouring electricity markets is considered. Power exchanges types and regulation issues are discussed by Meeus (2011) in a context of pursuing an integrated European electricity market. *"Merchant"* and *"Cost-of-service regulated"* type power exchanges are described and regulatory actions proposed, to avoid market power and to set desired quality-of-service standards. Low level of electricity market integration between the Irish single electricity market and the Austrian, Belgian, German, Dutch and Nordic electricity markets was found by Nepal and Jamasb (2012), using a time-varying Kalman filter technique. Additional cross-border transmission capacity is recommended, which would enhance market integration.

The convergence of European spot electricity markets was also studied by Pellini (2012b) through a fractional cointegration analysis, reporting that all electricity markets are fractionally cointegrated and that perfect integration is still not achieved. Fractional cointegration analysis was also used by de de Menezes and Houllier (2014) to assess the European IEM integration, through the investigation of mean reversion speed and spot price convergence in a rolling period. In this way time variations are captured and relevant events within the European electricity markets can be analysed. Convergence was not observed with the introduction of the TLC between the following electricity markets: (i) the Nordic and the Netherlands; (ii) France and Germany; (iii) France and Iberia; and (iv) France and UK. However, convergence is reported between the following electricity markets: (i) the Nordic and Germany; (ii) the Netherlands and Germany; and (iii) France and Italy. Decreasing price dispersion and cointegration after the introduction of the TLC was found between the following electricity markets: (i) UK and the Netherlands; (ii) the Netherlands and Germany; and (iii) France and Italy. With mixed results, a conclusion is drawn stating that IEM integration is still not increasing. Huisman and Kiliç (2013) report increasing electricity market efficiency and decreasing volatility of the CWE electricity markets, due to the increased connectivity and market integration. In a correlation analysis, increasing electricity market convergence is found within the CWE electricity markets and partially with the Nordic electricity markets. The Nordic electricity market convergence with the Netherlands is not found to increase. Moreover, probability of price spike occurrence was found to decrease in Belgium, France and the Netherlands, and to increase in Germany and the Nordic electricity markets. By using a network theory combined with Granger-causality, Castagneto-Gissey, Chavez, and De Vico Fallani (2014) established that the Dutch and the Norwish spot electricity prices were subject to the highest and the lowest influence from other electricity markets, respectively. The British spot electricity price has the most influence on other electricity markets, and the Danish and Belgium spot electricity prices have the least influence on other electricity markets. Furthermore, it is stated that European electricity market integration is still far from being achieved. Through systems dynamics modelling of coupled electricity markets, Ochoa and van Ackere (2014, 2015) demonstrate some benefits of electricity market integration: decreasing costs of supply and resource optimisation. Moreover, it was found that integration impacts are more relevant in smaller countries, whilst social welfare improvements favour larger countries. Furthermore, they state that absence of policy coordination between interconnected countries may create unbalanced benefits in the considered coupled electricity markets.

The development of European infrastructure required to achieve an integrated European electricity market, to increase network reliability and to improve renewables integration, was discussed by Zachmann (2013). The argued proposals were: (i) conclude the vertical unbundling; (ii) create an electricity system European control centre; and (iii) implement a binding network infrastructure planning process. J. M. Glachant and Ruester (2014) expressed concerns about the future of the European IEM, namely regarding the high level of RES electricity installed associated with supporting mechanisms and decentralisation of production-consumption. Furthermore, uncoordinated national policies for capacity availability payments can jeopardise competition and cross-border trade. The degree of market integration was assessed by Grossi, Heim, Hüschelrath, and Waterson (2015) through the analysis of effects on neighbouring countries of unilateral policy reforms. Specifically, the German decision on nuclear power phase-out and promotion of renewable power was demonstrated to have significant impacts on other European Member States. A high integration level is found between the German/Austrian and the Czech Republic, the Dutch and the Swiss electricity markets. Low integration level is found between the German/Austrian and both the Polish and the Spanish electricity markets. The same German unilateral decision on nuclear phase-out and renewables promotion was analysed by de Menezes and Houllier (2015), through fractional cointegration and MGARCH models, assessing the impact on market integration, spot electricity price level and volatility. Their hypotheses for less market integration following the nuclear phase-out and increasing renewable generation was rejected, however spot electricity prices were found negatively associated with wind power, which also contributes for high price volatility. Nevertheless, Spain and the UK were found not to be integrated with Germany after the above mentioned decision. Increasing integration is reported between Germany and Belgium, the Netherlands, France and the Nordic electricity markets. Through the use of localised autocorrelation function and fractional cointegration, de Menezes, Houllier, and Tamvakis (2016) were able to conclude that existing studies "may have overestimated the strength of market integration" and highlights the importance of the electricity mix shift to RES-E. Institutional arrangements for the integration of electricity markets are discussed by Oseni and

Pollitt (2016), where it is defended the existence of an overseeing operator to avoid market damaging behaviour.

2.2 Renewable power and electricity markets integration

The impact of the increase in RES-E generating capacity on electricity markets and prices is not yet fully understood. It is expected that wholesale electricity price decreases due to the large deployment of RES-E generation, driving the marginal plants out of the electricity spot market (Gelabert, Labandeira, & Linares, 2011; Jensen & Skytte, 2002; Klessmann, Nabe, & Burges, 2008; Pereira & Saraiva, 2013; Sáenz de Miera, del Río González, & Vizcaíno, 2008). These marginal plants can be conventional fuel or coal fired plants or as seen more recently Combined Cycle Gas Turbines (CCGT) (Redes Energéticas Nacionais, 2012b). Large scale penetration of RES-E generation introduces problems in transmission grid management and stability, that should be tackled, originating in excess production, supply/demand mismatch, quality of supply and transmission constraints (Franco & Salza, 2011). Moreover, the intermittent nature of RES-E generation poses additional challenges, which may be resolved by developing some form of backup capacity to supply the required electrical energy when RES-E generation becomes unavailable (Klessmann et al., 2008). Available stand-by conventional generation, increasing cross-border interconnections, increasing transmission grid capacity, and hydro-pump storage systems are the most adequate means to provide backup capacity, required to address the above mentioned problems. These need adequate funding to be available when required (Frondel, Ritter, Schmidt, & Vance, 2010). One example of this was the introduction in Iberia (Spain initially and lately in Portugal) of regulatory measures to have appropriate incentives to dispatchable power plants, for the provision of backup capacity to the transmission grid (namely to guarantee plant availability), which are then factored into the electricity costs (Diário da República Portuguesa, 2010).

Literature is still building on the analysis of the impacts of large scale RES-E generation. Holttinen, Vogstad, Botterud, and Hirvonen (2001) simulated the

Nordic electricity market to evaluate the introduction of large scale wind power generation. Results indicated the creation of interconnection constraints and the reduction of the spot electricity price, as the main outcomes from the simulation. Moreover, Lund and Münster (2006) simulated the West Danish electricity market considering a large scale wind power deployment, flexible Combined Heat and Power (CHP) generation and trade in the Nord Pool. Results demonstrate that investment in flexible CHP units in combination with international trade would provide the most benefits for the electricity system. Electricity system requirements for large scale wind power in an interconnected region are described in Söder et al. (2007) in order to achieve the required efficiency and reliability. Interconnection flows can provide back-up power, which can support demand requirements in the absence of RES-E or low wind conditions. Furthermore, interconnections can allow the export of surplus electricity and the required system balance. Wind power curtailment is also mentioned as a means to control excess wind power generation. The topic of integrating high shares of intermittent RES-E is also discussed by Lund (2007) on a 100% RES-E system perspective for Denmark, by including small flexible CHP units, heat pumping systems and wind power regulation. Amundsen and Bergman (2007) reported low spot market electricity prices originated by an excess in RES-E production, causing transmission constraints and market splitting. Additionally, differences in Nord Pool spot electricity prices were found when there was a high supply of hydropower generation in a region where market integration is well established.

Growing concerns about high-level penetration of RES-E generation exist and are also assessed in some of the existing wholesale electricity markets like in Denmark (Mauritzen, 2010), Spain (F. Moreno & Martínez-Val, 2011) and in Australia (Cutler, Boerema, MacGill, & Outhred, 2011). However, literature is still sparse on the impacts of large-scale wind power generation in interconnected markets. An optimisation model was developed by Lynch, Tol, and O'Malley (2012) to determine required interconnection capacities for a given level of RES-E generation, and found that investment on interconnections can be beneficial if including RES-E. Moreover, the expansion of the European transmission grid required for RES-E integration by 2020 is evaluated by Schaber, Steinke, and Hamacher (2012), establishing a requirement for the increase of 60% of capacity in new lines or 20% in new cables. A successful example is Denmark with its high share of wind power, which together with the development of CHP units and cross-border interconnections, managed to achieve an integrated electricity system with surrounding countries (Lund et al., 2013). Due to the existing cross-border interconnection between Germany and the Netherlands, associated with the large-scale wind power in Germany, the expected negative impact of German wind power on the Dutch wholesale electricity price is described by Mulder and Scholtens (2013). Furthermore, the same German large-scale wind power was demonstrated to have the same effect in the French wholesale electricity prices, together with a decrease in price variance if cross-border interconnections are increased (Phan and Roques, 2015).

The decrease in electricity price can have the effect of reducing the long-term signal for investment and deters future investments, as reported by Klessmann et al. (2008), creating, later on, a subsequent increase in electricity prices due to restricted supply. The impact of RES-E on wholesale electricity prices as been discussed throughout a number of scientific papers and reports. Due to the almost non-existing marginal costs of RES-E generation, they are first in the merit order of power plant dispatch, displacing higher marginal cost electricity generation (the *"merit-order effect"*). Therefore, some level of decrease on the electricity spot market prices is expected, as reported by several authors (Amorim, Martins, & Silva, 2010; Cruz, Muñoz, Zamora, & Espínola, 2011; Cutler et al., 2011; Gelabert et al., 2011; Jensen & Skytte, 2002; Klessmann et al., 2008; Mauritzen, 2010; Mulder & Scholtens, 2013; Pereira & Saraiva, 2013; Sáenz de Miera et al., 2008; Sensfuß, Ragwitz, & Genoese, 2008; Weigt, 2009; Würzburg, Labandeira, & Linares, 2013). However, this does not mean that consumer electricity prices also decrease (Silva & Cerqueira, 2017; Sisodia et al., 2015). In reality, B. Moreno, López, and García-Álvarez (2012) demonstrates that there is a small increase in household electricity prices attributable to RES-E generation.

One of the few studies found assessing the influence of existing high level wind power penetration on the behaviour of electricity price convergence was performed for the four price zones of Texas by Woo, Zarnikau, Moore, and Horowitz (2011), through the use of ordered-logit and log-linear regression models. It established that high wind power loads in west Texas causes interconnection congestion and electricity price differences with the remaining zones. The RES-E influence on interconnection congestion was also analysed by Sapio (2015) for Sicily and the rest of Italy, through the use of time-varying regime switching models and a dynamic probit, ruling the transition between regimes, with some distinct results. Wind power is found to decrease interconnection congestion, which according to the author may be due to wind curtailment practices by the TSO. Moreover, Italy was studied by Ardian, Concettini, and Creti (2015) through the use of multinomial logit and three stage least square models, reporting that probability of interconnection congestion increases with high wind power generation exiting a bidding area and decreases with high wind power generation in the destination bidding area. For Iberia, Figueiredo and Silva (2015) found that increasing wind power generation, or furthermore, increasing low marginal cost generation has a clear influence on market splitting, increasing its probability.

Additional wind power capacity has also been demonstrated to have an influence on ATC. Rious, Usaola, Saguan, Glachant, and Dessante (2008) found that an increasing wind power generation in Germany would increase ATC between France and Belgium due to counter-flows created. Also, concerning German wind power, Salic and Rebours (2011) demonstrate a clear negative impact of wind power generation on the day-ahead Net Transfer Capacity (NTC) from Germany to France. Luna and Martínez (2011) through a simulation study demonstrated that ATC decreased with additional wind power if the system balance is made within the same area, recommending that this balance is made by hydro power units. Furthermore, Barth, Apfelbeck, Vogel, Meibom, and Weber (2009) through a large-scale wind power electricity market optimisation model, established that load-flow market coupling would reduce operation costs and electricity prices, improving the usage of cross-border interconnections. Nevertheless, Neuhoff et al. (2013) argue that nodal pricing is more efficient in managing transmission constraints than zonal pricing (e.g. market coupling), demonstrating that congestion and prices vary according with the amount of wind power injected.

Some issues were highlighted concerning the high level penetration of RES-E: Benatia et al. (2013) argued for the importance of adequate interconnection and transmission capacities, capacity incentives for dispatchable power plants, demand management, reducing electricity trading constraints and further research on energy storage technology; Franco and Salza (2011) highlighted the risk of excessive production, the importance of energy storage and exports through interconnections to address balancing issues, appropriate system security and ancillary services; Söder et al. (2007) stressed the importance of enough dispatchable backup capacity with fast response dynamics, system robustness and reserves to cover uncertainty and/or withstand eventual electrical faults, and adequate transmission grid capacities to transport eventual excess renewable generation; and the importance of wind power forecasting, allowing for load management and system balancing, was highlighted in Milligan et al. (2009). Parsons et al. (2008) summarises findings from the knowledge international forum established by the International Energy Agency (IEA), to discuss the impacts of large-scale wind power integration. One of the most important findings is that large-scale wind power would need increasing transmission capacities to adjacent areas. Reporting two National Renewable Energy Laboratory (NREL) studies for large-scale wind power integration, Milligan et al. (2009) conclude that 20% RES-E is possible and can be managed, given an accurate wind power forecast and additional transmission capacity. However, a full 100% renewable energy system design is desired by Denmark by 2050 and the corresponding study is presented by Lund and Mathiesen (2009) advocating that it is physically possible to implement based on a mix of biomass, wind, solar and wave power. Roques, Hiroux, and Saguan (2010), by using the Mean-Variance Portfolio Theory, conclude that wind power deployment requires careful planning taking into account geographical diversification, in order to minimise balancing costs and maximise system reliability with the appropriate transmission system reinforcement.

2.3 Modelling Review

The main methodologies for electricity spot market evaluation involve numerical modelling techniques, which can be split into three different categories: Game Theory Models; Simulation Models; and Econometric Models, namely Time Series Models (Aggarwal, Saini, & Kumar, 2009). The use of econometric models, based in time-series statistical evaluation allows the analysis of complex relations between determinants in the electricity sector and electricity markets. To model electricity markets, reliable data is required, which in the energy sectors is generally found in good commercial, market operators, or power exchange data centres. In a context of electricity market integration, considering the influence of high level penetration of RES-E, the models and econometric techniques used in the literature are listed below:

- Unit root testing is performed throughout the literature using ADF, PP and KPSS tests (Bower, 2002; De Vany & Walls, 1999; Kwiatkowski, Phillips, Schmidt, & Shin, 1992; PHILLIPS & PERRON, 1988; Silva, 2007; Worthington et al., 2005; Zachmann, 2008),
- Autocorrelation testing is used to test if a time-series is random and independent, otherwise one observation can be correlated with a different observation some time later. Ljung and Box Q-statistic can be used for this effect (De Vany & Walls, 1999),
- The cointegration concept applied to non-stationary time-series means that some combinations are likely to move together over time. Consequently, two or more non-stationary variables, integrated of the same order, are cointegrated if there is any linear combination of these variables that is stationary (Bower, 2002; Bunn & Gianfreda, 2010; De Vany & Walls, 1999; R. F. Engle & Granger, 1987; Grewal, Mills, Mehta, & Mujumdar, 2001; M. P. Murray, 1994),
- Correlation Analysis of spot electricity prices in the first difference for each pair of markets (Bower, 2002; Bunn & Gianfreda, 2010; Silva, 2007),
- A MGARCH model can be used to examine transmission of spot electricity prices and price volatility across electricity markets (Higgs, 2009; Silva, 2007; Worthington et al., 2005),
- A VAR model can describe the dynamic behaviour and interdependencies of stationary economic and financial time series and can investigate the response of the different markets to price shocks (Bunn & Gianfreda, 2010; Lütkepohl, 2005; Park et al., 2006; Sims, 1980),

- A VECM incorporates the fact that there might be cointegration relations between the time series variables evaluated under a VAR (Bunn & Gianfreda, 2010; Lütkepohl, 2005; Sims, 1980),
- Granger Causality evaluates the causal relation between two variables in the sense of precedence and information content (Bunn & Gianfreda, 2010; Granger, 1969),
- Impulse Response Functions represent the responses to a shock or innovation of a variable in itself and in all other endogenous variables by the dynamic structure of a VAR (Bunn & Gianfreda, 2010; Lütkepohl & Krätzig, 2004),
- Logit are binary response models, which establish the probability of an event occurring dependent on some determinants, taking advantage of the logistic function properties (Woo et al., 2011; Jeffrey M. Wooldridge, 2003).

Chapter 3

Methodology and Methods

The main methodologies for electricity spot market evaluation involve numerical modelling techniques, which can be split into three different categories: Game Theory Models, Simulation Models and Econometric Models (Aggarwal et al., 2009). In the literature review it is evident that one of the most used method to evaluate electricity markets is econometric modelling therefore, it was decided to explore these type of models and further develop their use. **VAR/VECM** and **Logit** models were used in this research to capture the interdependence between adjacent electricity markets and establish integration determinants. Moreover, this research expands the above methodology through the use of **Non-parametric** models, overcoming known specification issues of parametric models, as described in this Chapter.

In the models developed, the introduction of exogenous explanatory variables is made in order to find the main determinants in electricity market behaviour. It is well established that weather has an influence on electricity demand however, with the growth of RES-E the hypothesis that weather also determines electricity supply, thus price and market integration behaviour, requires assessing. Data availability was an issue that influenced the path followed in the studies, as only now the awareness to make available some of the required variables is achieved. For example, solar power associated variables are only recently included in most weather stations. Moreover, solar power itself is not found in an aggregated basis, as it is common to be connected to the distribution networks, so data collection is not available. Therefore, concerning RES-E, the studies carried out throughout this thesis were mainly based on wind speeds, available in most weather stations, and wind power, which is normally connected to the high voltage grid, with associated metering available.

Summary statistics are calculated for all variables extracted, spot electricity prices and other exogenous variable time-series. Skewness, Kurtosis and Jarque-Bera statistics for normal distribution testing was carried out, together with ADF and PP statistics to test non-stationarity or unit root.

3.1 Electricity market integration

As described in Chapter 1, Section 1.2, one of the aims for this research is to assess electricity market integration, considering the influence of high penetration of RES-E. In the studies carried out, market integration was initially characterised in the SWE and CWE electricity markets. On this first approach, electricity market integration was studied through the use of VAR models, or VECM, in case that non-stationary variables are used. Depending on the results of unit root statistics, a VAR or VECM was designed, taking into account climate exogenous variables, in order to evaluate the key determinants of spot electricity pricing and market integration. Impulse response functions were then applied to find market interactions and assess level of integration. The models provided the basis to estimate the effect of a marginal change of RES-E generation on spot electricity prices and market integration (Bunn & Gianfreda, 2010; De Vany & Walls, 1999; Higgs, 2009; Park et al., 2006; Worthington et al., 2005). The VAR models and VECM are defined as follows:

- Vector autoregression VAR(p):

$$Y_t = \sum_{i=1}^{p} A_i Y_{t-i} + u_t, \qquad u_t \sim (0, \Sigma_u) \tag{3.1}$$

where,

$$Y_t = (y_{1t}, y_{2t}, ..., y_{kt})'$$

$$A_i = \begin{bmatrix} a^i_{1,1} & a^i_{1,2} & \cdots & a^i_{1,k} \\ a^i_{2,1} & a^i_{2,2} & \cdots & a^i_{2,k} \\ \vdots & \vdots & \ddots & \vdots \\ a^i_{k,1} & a^i_{k,2} & \cdots & a^i_{k,k} \end{bmatrix}$$

$$u_t = (u_{1t}, u_{2t}, ..., u_{kt})'$$

$$E(u_t u_t') = \Sigma_u$$

with time $t = 1, 2, 3, ...$ and p period lags.

- Vector error correction model VECM(p-1):

$$\Delta Y_t = \Pi Y_{t-1} + \sum_{i=1}^{p-1} \Gamma_i \Delta Y_{t-i} + u_t, \qquad u_t \sim (0, \Sigma_u) \tag{3.2}$$

where,

$$Y_t = (y_{1t}, y_{2t}, ..., y_{kt})'$$

$$\Delta Y_t = Y_t - Y_{t-1}$$

$$u_t = (u_{1t}, u_{2t}, ..., u_{kt})'$$

$$E(u_t u_t') = \Sigma_u$$

the short-term parameters are:

$$\Gamma_i = \begin{bmatrix} \gamma^i_{1,1} & \gamma^i_{1,2} & \cdots & \gamma^i_{1,k} \\ \gamma^i_{2,1} & \gamma^i_{2,2} & \cdots & \gamma^i_{2,k} \\ \vdots & \vdots & \ddots & \vdots \\ \gamma^i_{k,1} & \gamma^i_{k,2} & \cdots & \gamma^i_{k,k} \end{bmatrix} = -\sum_{j=i+1}^{p} A_j, \qquad \text{for } i = 1, ..., p-1$$

and the long-term parameters are:

$$\Pi = -(I_k - \sum_{j=1}^{p} A_j) = \alpha\beta'$$

where α is the loading matrix $(k \times r)$ and β a cointegration matrix $(k \times r)$, with $rk(\Pi) = r$, the time $t = 1, 2, 3, ...$ and p lags.

In another context, this methodology was used in Silva, Moreno, and Figueiredo (2016) demonstrating its flexibility in long-run and short-run relationships assessment.

3.2 Electricity price divergence in integrated electricity markets

After the electricity market integration analysis of the South-west Europe SWE and CWE electricity markets, it was felt that, even with the demonstration that electricity market integration had been achieved between some of the analysed markets, electricity prices would diverge, thus perfect integration (the concept of perfect integration is mentioned in Bosco et al. (2010) and De Vany and Walls (1999)) had still not been achieved. A deeper analysis was, therefore, required and the determinants of electricity price divergence were studied through probability response models. Due to the fact that, in the modelling attempts made, the probit model latent error does not follow a normal distribution, the option taken was to apply the logit model as a binary response model (Jeffrey M. Wooldridge, 2003). This was made for two well known integrated electricity markets: the Iberian spot electricity market and the Danish spot electricity market as part of the Nord Pool.

3.2.1 Logit probability response models

With the Logit binary response model, the probability of an event occurring can be established (the binary dependent variable vector Y), depending on some determinants (the exogenous variable matrix X), taking advantage of the logistic function properties (Jeffrey M. Wooldridge, 2003).

$$P(Y = 1|X) = G(X\beta), \tag{3.3}$$

where $G(.)$ is a Cumulative Distribution Function (CDF), best described, in this case, from a non-observable latent variable (Y^*) such that:

$$Y^* = X\beta + e, \qquad Y = 1[Y^* > 0], \tag{3.4}$$

Therefore:

$$P(Y=1|X)=P(Y^{*}>0|X)=P(X\beta+e>0|X), \tag{3.5}$$

where

$$\Lambda(X\beta)=\frac{exp(X\beta)}{1+exp(X\beta)}$$

Note that the $G(\cdot)$ function of equation 3.3 is now the logistic CDF $\Lambda(\cdot)$.

Nonetheless, logit models have known specification limitations, such as:

- The "Neglected Heterogeneity" specification issue, where the coefficient estimates may cause an underestimation of the effects (Mood, 2009; J. Wooldridge, 2010) – anyhow, extraction of explanatory variables relative effects can still be of use;
- Heteroskedasticity of the error term – a correction for the error term can be used (Davidson & Mackinnon, 2004).

Logit models can then provide some preliminary indications about probability response behaviour. However, in order to avoid the above mentioned specification limitations, non-parametric models were also used. These do not require parametric assumptions for the underlying data generation process. Non-parametric models are an alternative to parametric models, where specification issues are found to reject or at least to question such model. Moreover, data has the required information allowing for model estimation through kernel methods, which consist simply on weighting functions. Further details on non-parametric models are given in the next Section 3.2.2.

3.2.2 Non-parametric probability response models

Non-parametric models were developed to provide additional model performance and details on the behaviour of integrated electricity markets. The prior assumption for the underlying data generation process is not required for non-parametric models, avoiding specification issues that can question parametric models (Pagan & Ullah, 1999). Model estimation is performed through kernel methods with the information provided by the data. An introduction to non-parametric modelling can be found in Hayfield and Racine (2008) and Racine (2007). The non-parametric models used in this research were developed in R (The R Foundation for Statistical Computing, 2014) using the *"np"* package for non-parametric kernel estimation (Hayfield & Racine, 2008). Bandwidth choice is crucial in these methods and the data-driven bandwidth choice can present a quite demanding computational challenge, due to the nature of the kernel methods (Racine, 2007). With the evolution of computer processing speed, this situation is improving and namely the use of parallel processing presents as the most viable solution when using large datasets, as it is the case in this research.

Probability is estimated through the conditional Probability Density Function (PDF) expressing the probability of an event occurring, conditional on some explanatory variables. The conditional PDF is then:

$$\hat{f}(y^d|x^d, x^c) = \frac{\hat{f}(y^d, x^d, x^c)}{\hat{f}(x^d, x^c)}, \tag{3.6}$$

where $\hat{f}(y^d, x^d, x^c)$ is the joint PDF, $\hat{f}(x^d, x^c)$ the marginal PDF, y^d the discrete dependent variable, x^d the discrete explanatory variables and x^c the continuous explanatory variables.

The joint PDF can then be estimated by:

$$\hat{f}(y^d, x^d, x^c) = \frac{1}{n}\sum_{i=1}^{n} L_{\lambda_y, Y_i^d, y^d} \cdot L_{\lambda_x, X_i^d, x^d} \cdot W_{h_x, X_i^c, x^c}, \tag{3.7}$$

and the marginal PDF by:

$$\hat{f}(x^d, x^c) = \frac{1}{n}\sum_{i=1}^{n} L_{\lambda_x, X_i^d, x^d} \cdot W_{h_x, X_i^c, x^c}, \tag{3.8}$$

where $L(\cdot)$ and $W(\cdot)$ are product kernel functions for discrete and continuous variables, respectively.

For discrete variables:

$$L_{\lambda_x, X_i^d, x^d} = \prod_{s=1}^{r_{x,d}} l(X_{i,s}^d, x_s^d, \lambda_{x,s}), \tag{3.9}$$

$$l(X_{i,s}^d, x_s^d, \lambda_{x,s}) = \begin{cases} 1 - \lambda_{x,s}, & \text{if } X_{i,s}^d = x_s^d \\ \frac{\lambda_{x,s}}{c_s - 1}, & \text{otherwise} \end{cases}, \tag{3.10}$$

where $l(\cdot)$ is the discrete univariate kernel function proposed by (Aitchison & Aitken, 1976), $r_{x,d}$ the number of discrete explanatory variables, c_s the number of outcomes in x_s and $\lambda_{x,s}$ the bandwidth, with $\lambda_{x,s} \in [0, (c_s - 1)/c_s]$.

For continuous variables:

$$W_{h_x, X_i^c, x^c} = \prod_{s=1}^{r_{x,c}} \frac{1}{h_{x,s}} w\left(\frac{X_{i,s}^c - x_s^c}{h_{x,s}}\right), \tag{3.11}$$

$$w\left(\frac{X_{i,s}^c - x_s^c}{h_{x,s}}\right) = \frac{e^{\left(-\left(\frac{X_i - x_s^c}{h_{x,s}}\right)^2/2\right)}}{\sqrt{2\pi}}, \tag{3.12}$$

where $w(\cdot)$ is the continuous univariate Second-order Gaussian kernel function, $r_{x,c}$ the number of continuous explanatory variables and $h_{x,s}$ the bandwidth of variable s.

Bandwidth selection is a fundamental part of non-parametric estimation, therefore two methods were considered: the *"rule of thumb"* and *"likelihood cross-validation"*. The *"rule of thumb"* bandwidth is given by:

$$h = 1.06 \cdot \sigma \cdot n^{-1/(2P+l)} \tag{3.13}$$

where σ is the $min(\hat{\sigma}, \text{interquartile range}/1.349)$, n the number of observations, P the order of the kernel and l the number of continuous variables.

The *"likelihood cross-validation"* method selects the bandwidth (h) by maximizing the following log likelihood function:

$$\mathcal{L} = \sum_{i=1}^{m} log\left[\frac{1}{(n-1)h} \sum_{j=1, j\neq i}^{n} K\left(\frac{X_j - x}{h}\right)\right] \tag{3.14}$$

In this research, the non-parametric models were implemented: (i) without parallel processing, using the *"rule of thumb"* for bandwidth selection, and (ii) with parallel processing, using *"likelihood cross-validation"*, taking advantage of the *"npRmpi"* routines for bandwidths calculation and model estimation. The most adequate method was then selected according to model performance (Okumura & Naito, 2004).

Chapter 4

Electricity market integration

4.1 Introduction on Electricity Markets Integration

The Council Directive 90/547/EEC of 29th October 1990 on the transit of electricity through transmission grids and Council Directive 90/377/EEC of 29th June 1990 concerning a procedure to improve the transparency of gas and electricity prices charged to industrial end-users, provided the first steps for the creation of the internal European electricity market (Bower, 2002).

The establishment of common rules for the various electricity markets in Europe through European Directives[1] aimed the liberalisation of the sector without prejudice of the public service required and the access by the generators and consumers to the transmission and distribution grids (Jamasb & Pollitt, 2005). These requirements are guaranteed by regulating authorities established in each country (Silva, 2007).

To guarantee the supply of electricity, reduce costs, maintain competition and ensure security of supply, whilst respecting the environment, are the objectives set for European energy policies. However different degrees of market opening and development of interconnectors between electricity transmission grids across European countries are observed. European countries took necessary measures

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[1] European Directive 96/92/EC repealed by European Directive 2003/54/EC and by European Directive 2009/72/EC

to facilitate transit of electricity between transmission grids in accordance with the conditions laid down in the Directives. The adequate integration of national electricity transmission grids and associated increase of electricity cross-border transfers should ensure the optimization of the production infrastructure.

The aspect of transmission costs determination plays an important role and its allocation methods are usually either Flat Rate based or Flow-based. Flat rate methods are simple to calculate and implement, however, according to Galiana et al. (2003) unfair to generators that use less capacity and extent of the transmission lines. On the other hand, flow-based costs are most commonly used due to their dependence on the capacity and extent used by each generator of the transmission lines. Explicit auctioning, where interconnector capacity is sold to the highest bidder or implicit auctioning, which integrates electricity and transmission markets and also called *"Market Splitting" / "Price Coupling"*, are both used across Europe (Coppens & Vivet, 2006). In the Spain-France cross-border interconnection, the method of explicit auctioning is used however the mechanism of Market Splitting is applied to the Portuguese-Spanish cross-border interconnection.

In 2006 the ERGEG (currently the ACER established by the European Commission Regulation 713/2009 of 13 July 2009) launched seven Electricity Regional Initiatives (Karova, 2011; Meeus & Belmans, 2008) for the creation of seven Regional Electricity Markets(REMs): Baltic States (Estonia, Latvia, Lithuania); Central-East (Austria, Czech Republic, Germany, Hungary, Poland, Slovakia, Slovenia); Central-South (Austria, France, Germany, Greece, Italy, Slovenia); Central-West (Belgium, France, Germany, Luxembourg, Netherlands); Northern Europe (Denmark, Finland, Germany, Norway, Poland, Sweden); South-West (France, Portugal, Spain); and France-UK-Ireland (France, Republic of Ireland, UK). The objective for the creation of these REMs was to provide an intermediate step for the consolidated European Electricity Market (CEER, 2015; ERGEG, 2006). Moreover, in 2009, an initiative, denominated Price Coupling of Regions (PCR), was launched at the Florence Regulatory Forum by three power exchanges: Nordpool, EPEX and MIBEL (Europex, 2009), to be implemented by the end of 2012. In the mean time additional members joined the initiative, APX-Endex, Belpex and GME, reaching the 2860 TWh/year of potential electricity trading (Europex, 2011) and to be fully implemented by the end of 2014.

The European Directive 2001/77/EC repealed by the European Directive 2009/28/EC called for the promotion of electricity generation by Renewable Energy Sources (RES) in Europe in order to reduce dependency on imported fossil fuels and to allow the reduction in Greenhouse Gas (GHG) emissions. The Renewable Energy Sources Electricity (RES-E) generation capacity in Europe was 239.2 GW by 2010 with 52.1% hydroelectric, 25.7% wind, 17.86% biomass, 3.3% solar, 0.93% geothermal and 0.08% tidal or wave generation (Jäger-waldau et al., 2011). The RES-E generation technologies are in different stages of development which explain the different shares of deployment achieved in each technology (Brown et al., 2011). The large deployment of RES-E generation in Europe was achieved by strong financial support mechanisms (Meyer, 2003), like feed-in tariffs, fiscal incentives, tax exemptions and other (de Jager et al., 2011).

The objective in this Chapter is to assess the integration level of the SWE and CWE REMs. In Section 4.2 electricity market integration and associated determinants, considering a high level penetration of RES-E, are evaluated for the SWE REM. This is followed by the assessment of the CWE REM integration level, before and after the introduction of market coupling with Germany, in Section 4.3.

4.2 South-West Spot Electricity Markets Integration

Under this Section 4.2 electricity market integration and associated determinants, considering a high level penetration of RES-E, are evaluated for the SWE REM. In Sub-section 4.2.1, brief summaries about the French, Spanish and Portuguese electricity markets are provided. Sub-section 4.2.2 follows with a small description of the cross-border interconnections available between the considered electricity markets. In Sub-section 4.2.3 data used in this study is presented and discussed and in Sub-section 4.2.4 VAR model specifications are presented. Analysis and results are presented and discussed in Sub-section 4.2.5.

4.2.1 The SWE electricity markets

In France, there was no privatisation and no unbundling (Newbery, 2005). With several acts of legislation, France managed to carry out the electricity sector reform (through the law 2000-108 of the 10^{th} of February) without restructuring the main operator. An electricity market was created around a public monopoly (J.-M. Glachant & Finon, 2005). The law 2000-108 of the 10^{th} of February also created the *"Commission de Régulation de L'énergie"* (CRE) the French regulator (Journal Officiel de la République Française, 2000). It was considered that competition would come from abroad through the interconnections with the various European countries. The main reasoning behind this was the vast nuclear power capacity and associated low variable cost electricity (Newbery, 2005). EDF has currently 97.2 GW of installed electric capacity, of which 63.7 GW are of nuclear power and owns the complete transmission grid (EDF Group, 2010). The French electricity day-ahead market, Powernext, started operation in November 2001 (Bower, 2002) and by January 2006 explicit capacity auctions on interconnections was introduced (Commission de Régulation de L'énergie, 2011). The market coupling between France, Belgium and the Netherlands was launched in November 2006 and in November 2010 this was extended to Luxembourg and Germany (after the merger of Powernext and the European Energy Exchange EEX, the new EPEX Spot). "Powernext Intraday" and "Powernext Continuous" markets were introduced in July 2007. On the 7^{th} of December 2010 the law 2010-1488 was issued, the "Loi NOME", establishing a new model for the electricity market. The main objective of this law was to effectively open the market by resolving the problem of the competitors' access to competitive sources of electricity. It ensures the transitory right of access to the Historical Nuclear Regulated Electricity by alternative suppliers at a regulated price and volume, which are both determined annually by CRE with a maximum volume limitation by law to 100 TWh/year (Journal Officiel de la République Française, 2010). Additional details on the French electricity market can be found in (Lévêque, 2010).

In Spain, an agreement was reached between the authorities and the electricity companies late in December 1996 (Ministerio de Industria y Energía - Spain, 1996), allowing for the electricity sector reform. The law for the electricity sector issued in November 1997 established the electricity sector regulation with the objectives to guarantee the supply, the quality of supply at the minimum possible cost while respecting the environment. The existing public service was replaced by the guarantee of supply for all consumers; the electrical sector was privatised on the generation and commercialisation sides and regulated on the transmission and distribution sides (Boletín Oficial del Estado - Spain, 1997). The transmission system was assigned to *"Red Eléctrica de España"* (REE) and in January 1998 an electricity spot market was introduced in Spain, the *"OMEL"*. After successive delays the Iberian electricity market MIBEL started operation in July 2007 and by 2008 the corresponding spot electricity market comprised 88% of the total demand (Zachmann, 2008). Additional details on the Spanish electricity market can be found in Crampes and Fabra (2005), Furió and Lucia (2009) and Garrué-Irurzun and López-García (2009).

In Portugal, the Decree-law 7/91 of the 8th of January established the conversion of the Portuguese public electricity company Eletricidade de Portugal (EDP) into a private company still owned by the state. This would allow the unbundling of the Portuguese electricity sector and later privatisation. The re-privatisation of EDP was started in 1997 after the issue of the Decree-law 56/97 of the 14th of March which determined on the first phase the sale of 29.99% of its capital and was followed by several other phases, the last one in 2012. The transmission system operation was assigned to Redes Energéticas Nacionais (REN), created in 1994, under the ownership of EDP. In the end of the year 2000 the Portuguese state acquired 70% of REN from EDP. Only in 2007 the initial phase of REN's privatization (Redes Energéticas Nacionais, 2012c) took place. Currently EDP still owns a 5% share in REN (Redes Energéticas Nacionais, 2012a). The Portuguese regulator for the energy sector (ERSE) was created in 1995 with the Decree law 187/95 of 27th of July (Diário da República Portuguesa, 1995) and has since then been adjusted through several other laws to the requirements of the energy sector and EU requirements (Silva, 2007). The Iberian electricity market was only a reality in July 2007 after several years of preparation and negotiation between the Portuguese and the Spanish states. The MIBEL is composed by a spot (OMIE) and a bilateral (OMIP) electricity markets (Conselho de Reguladores do MIBEL, 2009). Additional details on the Portuguese electricity market can be found in

Amorim et al. (2010).

4.2.2 Interconnections between Portugal, Spain and France

Interconnections offer numerous advantages under normal operating conditions, such as optimal power station daily production, increasing opportunities for operation with renewable energies, the creation of competition and improvement of supply security. However interconnectors are limited and have constraints due to physical behaviour. Electrical current behaves like a fluid in a pipe; it flows through the easiest path. Therefore we have high voltage grids interconnected through many interconnectors placed in different geographic positions, which originate unidentified flows not necessarily related with cross-border contracts. Also, a consumer that contracted with one generator across the border will probably receive electricity from a different generator. All this physical properties of high voltage grids can create congestion of transmission lines and interconnectors causing the so called Loop Flow Problem (Coppens & Vivet, 2006).

Constraints have then to be managed by the Transmission System Operators TSO and specifically cross-border exchanges in electricity have to comply with European Community Regulation 1228/2003/EC of 26th June 2003 and later with European Community Regulation 714/2009 of 13th July 2009. These Regulations established initially a set of rules for cross-border exchanges in electricity, in order to enhance competition, establish a compensation mechanism for cross-border flows of electricity, setting principles on cross-border transmission charges and allocating available capacities of interconnections (European Union, 2003c). With the latest Regulation the creation of the European Network of Transmission System Operators (ENTSO) was established, aiming to prepare network codes to guarantee an efficient transmission network management, together with allowing trade and supply of electricity across borders.

Transmission Costs allocation methods can be Flat Rate based or Flow-based. Flat rate methods are simple to calculate and implement, however unfair to generators that use less capacity and extent of the transmission lines (Galiana et al., 2003). Flow-based costs are most commonly used due to their dependence on the capacity and extent used by each generator of the transmission lines. Explicit auctioning, where interconnector capacity is sold to the highest bidder or implicit auctioning, which integrates electricity and transmission markets and also called Market Splitting/Price Coupling, are both used across Europe (Coppens & Vivet, 2006). During the period of this study, the method of explicit auctioning is used in the Spain-France interconnection, however the market splitting mechanism is applied to the Portuguese-Spanish interconnection.

The Spain-France electrical interconnection currently consists of five HV lines: Arkale-Argia, Hernani-Argia, Biescas-Pragneres, Vic-Baixas and INELFE. These have a total commercial exchange capacity of 2550 MW for transits from France to Spain and 2900 MW for transits from Spain to France. To fulfill the requirements of the European Commission the new HV line built by INELFE, a consortium with equal shares of the Spanish National Grid (REE) and French National Grid (Réseaux de Transport d'Électricité - RTE), doubled the former interconnection capacity and is in operation since 2015. The development of the interconnection capacity will allow a better market integration and provide additional security of electricity supply, being considered a critical factor to ensure integration (Everis & Mercados EMI, 2010). The Portugal-Spain electrical interconnection currently consists of eleven HV lines, of which the last two have in practice no use, with an indicative commercial capacity of 3150 MW for transits between Portugal and Spain and 2520 for transits from Spain to Portugal: Alto Lindoso – Cartelle 1, Alto Lindoso – Cartelle 2, Lagoaça – Aldeadávila, Pocinho – Aldeadávila 1, Pocinho – Aldeadávila 2, Pocinho – Saucelle, Falagueira – Cedillo, Alqueva – Brovales, Tavira – P. Guzman. A new interconnection line between Viana do Castelo and Fontefria is planned to be constructed and forecasted to be in service by 2017, which with several other internal line reinforcements will allow the completion of the interconnection capacity between Portugal and Spain, essential for the joint Iberian electricity market (Redes Energéticas Nacionais, 2015).

4.2.3 Data

Day-ahead spot electricity prices in Euro/MWh (base, peek and off-peak), obtained from Datastream, were used in this study from the 1st of January 2012 to the 31st of December 2014. The data for the day-ahead base, peak and off-peak spot electricity prices is plotted in Figure 4.1.

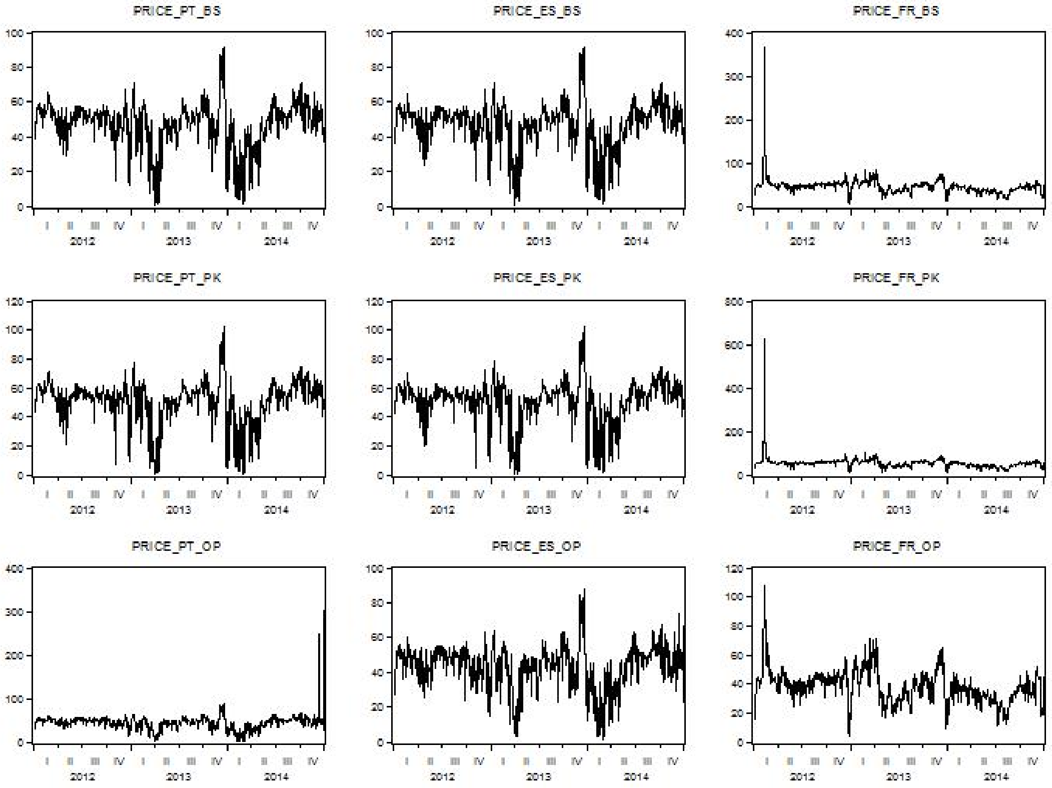

Figure 4.1: Day-ahead base spot electricity prices – $PRICE\_PT$ (Portugal), $PRICE\_ES$ (Spain) and $PRICE\_FR$ (France) - BS (Base load), PK (Peak load), OP (Off-peak load)

Price spikes are observed in electricity markets, which confirms the high volatility behaviour of electricity spot prices, as in Goto and Karolyi (2004), Hadsell, Marathe, and Shawky (2004) and Higgs (2008). The limited possibility of storage, the physical characteristics of simultaneous electricity production and consumption, technical constraints in transmission and generating plants are the main reasons for these spikes (Coppens & Vivet, 2006; Silva & Soares, 2008). After transforming the prices into their natural logarithms, to obtain directly the elasticity values from the parameter estimates, summary statistics were calculated (4.1). Skewness and kurtosis values indicate non-normal distribution, which is confirmed by Jarque-

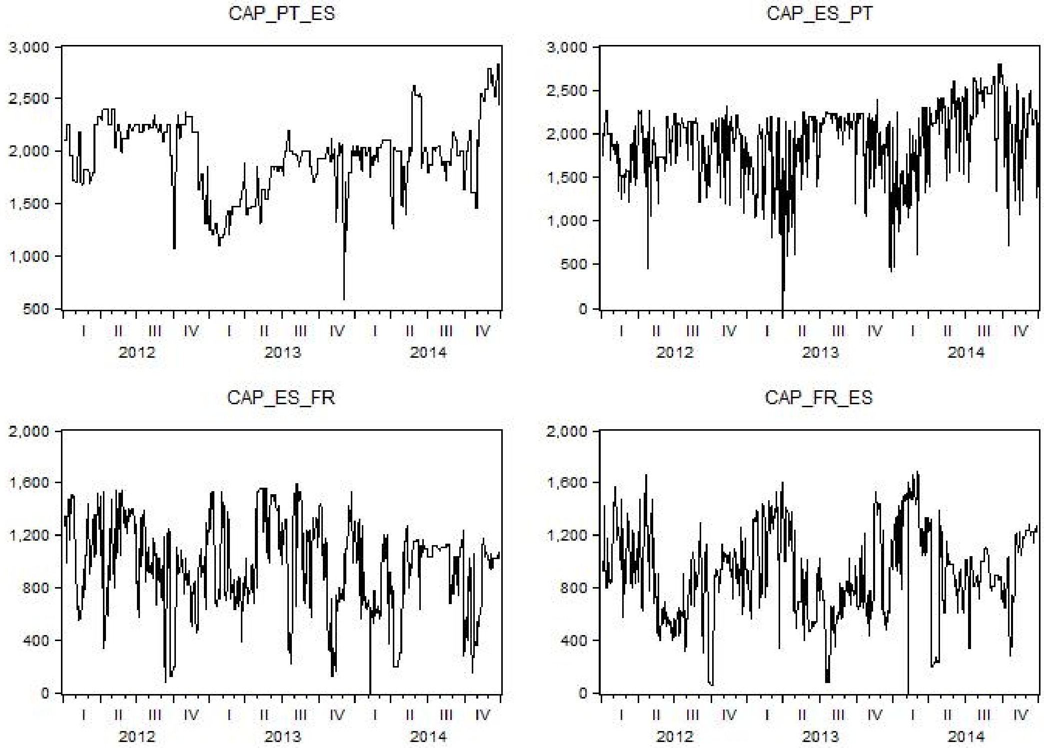

Figure 4.2: Import and export interconnection capacities between Portugal-Spain and Spain-France [MW]

Bera statistic. Unit root tests were made to all daily-log spot electricity prices. As per Table 4.2 we observe that all time series are considered to be stationary at 5% agreeing with findings in Park et al. (2006) and Bunn and Gianfreda (2010). Daily average interconnection capacities were obtained from the corresponding system operator (REN, REE and RTE) and are plotted in Figure 4.2. Daily weather data was retrieved from the website *www.wunderground.com*: maximum and minimum ambient temperatures (in °C) and average wind speed (in km/h) for each country of the SWE REM (Figure 4.3). Given the large number of installed wind power plants in the SWE electricity markets, it is believed to be a good approximation to use averaged weather variables across the existing weather stations linked to the *www.wunderground.com* website. In this way a country average is calculated for every hour and then averaged for every day. Maximum and minimum ambient temperatures were then used to calculate Heating Degree-days (HDD) and Cooling Degree-days (CDD) according to the United Kingdom (UK) Meteorological Office method (Mourshed, 2012; UK Climate Projections, 2013). It is to note the big variability in the average wind speed. Literature reports some related issues, such as: transport of excess production, electrical system fault endurance, available and flexible standby generating capacity and effective control or curtailment of wind power production (Benatia et al., 2013; Franco & Salza, 2011; Söder et al., 2007).

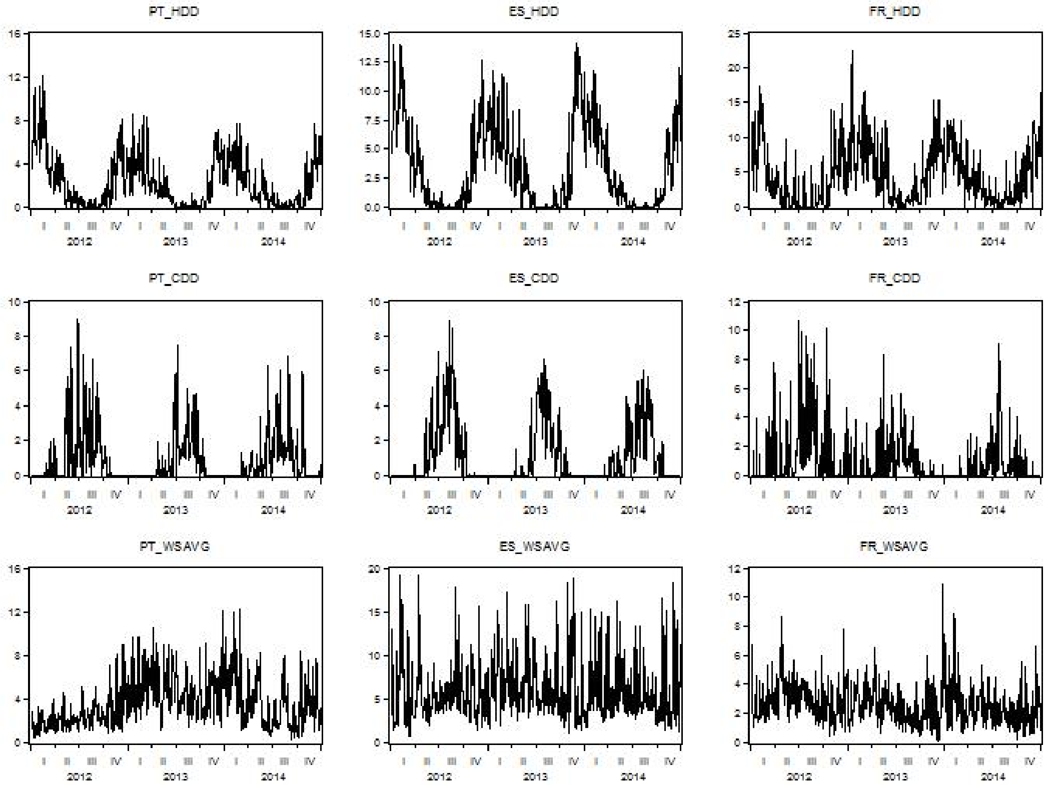

Figure 4.3: HDD, CDD [°C] and Average Wind Speed [km/h] in Portugal, Spain and France

4.2.4 Model Estimation

The VAR model has proven to be especially useful for describing the dynamic behaviour of economic and financial time series and for forecasting. It is known to provide superior forecasts to those from univariate time series models and elaborate theory-based simultaneous equations models. In addition to data description and forecasting, the VAR model is also used for structural inference and policy analysis (Lütkepohl, 2005; Sims, 1980). In structural analysis, certain assumptions about the causal structure of the data under investigation are imposed, and the resulting causal impacts of unexpected shocks or innovations to specified variables on the variables in the model are summarized. These causal impacts are usually summarized with impulse response functions, as is performed in this work.

A Vector Autoregressive with eXogenous variables (VARX) model was then considered to proceed with the evaluation of the determinants in the electricity market integration, due to its ability in capture the linear interdependencies among multiple time series.

Considering a VARX model for the three log prices:

$$Y_t^{(z)} = C^{(z)} + \sum_{i=1}^{p} A_i^{(z)} Y_{t-i}^{(z)} + B^{(z)} X_t^{(z)} + u_t^{(z)}, \tag{4.1}$$

where z is the base, peak or off-peak model,
$Y_t^{(z)} = [Ln(Price_{PT,t})^{(z)}, Ln(Price_{ES,t})^{(z)}, Ln(Price_{FR,t})^{(z)}]'$ the day-ahead electricity price matrix, $X_t^{(z)}$ the exogenous variables matrix, $C^{(z)}$ are (3×1) constant matrices, $A_i^{(z)}$ and $B^{(z)}$ are (1×3) coefficient matrices and $u_t^{(z)}$ are (3×1) matrices of unobservable error terms. In order to determine the order of each the models, successive VAR models were estimated by a sequential test procedure, starting with the estimation of the models with $p = 15$ lags and calculating-down for lower lags the Schwarz Bayesian criterion (BIC) and the Hannan-Quinn criterion (HQC). In Table 4.3 the best values for the endogenous variable lags where criteria are minimised are presented. For each model a lag exclusion Wald test was performed in order to detect lags where the respective coefficients do not present significance in the model, which were then removed as indicated. Autocorrelation testing in all models was performed (Davidson & Mackinnon, 2004).

4.2.5 Analysis and discussion of results

Weather conditions have impacts on both demand and supply of electricity. The estimated VARX model provides insights of the related dynamics between the considered exogenous variables and spot electricity prices. CDD and HDD are considered proxies for electricity demand, therefore a positive contribution in the models is expected. The results shown in Table 4.4 demonstrate that the exogenous variables related with CDD do not contribute too much for the model specification, whereas HDD improves the model in some cases. Positive significant contributions are found for the Spanish HDD in both spot electricity prices for Portugal and Spain. However, it is interesting to note that the Portuguese HDD has significant negative contributions to these same prices, which might be related with weather dynamics (which were not modeled here) rather than price dynamics. The French HDD only provides a positive contribution to the spot electricity price in France. Furthermore, during peak periods only the Spanish HDD significant positive contributions on both Iberian spot electricity prices remain. A relevant improvement in model specification is found by incorporating as exogenous variables the average wind speeds. It is expected that average wind speed contributes negatively to spot electricity prices due to the normally low marginal prices bid into spot markets. This is actually seen for almost all Portuguese, Spanish and French average wind speeds where significant negative contributions to spot electricity prices are found. Some small positive contributions are found, however weather dynamics might explain these. It is to note that an increase of 1 km/h in the Portuguese average wind speed contributes to a 4,46% decrease in the base Portuguese spot electricity price (Table 4.4). Furthermore, there is a 3.06% negative contribution of the French average wind speed to the base Portuguese spot electricity price. However, given the small existing interconnection between France and Spain, this contribution might be related with weather dynamics rather than arbitrage between markets. It would also be expected that the growth in ATC would contribute to a higher level of arbitrage, thus with negative effects to spot electricity prices. However, ATC significant contributions to spot electricity prices do not have a major contribution to the model specification (Table 4.5). As per Figure 4.4 all three models satisfy the stability condition of no roots outside the unit circle.

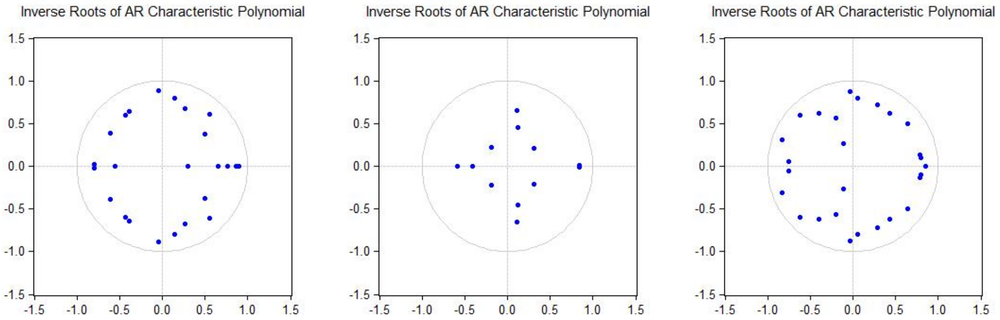

Figure 4.4: Unit circle plot for base, off-peak and peak models (from left to right)

Granger Causality tests to the time-series variables and impulse response analysis displaying the responses of each daily-log price time-series to a standard error shock in one of the time-series were carried out to the models considered and are presented, respectively, in Table 4.6 and in Figure 4.5 to Figure 4.7.

Outcomes in Table 4.6 show that both MIBEL market prices fail to Granger-cause the Powernext market prices on a pairwise relation. This can likewise be observed in the impulse responses of the French spot electricity market prices, which are practically inexistent to shocks in any one of the MIBEL spot electricity market prices. In spite Powernext market prices Granger-cause the MIBEL_ES price in all models, the impulse response analysis indicates a very weak effect. Additionally, there is a Granger-causality relation between Powernext and MIBEL_PT base and peak prices, yet fairly weak as confirmed by the impulse response analysis.

Within Iberia both MIBEL prices Granger-cause each other in all base, peak and off-peak models, which confirms the good integration between both Iberian electricity markets. This is also seen in the impulse response plots with strong responses of the Spanish spot electricity price to shocks in the Portuguese spot electricity price in all base, off-peak and peak models and vice-versa.

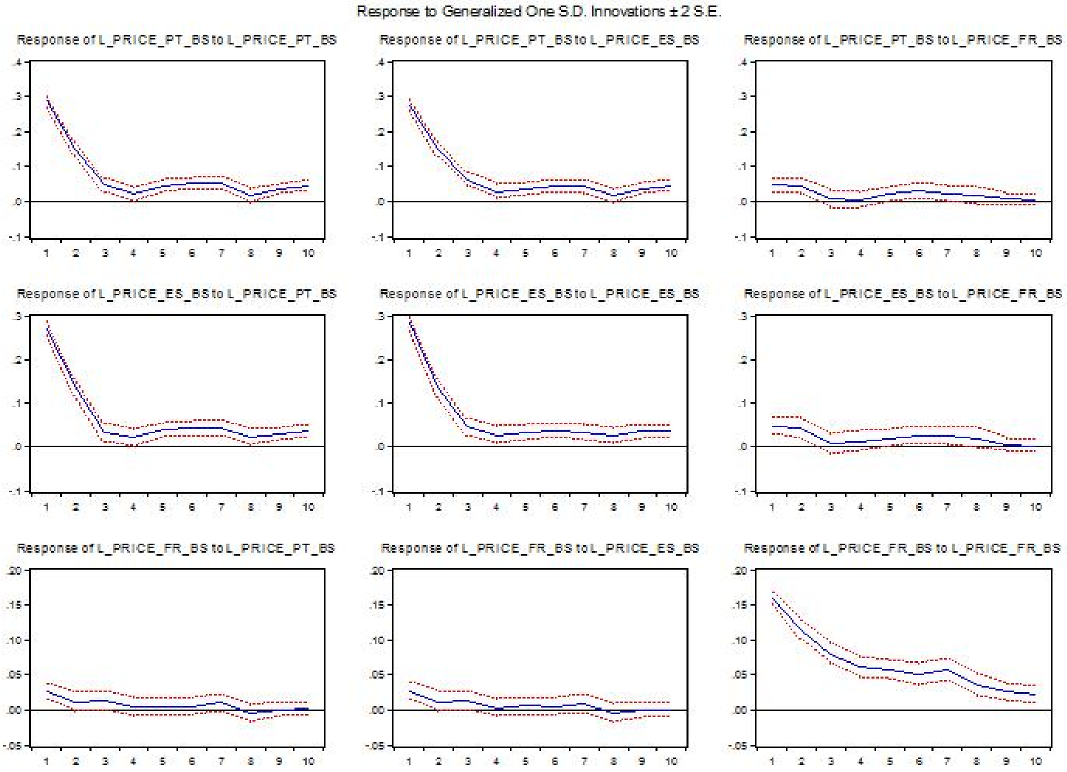

Figure 4.5: Impulse response plots for daily-log base price models

Table 4.1: Summary Statistics

	$Price^{base}_{PT}$	$Price^{base}_{ES}$	$Price^{base}_{FR}$	$Price^{peak}_{PT}$	$Price^{peak}_{ES}$	$Price^{peak}_{FR}$
Mean	46.56047	46.75766	45.57176	50.50936	50.88954	52.8457
Median	49.2	49.15	45.71	53.4	53.42	53.31
Maximum	91.89	91.89	367.6	102.42	102.42	627.59
Minimum	0.79	0.79	7.11	0.05	0.05	10.67
Std.Dev.	13.64581	13.32416	17.45264	15.17455	14.85422	25.77347
Skewness	-0.91986	-0.884998	8.5148	-1.038287	-1.049672	14.57907
Kurtosis	5.079319	5.340286	151.869	5.358144	5.676603	318.9676
$Jarque-Bera$	251.4779	280.8955	732495.9	322.1068	377.5185	3284872
Probability	0	0	0	0	0	0
Observations	783	783	783	783	783	783

	$Price^{off-peak}_{PT}$	$Price^{off-peak}_{ES}$	$Price^{off-peak}_{FR}$	HDD_{PT}	HDD_{ES}	HDD_{FR}
Mean	43.08826	42.55379	38.2928	2.251454	3.330681	4.43684
Median	45.195	45.015	38.16917	1.282996	1.819442	3.077545
Maximum	301.285	87.805	107.6158	12.00704	14.10248	22.43006
Minimum	1.745833	1.72	3.538333	0	0	0
Std.Dev.	17.47134	12.71196	11.61162	2.363278	3.599877	4.265026
Skewness	5.878117	-0.644137	0.70576	1.149727	0.905703	0.953528
Kurtosis	87.1428	4.479365	6.233589	3.893398	2.752871	3.153219
$Jarque-Bera$	235494.4	125.5465	406.1317	198.5441	109.0414	119.4185
Probability	0	0	0	0	0	0
Observations	783	783	783	783	783	783

	CDD_{PT}	CDD_{ES}	CDD_{FR}	$WSavg_{PT}$	$WSavg_{ES}$	$WSavg_{FR}$
Mean	0.874864	1.071543	0.900092	3.529939	5.966993	2.601971
Median	0	0	0	2.908853	4.976699	2.429253
Maximum	9.009729	8.91479	10.60773	12.22416	19.2016	10.84552
Minimum	0	0	0	0.275082	0.606043	0.042626
Std.Dev.	1.472858	1.751397	1.724336	2.205962	3.488747	1.39227
Skewness	2.252565	1.754339	2.685284	0.945743	1.29511	1.141516
Kurtosis	8.432273	5.339177	10.9702	3.41704	4.545661	5.79865
$Jarque-Bera$	1624.914	580.1562	3013.477	122.3973	296.8325	425.5825
Probability	0	0	0	0	0	0
Observations	783	783	783	783	783	783

	$CAP_{PT,ES}$	$CAP_{ES,PT}$	$CAP_{ES,FR}$	$CAP_{FR,ES}$
Mean	1943.556	1914.928	968.0859	907.9869
Median	2000	1991.667	1025	893.7917
Maximum	2825	2800	1592	1686
Minimum	583.3333	0	0	0
Std.Dev.	354.9334	422.2091	343.1235	338.215
Skewness	-0.354533	-0.830241	-0.412352	-0.138102
Kurtosis	3.246843	3.979948	2.663116	2.711556
$Jarque-Bera$	18.39094	121.2834	25.89208	5.203325
Probability	0.000101	0	0.000002	0.07415
Observations	783	783	783	783

Table 4.2: Unit root tests

	$Ln(Price_{PT})$			$Ln(Price_{ES})$			$Ln(Price_{FR})$		
	Base	Peak	Off-peak	Base	Peak	Off-peak	Base	Peak	Off-peak
ADF test	-5.50968	-5.081277	-5.591612	-5.742864	-5.229794	-5.855462	-8.129518	-6.506648	-8.019838
(p-value)	0	0	0	0	0	0	0	0	0
PP test	-12.14137	-11.938	-10.5178	-12.8374	-13.49797	-10.08297	-8.370438	-10.17346	-8.134704
(p-value)	0	0	0	0	0	0	0	0	0

Table 4.3: Lag selection for estimated models

	Price VAR model				Price VARX model			
	Base				Base			
Lag Length Criteria	Lags	SC	HQ	Lag removed	Lags	SC	HQ	Lag removed
	5	-1.908569	-2.087095*	NA	8	-1.906685	-2.330686*	5
	Off-peak				Off-peak			
Lag Length Criteria	Lags	SC	HQ	Lag removed	Lags	SC	HQ	Lag removed
	4	-1.8528	-1.997853*	3 and 5	4	-2.02962	-2.319726*	2 and 3
	Peak				Peak			
Lag Length Criteria	Lags	SC	HQ	Lag removed	Lags	SC	HQ	Lag removed
	9	-0.18936	-0.501781*	NA	9	-0.156834	-0.614308*	NA

Table 4.4: Wind [km/h], HDD [°C] and CDD [°C] significant coeficients in the VARX model

Price	Base			Off-peak			Peak		
	$Wind_{PT}$	$Wind_{ES}$	$Wind_{FR}$	$Wind_{PT}$	$Wind_{ES}$	$Wind_{FR}$	$Wind_{PT}$	$Wind_{ES}$	$Wind_{FR}$
$Ln(Price_{PT})$	-0.044595***	-0.00698**	-0.030555***	-0.039812***	-0.008918***	-0.028936***	-0.044023***		-0.028454***
$Ln(Price_{ES})$	-0.039216***	-0.008206**	0.001949***	-0.034467***	-0.011182***	-0.030569***	-0.040425***		-0.035842***
$Ln(Price_{FR})$	-0.011778***	0.004933***	-0.026043***	-0.013359***	0.005413***	-0.031827***	-0.011167***	0.005514**	-0.023559***

Price	Base			Off-peak			Peak		
	HDD_{PT}	HDD_{ES}	HDD_{FR}	HDD_{PT}	HDD_{ES}	HDD_{FR}	HDD_{PT}	HDD_{ES}	HDD_{FR}
$Ln(Price_{PT})$	-0.022793**	0.021173***		-0.018878**	0.01577**			0.029344***	
$Ln(Price_{ES})$	-0.023982**	0.022046***		-0.02115***	0.01539***			0.03198***	
$Ln(Price_{FR})$			0.005925**			0.006523***			

Price	Base			Off-peak			Peak		
	CDD_{PT}	CDD_{ES}	CDD_{FR}	CDD_{PT}	CDD_{ES}	CDD_{FR}	CDD_{PT}	CDD_{ES}	CDD_{FR}
$Ln(Price_{PT})$									
$Ln(Price_{ES})$									
$Ln(Price_{FR})$		0.009751**			0.012561**				

***Significant at 1% level; **Significant at 5% level

Table 4.5: ATC [MW] significant coeficients in the VARX model

Price	Base				Off-peak				Peak			
	ATC_{PT-ES}	ATC_{ES-PT}	ATC_{ES-FR}	ATC_{FR-ES}	ATC_{PT-ES}	ATC_{ES-PT}	ATC_{ES-FR}	ATC_{FR-ES}	ATC_{PT-ES}	ATC_{ES-PT}	ATC_{ES-FR}	ATC_{FR-ES}
$Ln(Price_{PT})$		0.000219	0.0001			0.000194	0.000107			0.000234		
$Ln(Price_{ES})$	-0.0000783	0.000217	0.000101	-0.0000804	-0.0000772	0.000204	0.0000983			0.000234	0.000098	
$Ln(Price_{FR})$		-0.0000396	-0.000048			-0.0000426	-0.0000474				-0.0000559	

Table 4.6: Granger Causality test output

Base				Off-peak				Peak			
Dependent variable: $Ln(PRICE_{PT}^{Base})$				Dependent variable: $Ln(PRICE_{PT}^{Off-peak})$				Dependent variable: $Ln(PRICE_{PT}^{Peak})$			
Excluded	Chi-sq	df	Prob.	Excluded	Chi-sq	df	Prob.	Excluded	Chi-sq	df	Prob.
$Ln(PRICE_{ES}^{Base})$	64.20628	7	0	$Ln(PRICE_{ES}^{Off-peak})$	7.479638	2	0.0238	$Ln(PRICE_{ES}^{Peak})$	82.37085	9	0
$Ln(PRICE_{FR}^{Base})$	9.849958	7	0.1972	$Ln(PRICE_{FR}^{Off-peak})$	6.28496	2	0.0432	$Ln(PRICE_{FR}^{Peak})$	16.57064	9	0.0559
All	75.2216	14	0	All	13.68529	4	0.0084	All	96.15434	18	0
Dependent variable: $Ln(PRICE_{ES}^{Base})$				Dependent variable: $Ln(PRICE_{ES}^{Off-peak})$				Dependent variable: $Ln(PRICE_{ES}^{Peak})$			
Excluded	Chi-sq	df	Prob.	Excluded	Chi-sq	df	Prob.	Excluded	Chi-sq	df	Prob.
$Ln(PRICE_{PT}^{Base})$	59.98194	7	0	$Ln(PRICE_{PT}^{Off-peak})$	21.9215	2	0	$Ln(PRICE_{PT}^{Peak})$	81.87286	9	0
$Ln(PRICE_{FR}^{Base})$	12.4388	7	0.087	$Ln(PRICE_{FR}^{Off-peak})$	3.488184	2	0.1748	$Ln(PRICE_{FR}^{Peak})$	14.41109	9	0.1084
All	74.3406	14	0	All	26.26963	4	0	All	93.56819	18	0
Dependent variable: $Ln(PRICE_{FR}^{Base})$				Dependent variable: $Ln(PRICE_{FR}^{Off-peak})$				Dependent variable: $Ln(PRICE_{FR}^{Peak})$			
Excluded	Chi-sq	df	Prob.	Excluded	Chi-sq	df	Prob.	Excluded	Chi-sq	df	Prob.
$Ln(PRICE_{PT}^{Base})$	3.494701	7	0.8358	$Ln(PRICE_{PT}^{Off-peak})$	2.647241	2	0.2662	$Ln(PRICE_{PT}^{Peak})$	7.570412	9	0.5779
$Ln(PRICE_{ES}^{Base})$	1.431145	7	0.9846	$Ln(PRICE_{ES}^{Off-peak})$	3.714591	2	0.1561	$Ln(PRICE_{ES}^{Peak})$	7.315651	9	0.6043
All	11.49062	14	0.6471	All	5.277497	4	0.26	All	22.52213	18	0.2096

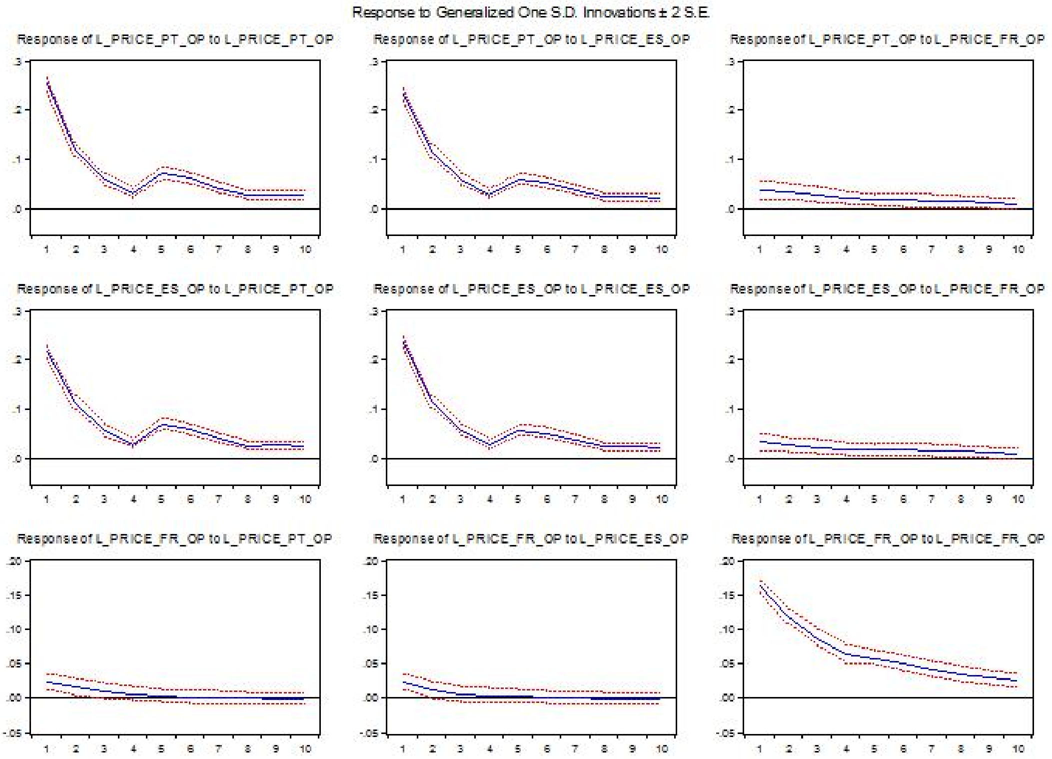

Figure 4.6: Impulse response plots for daily-log off-peak price models

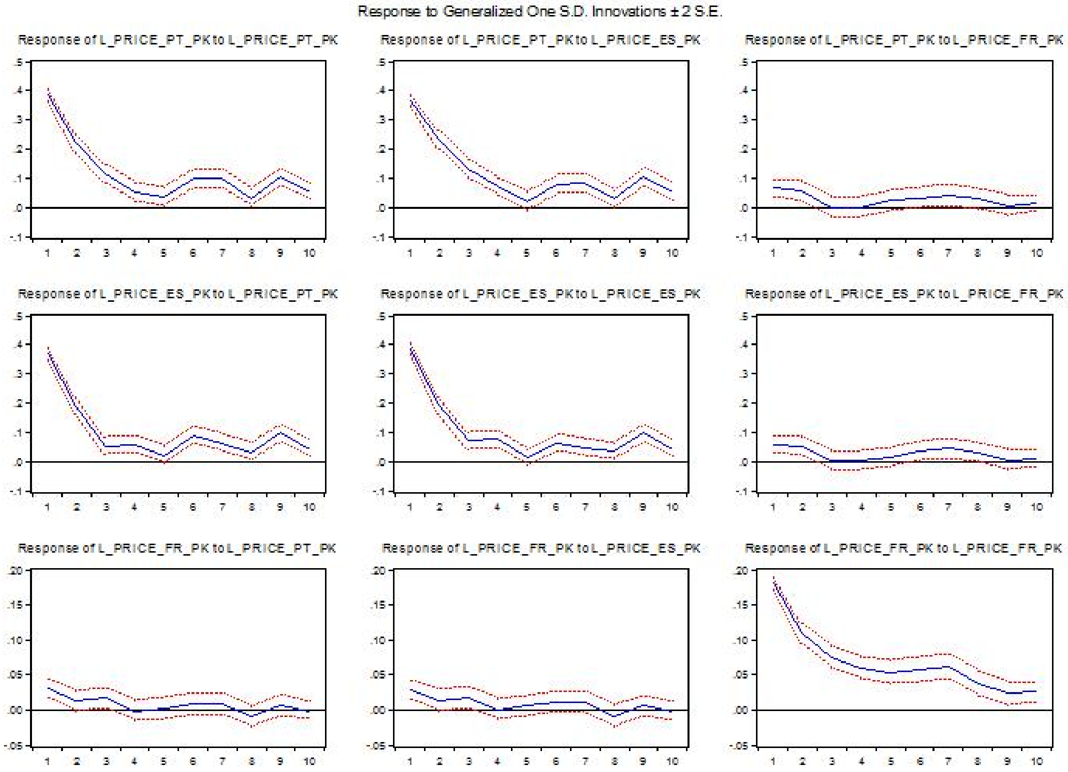

Figure 4.7: Impulse response plots for daily-log peak price models

4.3 Central-West Spot Electricity Markets Integration

Under this Section 4.3 the reader can find an assessment of the CWE REM integration level, before and after the introduction of market coupling with Germany. In Sub-section 4.3.1 overviews of the Belgium, Dutch, French, German and Luxembourg Electricity Markets are presented. Also in Sub-section 4.3.1 we provide a summary of the standing interconnections between the electricity transmission systems and of the existing power exchanges. A brief literature review is made in Sub-section 4.3.2. The spot electricity market data used in this study is presented and discussed in Sub-section 4.3.3 and in Sub-section 4.3.4 model estimation is described. Analysis and results are discussed in Sub-section 4.3.5.

4.3.1 The CWE electricity markets

The European Directive 96/92/EC was implemented in Belgium with the Electricity Act in April 1999, which created the regulator for the electricity market (CREG). Additionally, for electricity distribution below 70 kV three regional regulators were also created (VREG, CWaPE and Brugel) (International Energy Agency, 2010). Liberalisation was only initiated in June 2003 by phases, achieving completion on the end of 2006. In 2007 the legal unbundling was fully achieved with the TSO (ELIA) constituted as a legal monopoly (ELIA, 2013). Generation still remains highly concentrated (79% owned by Electrabel with the second largest 10% owned by Électricité de France (EDF) (ELIA, 2013; International Energy Agency, 2010). Additional details on the Belgian electricity market can be found in International Energy Agency (2010) and Verbruggen and Vanderstappen (1999).

In the Netherlands, the production cartel made of four companies was separated by the 1998 Electricity Act, together with non-discriminatory access to transmission network and creation of the TSO (TenneT), following the European Directive 96/92/EC (OECD, 1998). At the same time an independent regulator was created on the 1st August 1998 (the DTe) for the electricity sector supervision (van Damme, 2005). Liberalisation of the retail market was done in July 2004, together with the unbundling of the supply and distribution network (International Energy Agency, 2009b). Additional details on the Dutch electricity market can be found in van Damme (2005).

In France, EDF remains untouched, neither privatisation nor unbundling occurred (Newbery, 2005). With several acts of legislation, France managed to carry out the electricity sector reform (through the law 2000-108 of the 10th of February) without restructuring the main operator. An electricity market was created around a public monopoly (J.-m. Glachant & Lévêque, 2005). Further, the law 2000-108 of the 10th of February created the "Commission de Régulation de L'énergie" (CRE), the French regulator (Journal Officiel de la République Française, 2000). It was considered that competition would arise from abroad through the interconnections with the various European countries. The main reasoning behind this was the existence of a vast nuclear power capacity and associated low variable cost electricity (Newbery, 2005). Additional details on the French electricity market can be found in Lévêque (2010).

The German electricity market was fully opened with all consumers to be eligible. In April 1998 Germany implemented the European Directives with significant different measures from other Member States (Brunekreeft & Keller, 2000), namely, the negotiated Third Party Access (nTPA) with discrimination monitored by the federal antitrust agency (the Bundeskartellamt) (Green, Lorenzoni, Perez, & Pollitt, 2005). A regulator (the Bundesnetzagentur) was created by the new Energy Act in July 2005 in order to comply with the requirements set on the European Directive 2003/54/EC, paving the way for the necessary unbundling, after the vertically increasing market concentration observed (Newbery, 2005; Joskow, 2008). Additional details on the German electricity market can be found in Brunekreeft and Keller (2000) and International Energy Agency (2007).

Luxembourg is the smallest Member State in the European Union (EU). Here the European Directives were transposed into national law in August 2007. A regulator was accordingly created, the Institut Luxembourgeois de Régulation (ILR) and the electricity market became fully opened in July 2007 (International Energy

Agency, 2009a). The transmission network is legally unbundled having two TSOs (creos and Sotel) (Creos, 2013). Additional details on the Luxembourg electricity market can be found in (International Energy Agency, 2009a).

Creation of competition, improvement of supply security and increasing opportunities for operation with renewable energies are some of the advantages of interconnections (Figueiredo & Silva, 2012). However, constraints can occur and have to be managed by each TSO (Turvey, 2006). European Regulations established a set of rules for cross-border exchanges in electricity (European Union, 2010, 2009d, 2003c). The European Network of Transmission System Operators (ENTSO) was established, aiming to guarantee an efficient transmission network management, together with allowing trade and supply of electricity across borders. Interconnection costs are currently based on implicit auctioning, integrating electricity and transmission markets, also known as Market Coupling (Coppens & Vivet, 2006). The Net Transfer Capacities (NTC) declared between the CWE countries and respective installed electricity generation capacities are shown in Table 4.7 (ENTSO-E, 2011; European Commission, 2012).

Table 4.7: Indicative Values for NTC in CWE

from / to	NTC in MW agreed by both countries				
	BE	DE	FR	LU	NL
BE [19500][a]			3400		2400
DE [163800][a]			2700		3000
FR [125900][a]	2300	3200			
LU [1800][a]		980			
NL [28200][a]	2400	3850			

[a] Installed Electricity Generation Capacity in MW (European Commission, 2012)

In the Netherlands the APX power exchange was launched on the 18th of June 1999 with a day-ahead spot market (APX Group, 2014), followed by two exchanges in Germany in the year 2000: the Leipzig Power Exchange (LPX) and the European Energy Exchange (EEX). These were then merged in December 2001 (Bower, 2002). The French Powernext (PWNX) started operation in November 2001 (Bower, 2002). Market coupling between France, Belgium (BPX) and the Netherlands was launched in November 2006 (Powernext, 2013) and in November 2010 this was extended to Luxembourg (also EEX) and Germany (after the transfer of PWNX and EEX spot market into the new EPEX Spot in 2009) completing the coupling of the CWE electricity markets (EPEX, 2016).

4.3.2 Applicable Literature

European electricity market integration has been studied by several authors using econometric methods based on more or less recent data covering the initial phase of market functioning. Bower (2002) is believed to be one of the pioneer authors producing a study for Europe, relying on statistical methods. He based his study in correlation and cointegration analysis of daily electricity market prices for the year 2001 and reported good integration between the Netherlands (APX) and both German power exchanges (in Frankfurt and Leipzig - EEX). Recommendations for the implementation of the market splitting mechanism, the increase of interconnection capacity and the reduction of market concentration were then assumed.

The use of data correlation analysis was further used by Boisseleau (2004), Bosco et al. (2010), Bunn and Gianfreda (2010), and Figueiredo and Silva (2012). For the year 2002, high correlation between France and Germany was found and said to be “imperfectly integrated” as per the regression analysis made. Also weak correlation was reported between the pairs France-Netherlands and Germany-Netherlands, also confirmed by the regression analysis carried out (Boisseleau, 2004). With data from 1999 to 2006 (Bosco et al., 2010) or considering the period from July 2001 to July 2005 (Bunn & Gianfreda, 2010), strong correlation was found between France, Germany and the Netherlands. However, from cointegration testing (non-stationary data) France-Germany were found to be the only pair of strongly integrated markets (Bosco et al., 2010). By using Vector Autoregressive (VAR) models and Impulse Response Analysis, unidirectional shock transmissions were identified between the electricity market pairs France-Netherlands, France-Germany and Germany-Netherlands (Bunn & Gianfreda, 2010).

Electricity market convergence is also suggested by Armstrong and Galli (2005) between France, Germany and the Netherlands, through an exploratory data analysis of price differences variability, in spite of transmission constraints and lack of price transparency. Another approach was used by Zachmann (2008) who based his study on Principal Component Analysis of hourly electricity prices, concluding that market integration had not been achieved. Furthermore in his study, convergence was assessed through stationarity testing of price differences and price difference analysis, concluding that Germany and France electricity markets were converging.

Pellini (2012b) more recently reported "ongoing convergence" between the market pairs Belgium-France, France-Netherlands, Germany-Netherlands, based on fractional cointegration. Volatility transmission was also assessed using Multivariate Generalised Autoregressive Conditional Heteroskedasticity (MGARCH) models, establishing high return volatility spillover in the CWE electricity markets.

4.3.3 Data

Data was obtained from Datastream (2013) for the day-ahead spot electricity prices in Euro/MWh, except weekends. For this study base hours (1-24), peak hours (9-20) and off-peak hours (21-8) time series were used from the 1st of January 2007 to the 31st of December 2012. Figure 4.9 show that price spikes are easily detected in electricity markets, which confirm the high volatility behaviour of electricity spot prices, as in Goto and Karolyi (2004), Hadsell et al. (2004) and Higgs (2008). The limited possibility of storage, the physical characteristics of simultaneous electricity production and consumption, technical constraints in transmission and generating plants are among the main reasons for these spikes (Coppens & Vivet, 2006; Silva & Soares, 2008).

Bearing in mind that the so-called *"Trilateral Market Coupling"* (TLC) between Belgium, France and the Netherlands is being operated since the 21st of November 2006 (Powernext, 2013) and that later the CWE complete market coupling was achieved on the 9th of November 2010 (EPEX, 2016), we considered this date as the only structural break point in the time series data set.

To test for non-stationarity, or unit root, the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) statistics were performed in each time-series. As shown in Table 4.8 in both ADF and PP tests the null hypotheses was rejected, indicating stationarity for all time-series and agreeing with findings in Boisseleau (2004), Bunn and Gianfreda (2010) and Park et al. (2006).

4.3.4 Model Estimation

In order to describe the dynamic behaviour of economic and financial time series and to investigate the response of the different markets to price shocks, accounting for the stationarity of the data, VAR models were used (Bunn & Gianfreda, 2010; Lütkepohl, 2005; Sims, 1980). Consequently, 2 different models were estimated: one for data until the considered break point and another for data ranging from the break point until the end of the data set. A third VAR model considering the complete data set was estimated in order to apply a Chow Test to the structural break point for each of the four equations (Lütkepohl, 2005; Jeffrey M. Wooldridge, 2003). Results show the null rejection and a more detailed analysis had to be followed. Investigation of the resulting impacts of unexpected shocks or innovations on the variables in each model are evaluated and compared through impulse response functions IRF and Granger-causality. The VAR models applied to proceed with the evaluation of the electricity market integration are well known in the literature to have the ability to capture the linear interdependencies among the four price time series (Bunn & Gianfreda, 2010; Lütkepohl, 2005; Sims, 1980):

$$Y_t^{(z)} = C^{(z)} + \sum_{i=1}^{p} A_i^{(z)} Y_{t-i}^{(z)} + u_t^{(z)}, \tag{4.2}$$

where z is the base, peak or off-peak model, $Y_{t-i}^{(z)}$ are (4×1) day-ahead electricity price matrices, $C^{(z)}$ are (4×1) constant matrices, $A_i^{(z)}$ are (4×4) coefficient matrices and $u_t^{(z)}$ are (4×1) matrices of unobservable error terms.

In order to determine the lag length of each model, successive VAR models were estimated by a sequential test procedure, starting with the estimation of the models with $p = 12$ lags and calculating-down for lower lags the Akaike Information Criterion ((AIC), the Schwarz Bayesian criterion (BIC) and the Hannan-Quinn criterion (HQC). Table 4.9 reveals the best values for the endogenous variable lags where criteria are minimised. Residual autocorrelation testing using the Breusch-Godfrey

Table 4.8: Unit Root Statistics

	1st of January 2007 to 31st of December 2012			
	APX_{Base}	BPX_{Base}	EEX_{Base}	$PWNX_{Base}$
ADF test	-6.042278	-7.71214	-3.15675	-9.342647
(p-value)	0	0	0.0228	0
PP test	-16.21106	-18.47128	-12.80739	-31.67266
(p-value)	0	0	0	0
	APX_{Peak}	BPX_{Peak}	EEX_{Peak}	$PWNX_{Peak}$
ADF test	-7.068966	-4.187612	-3.146562	-8.567335
(p-value)	0	0.0007	0.0235	0
PP test	-22.79873	-25.868	-16.38921	-23.28758
(p-value)	0	0	0	0
	$APX_{Off-peak}$	$BPX_{Off-peak}$	$EEX_{Off-peak}$	$PWNX_{Off-peak}$
ADF test	-3.479258	-6.374085	-5.205614	-6.664819
(p-value)	0.0087	0	0	0
PP test	-7.041482	-18.0891	-14.54047	-17.26261
(p-value)	0	0	0	0

test in all models was performed, leading to some adjustment of the number of lags used in each model (results also presented in Table 4.9) (Lütkepohl, 2005). For each model a lag exclusion Wald test was performed in order to detect lags where the respective coefficients do not present significance in the model (Davidson & Mackinnon, 2004). These were then removed as also indicated in Table 4.9, notwithstanding further adjustments required by the residual autocorrelation testing. All equations in the VAR models satisfy the stability condition of no roots outside the unit circle.

4.3.5 Analysis and Discussion of Results

Granger Causality tests to the time-series variables and generalised IRF (Pesaran & Shin, 1998) displaying the responses of each daily-log price time-series to a standard error shock in one of the time-series, were carried out to the VAR models estimated.

4.3.5.1 Before market coupling with EEX

Considering the data set before the break point, results from the models establish that PWNX does not Granger-cause the other three CWE day-ahead base market prices at a 5% significance level. The IRF plots seen in Figure 4.10 show that there is a very weak response of APX and EEX and a slightly better response of BPX to a shock in PWNX, consistent with the Granger-causality test results and confirming results found by Bunn and Gianfreda (2010). However, APX, BPX and EEX Granger-cause PWNX day-ahead base market prices, confirmed by the response of PWNX to shocks in APX, EEX and especially in BPX as per the IRF plot in Figure 4.10. Granger-causality in both directions was found between APX, BPX and EEX. The IRF plots confirm this with stronger responses between APX and BPX, but still with some small measurable impact on EEX in spite of the absent price coupling mechanism at this stage (Figure 4.10).

Likewise with this data set, PWNX does not Granger-cause EEX and BPX day-ahead off-peak market prices, while BPX does not Granger-cause EEX and APX day-ahead off-peak market prices. It is worth mention that in spite PWNX Granger-causes APX day-ahead off-peak market prices, the IRF plot in Figure 4.11 indicate a weak response of APX to a shock in PWNX day-ahead off-peak market prices. Similarly to refer is the strong response of PWNX to BPX day-ahead off-peak market prices and vice-versa (Figure 4.11), indicating strong integration as also found in the day-ahead base market prices (Figure 4.10).

Regarding day-ahead peak market prices, there is Granger-causality established in both directions for all markets, confirmed by strong responses in all cases. A remark should be taken to a weaker response of EEX to shocks in other markets (Figure 4.12). This complement findings in Bunn and Gianfreda (2010) by establishing evidence that there is higher integration during peak periods.

4.3.5.2 After market coupling with EEX

Considering the data set after the break point, results establish that PWNX Granger-causes the other three CWE day-ahead base market prices. This is an indication that something changed at the break point. However, the IRF plots still show weak responses of all other three CWE markets to PWNX shocks (Figure

4.13). Plus, APX and BPX are found not to Granger-cause EEX in the day-ahead base market prices, having the IRF plot showing small positive responses on EEX (Figure 4.13). EEX does not Granger-cause PWNX in the day-ahead base, off-peak and peak market prices, notwithstanding the strong response observed in PWNX to a shock in EEX day-ahead peak market prices (Figure 4.15).

It was also found that APX does not Granger-cause PWNX and BPX day-ahead off-peak market prices, confirmed by the weak response observed in the IRF (Figure 4.14). Additionally, in this data set we can observe non Granger-causality between BPX and EEX day-ahead peak market prices in both directions. The IRF plots (Figure 4.15) show a weak response in both these cases. EEX is found not to Granger-cause APX, which is confirmed by the weak response observed (Figure 4.15). BPX does not Granger-cause EEX and APX, however there is a strong response of PWNX to BPX day-ahead peak market prices, also seen in PWNX to a shock in APX (Figure 4.15).

Figure 4.8: Illustration of Net Transfer Capacities in Europe (summer 2010/11) (ENTSO-E, 2012)

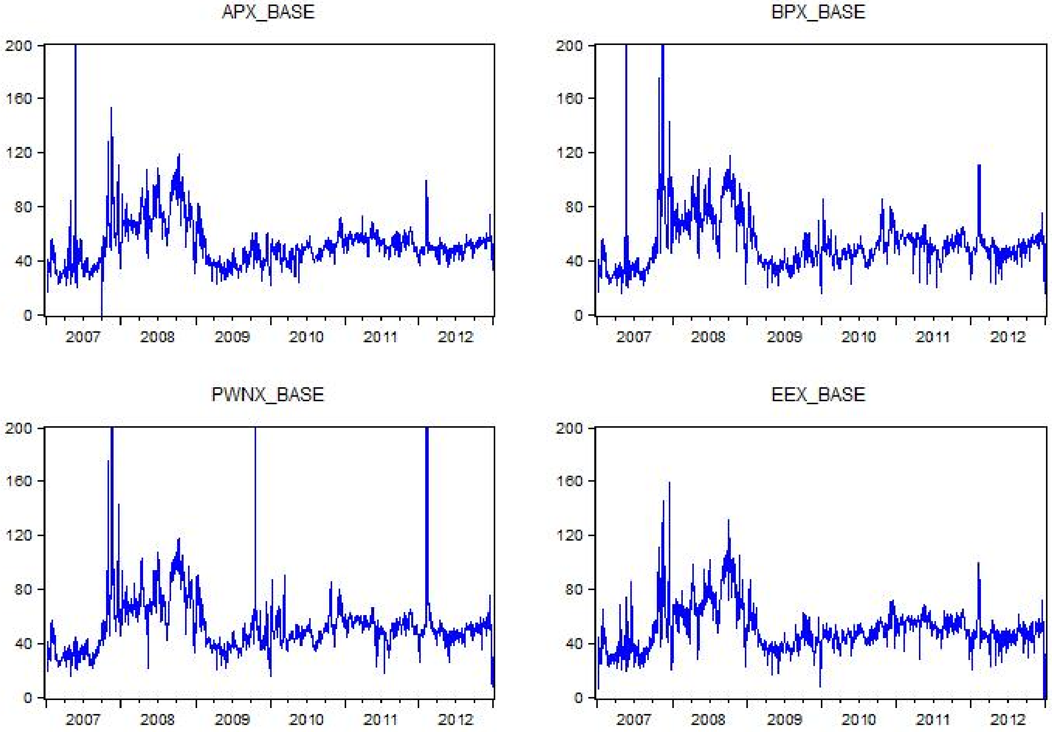

Figure 4.9: Day-ahead daily-base spot electricity prices in Euro/MWh

Table 4.9: Model Lag Length

	1st of January 2007 to 31st of December 2012			
	Base - 5 lags			
Lag Length Criteria	Lags	AIC	SC	HQ
	4	29.10494*	29.3385	29.19178*
Breusch-Godfrey LM test	Lags	test value	p-value	Note: No lags removed
	6	17.14379	0.3764	
	Off-peak - 6 lags			
Lag Length Criteria	Lags	AIC	SC	HQ
	3	24.03271	24.21169*	24.09927*
Breusch-Godfrey LM test	Lags	test value	p-value	Note: No lags removed
	7	22.66547	0.123	
	Peak - 5 lags			
Lag Length Criteria	Lags	AIC	SC	HQ
	4	31.5571	31.79115	31.64414*
Breusch-Godfrey LM test	Lags	test value	p-value	Note: No lags removed
	6	19.54786	0.2413	
	1st of January 2007 to 8th of November 2010			
	Base - 4 lags			
Lag Length Criteria	Lags	AIC	SC	HQ
	3	30.1222	30.37863*	30.21969*
Breusch-Godfrey LM test	Lags	test value	p-value	Note: No lags removed
	5	25.72287	0.0581	
	Off-peak - 6 lags			
Lag Length Criteria	Lags	AIC	SC	HQ
	3	23.94289	24.19931*	24.04037*
Breusch-Godfrey LM test	Lags	test value	p-value	Note: No lags removed
	7	26.20246	0.0512	
	Peak - 5 lags			
Lag Length Criteria	Lags	AIC	SC	HQ
	4	31.55327	31.8886	31.68076*
Breusch-Godfrey LM test	Lags	test value	p-value	Note: No lags removed
	6	23.40181	0.1034	
	9th of November 2010 to 31st of December 2012			
	Base - 6 lags			
Lag Length Criteria	Lags	AIC	SC	HQ
	3	25.073	25.47488	25.22992*
Breusch-Godfrey LM test	Lags	test value	p-value	Note: Lag 5 removed
	5	12.80029	0.6873	
	7	12.82715	0.6854	
	Off-peak - 6 lags			
Lag Length Criteria	Lags	AIC	SC	HQ
	3	22.63323	23.03511	22.79015*
Breusch-Godfrey LM test	Lags	test value	p-value	Note: No lags removed
	7	25.00172	0.0698	
	Peak - 6 lags			
Lag Length Criteria	Lags	AIC	SC	HQ
	2	27.20328	27.48151	27.31192*
Breusch-Godfrey LM test	Lags	test value	p-value	Note: No lags removed
	7	14.22682	0.5818	

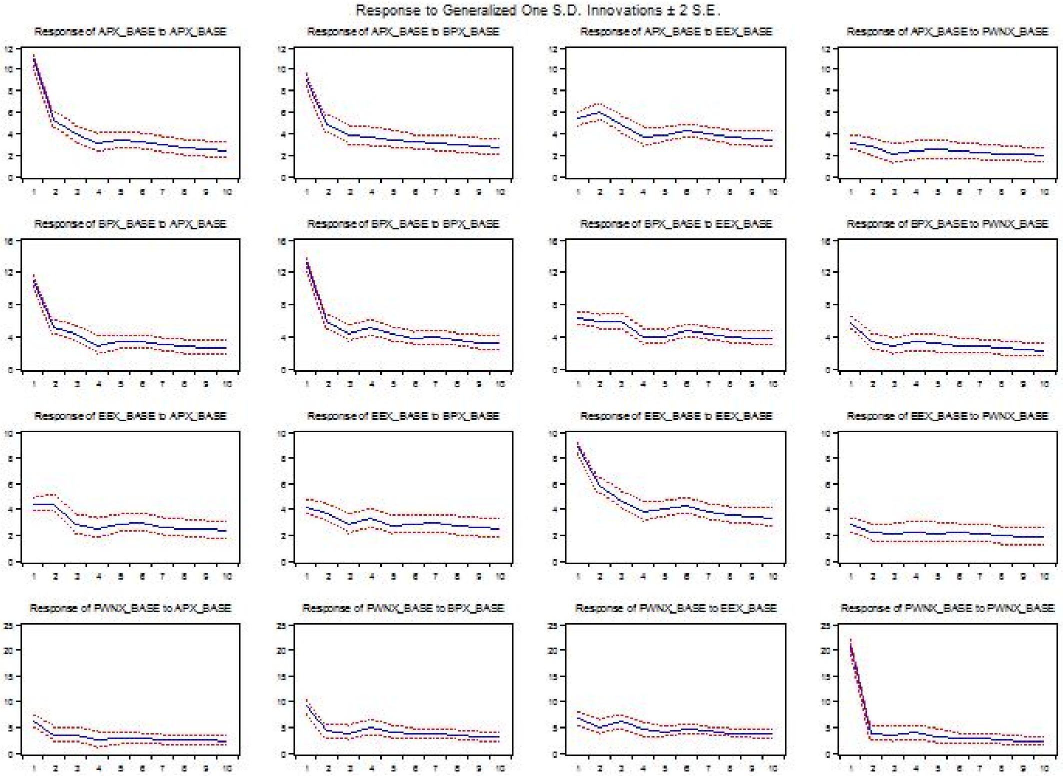

Figure 4.10: IRF plots – day-ahead base market prices – data set before break point

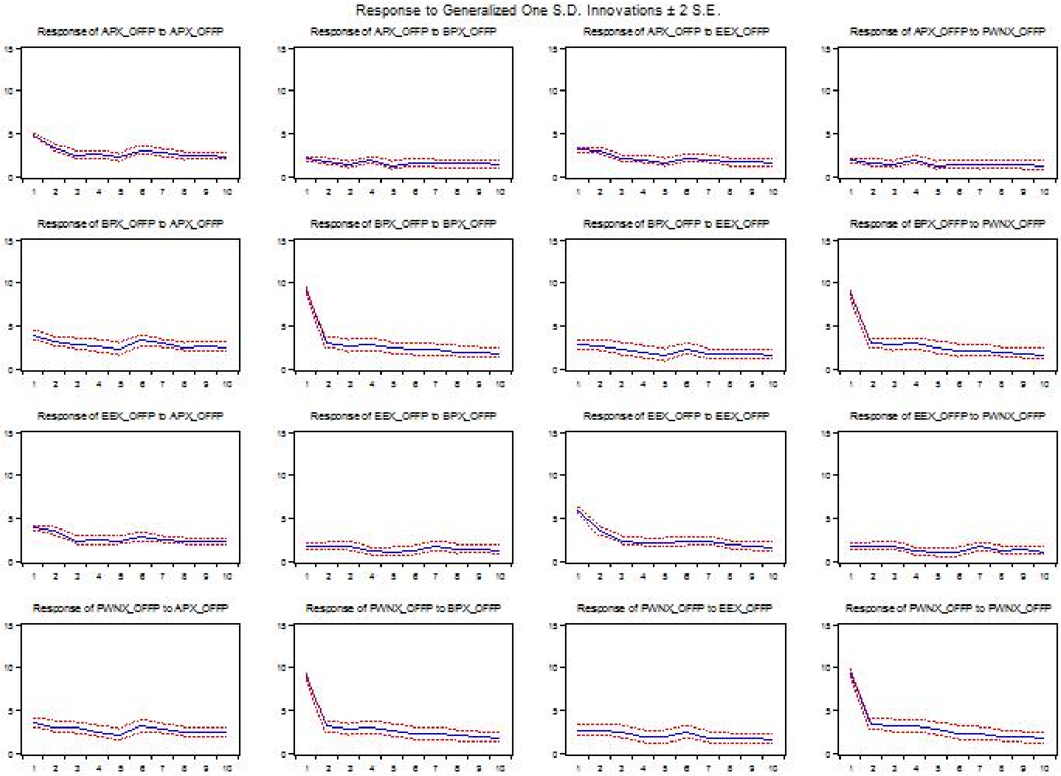

Figure 4.11: IRF plots – day-ahead off-peak market prices – data set before break point

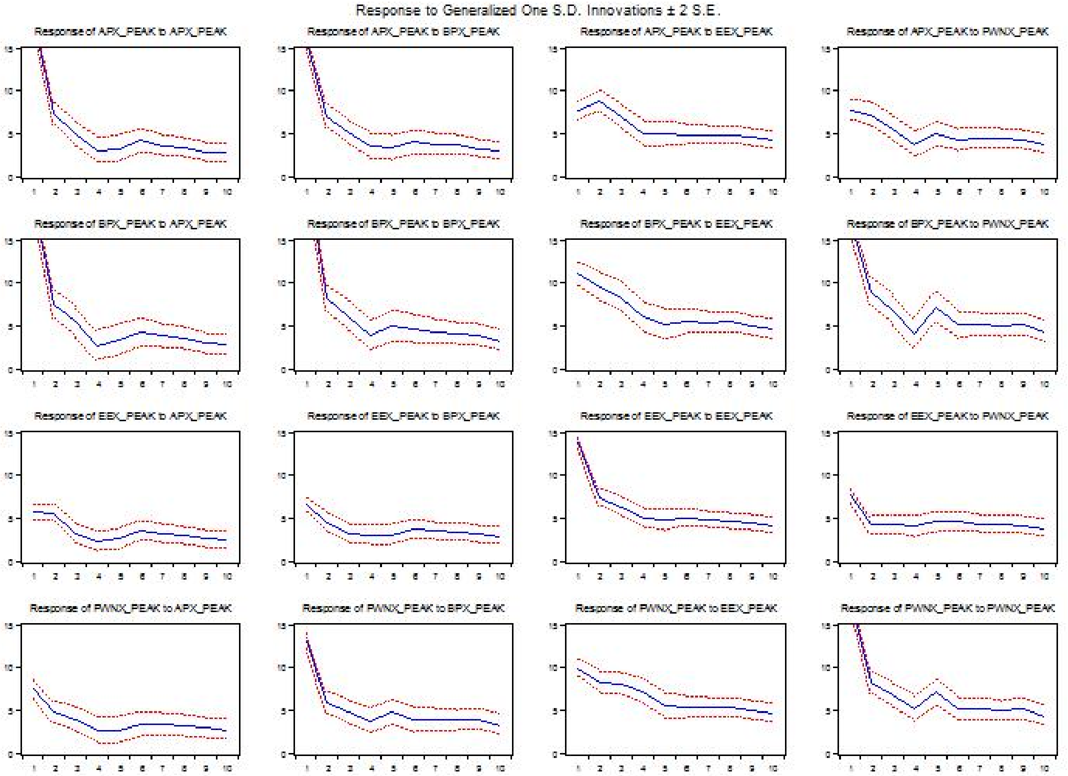

Figure 4.12: IRF plots – day-ahead peak market prices – data set before break point

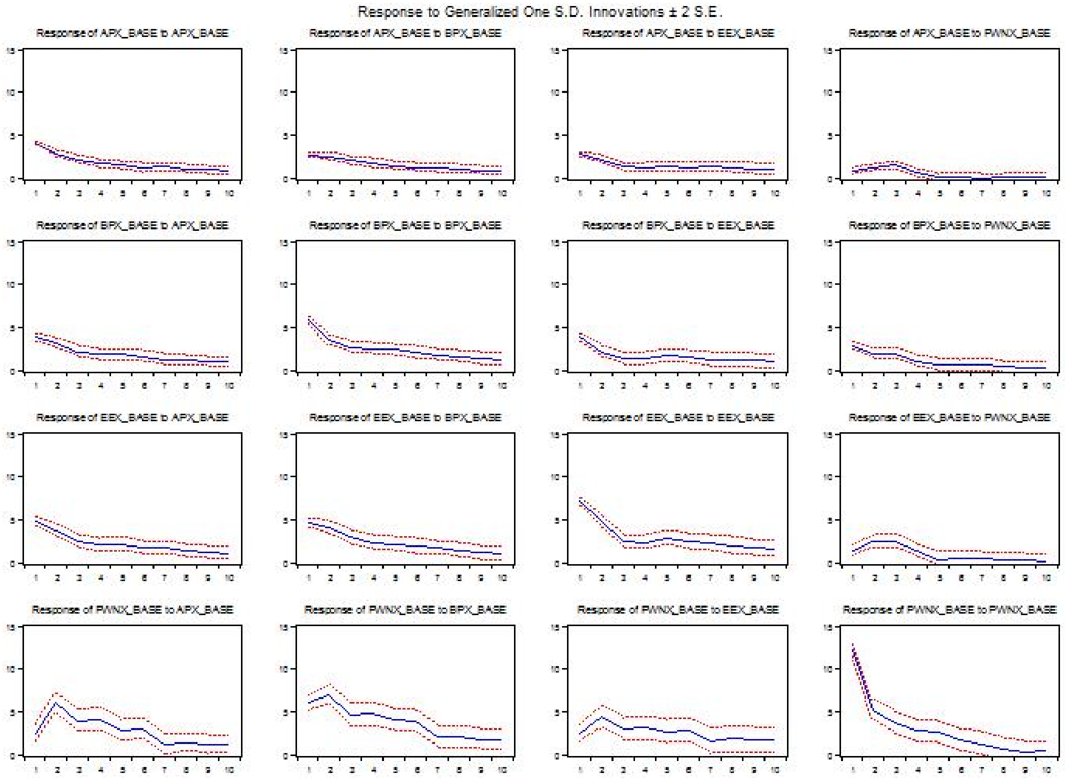

Figure 4.13: IRF plots – day-ahead base market prices – data set after break point

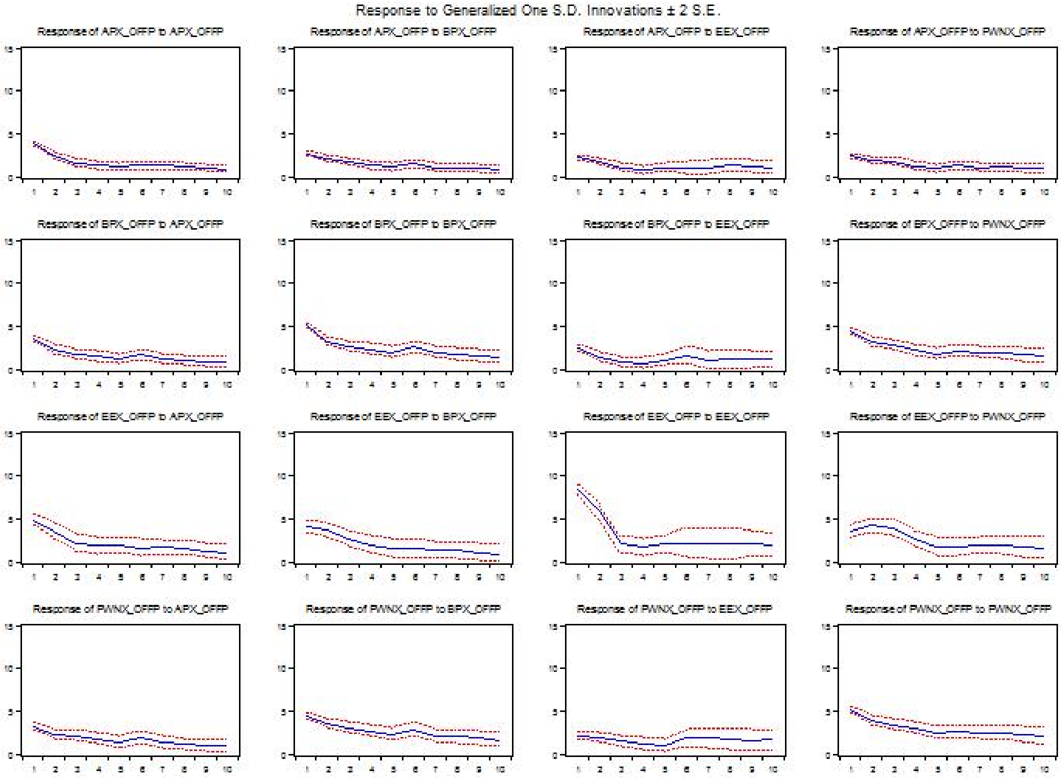

Figure 4.14: IRF plots – day-ahead off-peak market prices – data set after break point

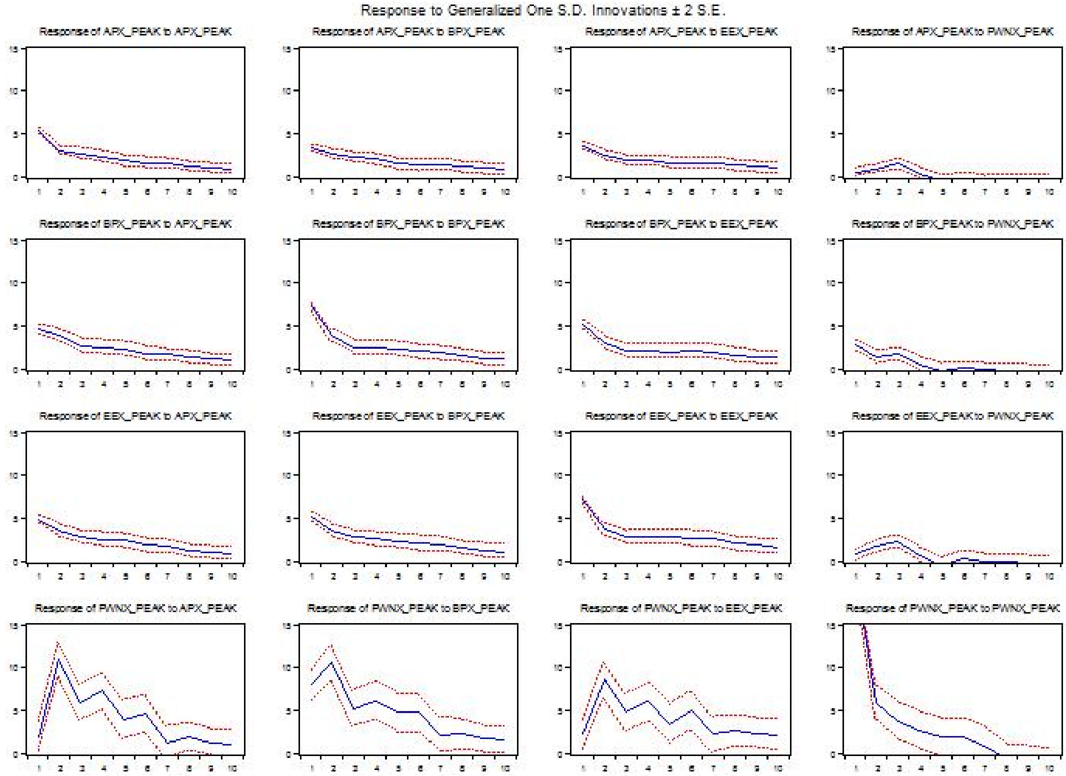

Figure 4.15: IRF plots – day-ahead peak market prices – data set after break point

Chapter 5

Regional transmission of renewable energy price effects

5.1 Motivation

European policy to increase market integration in wholesale electricity trading has been intensively pursued since the vision of a single energy market emerged in the 1990s. Whilst the need for more interconnectors and harmonisation of trading was initially motivated by the pursuit of economic efficiency and greater competition, policy-makers have been encouraged further in this direction by the emergence of substantial amounts intermittent renewable generation. The rapid rise in generation from wind and solar in particular, again motivated primarily by policy, raises concerns about security of supply in the longer term and also efficient system balancing in the short term, both of which appear to be remedied to some extent by more regional interconnectivity. Moreover, with the renewable energy sources (RES) capacity forecast to grow substantially, ENTSO-E (2015b) emphasise the growing importance of cross-border electricity flows in order to maintain generation adequacy. In this context, therefore, it is easy to understand why there has been extensive research on modelling the progress of market integration in electricity prices, expressed both in terms of price convergence and the dynamics of shock transmissions. However, the inter-regional price effects of large volumes of renewable energy are awkward to clarify, and the impact of weather has generally been under-specified in the market integration studies. Large volumes of renewable energy are weather induced, and their local price effects might transmit to neighbouring markets, arbitrage permitting, but weather conditions are also correlated across regions. Thus, even without interconnections, common weather conditions induce price co-movements. Furthermore, weather affects both the demand and supply sides of the markets in different ways and these will be idiosyncratic to the consumption drivers and generation technology mixes in each market. Unravelling these confounding factors is particularly important for system operations and price risk management. For example, the use of weather insurance, derivatives or other hedges require explicit models of price transmission between regions that distinguishes arbitrage effects from weather spillovers.

The objective of this paper is therefore to undertake a detailed econometric analysis of price transmission in the daily coupled wholesale market of Central-West Europe (CWE) taking explicit account of renewable energy generation and with a focus upon the particular weather variables wind, temperature and their interaction (wind chill). The next section provides a review of relevant background research, followed by summaries of the European Union initiatives for market integration, renewable energies and the emergence of the CWE market. The data and analysis follow. On the basis of results from some large vector-autoregression models in section, we offer some new insights.

5.2 Background research

Weather conditions are essential variables for demand forecasting and numerous methods have developed over many years to model ambient temperatures in various forms, wind speed with its associated wind chill effects, humidity, cloud coverage and others. Maximum and minimum ambient temperatures were used for demand forecasting in Italy by Sforna (1995), whilst Islam, Al-Alawi, and Ellithy (1995) in Muscat used selected climate variables according to their correlation with electricity demand (maximum temperature, maximum and average relative humidity, wind speed, duration of sunshine, global radiation, degree days and a comfort index). Correlation of electricity demand and climate variables was also used to select adequate input variables by Santos, Martins, and Pires (2007) and

Amjady and Keynia (2009). Robinson (1997) simply used a daily average ambient temperature in demand forecasting. Sailor and Muñoz (1997) used in addition to ambient temperature, relative humidity (in the form of enthalpy latent days) and wind speed, all population-weighted. Taylor (2003) improved on the existing use by the UK National Grid of single point weather forecasts, by using weather ensembles. A population-weighted mean daily outdoor temperature was used by Pardo, Meneu, and Valor (2002) to calculate heating and cooling degree days (Heating Degree-dayss (HDDs) and Cooling Degree-dayss (CDDs)) for a demand model to account for the influence of temperatures on demand. The use of HDD, CDD and the mean relative humidity was also used by Mirasgedis et al. (2006) in statistical models for the daily and monthly electricity demand prediction for Greece. Bessec and Fouquau (2008) assessed the influence of temperature on demand across Europe and found a non-linear relation with a clear heating effect. Moreover, the cooling effect was more important in the south European countries with a clear U-shape relation. Suganthi and Samuel (2012) performed a comprehensive review of the types of models used for demand forecasting, most of them involving climate conditions as explanatory variables. A study of climate determinants on demand was carried out for Italy (De Felice, Alessandri, & Ruti, 2013) highlighting the importance of the increasing installation of air conditioning in the electricity demand since 2003. To the extent that price forecasts depend upon demand, all of these weather effects pass through implicitly (Bordignon, Bunn, Lisi, & Nan, 2013; Karakatsani & Bunn, 2008b). The introduction of weather determinants on electricity price forecasting is explicitly mentioned by many researchers (Gianfreda & Grossi, 2012; Karakatsani & Bunn, 2008a). However, Lei Wu and Shahidehpour (2010) suggest that weather variables might cause overfitting and model inaccuracies. Nevertheless, Weron and Misiorek (2008) used ambient temperatures in the electricity price forecasting model for Nord Pool. Comprehensive reviews of electricity spot price modelling are made by Higgs (2008) and by Aggarwal et al. (2009), which report the use of ambient temperature as an input variable. Furthermore, Higgs and Worthington (2008), Christensen, a.S. Hurn, and Lindsay (2012) and Zachmann (2013) recognise that, in their multi-state models, the transition probabilities and electricity price spikes are, or may be, weather dependent. Wind power forecasts are used in electricity price forecasting by Cruz et al. (2011), Jónsson, Pinson, Nielsen, Madsen, and Nielsen (2013) and Ziel, Steinert, and Husmann (2015) with appealing results, demonstrating model performance improvements. The latter also included solar power in the electricity price forecasting of Germany and Austria. Additionally, Keles, Genoese, Möst, Ortlieb, and Fichtner (2013) introduces a self-contained wind power forecast, which is then used in the electricity price forecast.

Regarding the interconnection of regional electricity markets, De Vany and Walls (1999) looked at market integration across eleven regions in the western United States using spot market electricity prices from 1994 to 1996, aggregated by peak and off-peak values, as did Park et al. (2006). In Australia, Worthington et al. (2005) examined the integration of the Australian National Electricity Market, but found poor integration. Later, Higgs (2009) also assessed the Australian National Electricity Market in terms of the level of integration, examining the inter-relationships of wholesale spot electricity prices among four markets, finding by then that the highly interconnected markets have higher conditional correlations. In Europe several studies have looked at market integration (e.g. Bunn and Gianfreda (2010), Figueiredo and Silva (2013c)). Econometric methods have been based upon on correlations, cointegration analysis, fractional cointegration, exploratory data analysis of price differences variability, vector autoregressive (VAR), vector error correction models (VECM), Granger-causality, principal components and impulse response analyses. The Central-West Europe (CWE) region was found to be integrated in these studies and increasingly so over time. Lately the authors specified a number of VAR models to evaluate the effects of the introduction of the market coupling mechanism between the trilateral market (Belgium, France and the Netherlands) and Germany, leading to the conclusion that this has created an apparent smoothing of the responses to innovations of the integrated CWE markets (Figueiredo & Silva, 2013c).

5.3 Market integration, renewable energies and the CWE

Directive 90/547/EEC on the transit of electricity through transmission grids (European Union, 1990b) aligned to Directive 90/377/EEC concerning the transparency of gas and electricity prices charged to industrial end-users (European Union, 1990a), provided the first steps for the creation of the internal European electricity market. Later, Directives 96/92/EC, 2003/54/EC and 2009/72/EC established harmonised rules for the various electricity markets (European Union, 1997, 2003a, 2009b). Regulatory agencies were created throughout the European Member States in order to transpose and implement the local corresponding laws and regulations. The main regulatory functions aimed to: provide licensing, perform monitoring of activities, set and implement tariffs, and to protect customers (Banovac, Glavic, & Tesnjak, 2009). In 2006, market integration in Europe was still far from being achieved (Coppens & Vivet, 2006), and this led the European Commission to foster an Agency for the Cooperation of Energy Regulators (ACER) which in turn launched seven Electricity Regional Initiatives (Karova, 2011; Meeus & Belmans, 2008), one of which, the Central West (Belgium, France, Germany, Luxembourg, Netherlands) is the focus here.

Almost simultaneously with the initiatives for market integration, Directives 2001/77/EC and 2009/28/EC, called for the promotion of electricity generation by RES in Europe. The aim was to reduce dependency on imported fossil fuels for both security and low carbon reasons. The large deployment of RES generation in Europe was achieved through a programme of strong financial support mechanisms (Amorim, Vasconcelos, Abreu, Silva, & Martins, 2013; de Jager et al., 2011; Meyer, 2003), including feed-in tariffs, feed-in premia, fiscal incentives, tax exemptions and others. The RES electricity (RES-E) generation in Europe was 467,7 TWh in 2013 consisting of 42.4% hydroelectric, 27.4% wind, 10.4% solar, 9,9% biomass and 10% of other renewable technologies (Eurostat, 2015). The CWE electricity markets, in particular Germany, have been prominent in this structural change and Figure 5.1 displays the generating capacity mix in 2012 (excluding Luxembourg). Clearly the four countries are very different in both scale and mix.

The impact of RES-E on electricity markets has been discussed widely. Wind,

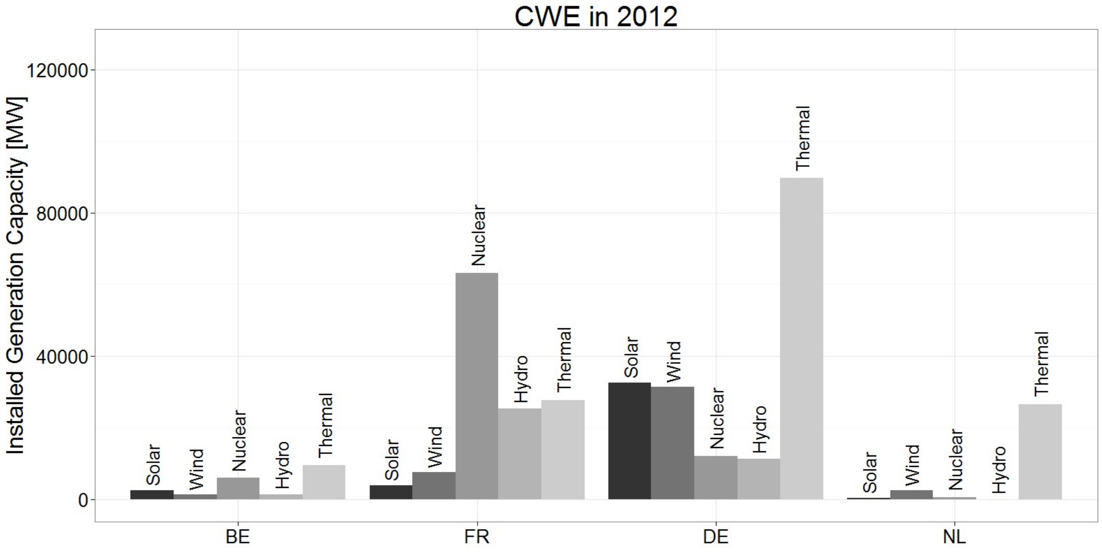

Figure 5.1: CWE installed generation capacities in 2012

for example, like any low marginal cost generation displaces higher marginal cost technologies and this ”merit-order effect” is well recognised in leading to lower wholesale prices (Würzburg et al., 2013). Evidently, the extent of this merit order effect will depend upon the slope of the merit order stack around the demand levels. If it is quite flat, with a lot of similar generating technology, e.g. the stack of thermal coal plant in Germany, the wind depression on prices may not show at normal times but only perhaps at low demand periods. How the wind effects may then transmit to neighbouring markets is even more complex. We analyse this process in the following sections.

5.4 Transmission of renewable energy and CWE market specificities

Whilst we expect higher renewable energy volumes in a particular market to lower prices, depending upon the slope of the supply function, how that effect spills over to neighbours will depend upon various circumstances. Thus, if the interconnector is congested or if the price spread does not motivate arbitrage, no power will flow, and if the slope of the neighbour's supply function is too flat, or if the volumes involved are immaterial, the price changes will be minimal. Thus, we cannot simply presume that a country with a lot of wind generation will necessarily be a major influence on neighbouring prices. Likewise, we cannot expect a small country to make a substantial impact on a much larger country's prices. Furthermore, it is possible to envisage a process whereby wind volumes may not affect one country, because of a flat supply function, but may get exported and substantially reduce prices for a neighbour. And weather conditions in neighbouring countries could have counter-balancing demand side effects that induce apparently counter-intuitive spillovers. For example, high wind in one country that has relatively little wind production but a substantial amount of electric heating (e.g. France) could cause an increase demand (and hence prices) because of wind-chill (Agency, 2009), and so the import of wind-generated excess power from a neighbouring country (e.g. Germany) may actually appear to be correlated with higher price. To explore these and other specificities, we first look at the CWE interactions.

In Figure 5.2, taken from ENTSO-E (2015a) we see that most of the cross-border export flows are from France to Germany and to Belgium, from Germany to the Netherlands, and from the Netherlands to Belgium, but they are all variable and flows do reverse. Figure 5.3 shows the influence of wind speed [1] on electricity cross-border flows and these scatter plots do not indicate strong correlations of cross-border flows with wind speed [2]. Only flows from Germany to the Netherlands seem to be associated with higher wind speeds, but this appears to be due a few influential observations. All of which raises the question of whether there is indeed less cross-border impact of wind than expected, or whether there are confounding factors. In the next section, therefore, we estimate some vector time-series models to identify weather and price spillover effects and explore these interactions.

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[1] Daily average wind speed (in km/h) taken from www.wunderground.com (Weather Wunderground, 2015)

[2] Correlations between cross-border-flows and wind speed are available upon request

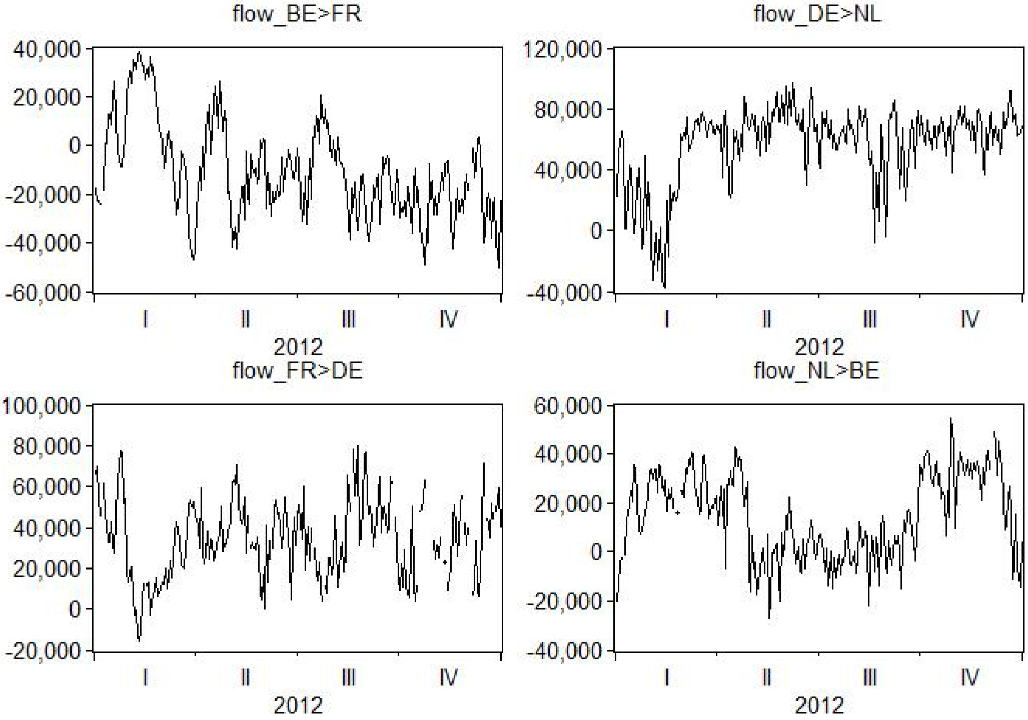

Figure 5.2: CWE electricity cross-border flows (flow) [MWh] in CWE in 2012 (Belgium – BE, France – FR, Germany – DE and the Netherlands - NL)

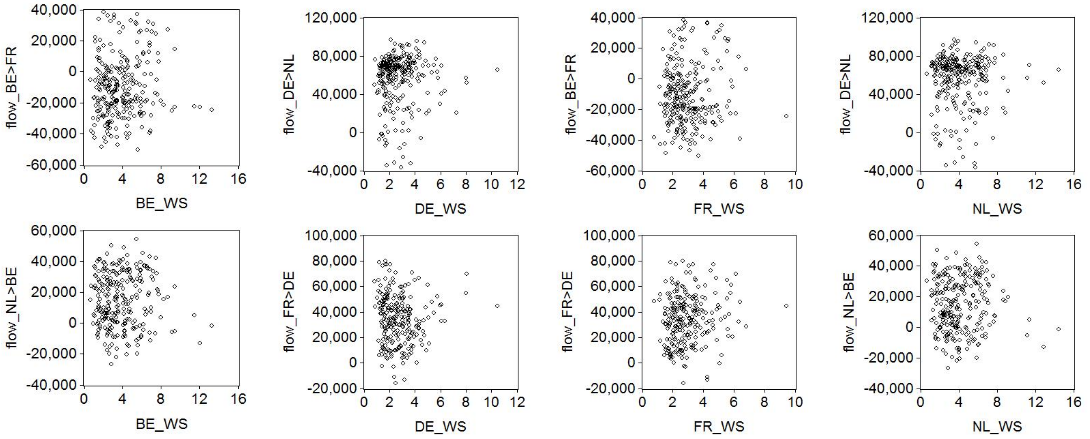

Figure 5.3: Scatter plots of Daily Average Wind Speed (WS) [km/h] vs Electricity Cross-border Flows (flow) [km/h] in 2012 (Belgium – BE, France – FR, Germany – DE and the Netherlands - NL)

5.5 Data and vector modelling

Price data was extracted from Datastream (Datastream, 2015) for the day-ahead spot electricity prices in Euro/MWh, except weekends, from the 1st November 2007 to the 31st December 2014. We focus on peak prices (hours 9-20) since it is during high demand periods that extra transmission capacity should be valued efficiently. Figure 5.4 displays the price time series, which exhibit the usual characteristics of volatility clustering and spikes (Goto & Karolyi, 2004; Hadsell et al., 2004; Higgs, 2008; Coppens & Vivet, 2006; Silva & Soares, 2008). The mean-reverting nature was confirmed with Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) test statistics indicating stationarity as in Boisseleau (2004), Park et al. (2006) and Bunn and Gianfreda (2010). Daily weather data was retrieved from www.wunderground.com (Weather Wunderground, 2015): maximum and minimum ambient temperatures (in degrees Celsius) and average wind speed (in km/h) for each country of the CWE. Maximum and minimum ambient temperatures were then used to calculate Heating Degree-days (HDD) [3] according to the UK Meteorological Office method (Mourshed, 2012; UK Climate Projections, 2013). A proxy for wind power was obtained through the product of average wind speed and installed wind power capacity [4]. Also a proxy for the wind chill effect was obtained through the product of wind speed and HDD. In previous work (Figueiredo & Silva, 2013a), the authors established that cloud cover as an exogenous variable did not contributed significantly to explain CWE electricity market prices, therefore this variable was not used. Furthermore, as precipitation would only be fully specified if used in conjunction with reservoir levels, that was, for practical reasons, outside our scope for such a large region being studied.

Following the widespread use of VAR models (Lütkepohl, 2005; Sims, 1980), to evaluate electricity market integration, as in Bunn and Gianfreda (2010) and Freitas and Silva (2013), VARX models were estimated. These models allowed separate contemporaneous and lagged effects of price and weather induced spillovers to be assessed. Since our analysis was not concerned with the intraday effects of weather forecast errors, we used the actual measured daily climate data. Ge-

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[3] Base temperature of 15.5 degrees Celsius.

[4] Some assumptions were made: perfect wind speed predictions and average wind speed representative for the peak period.

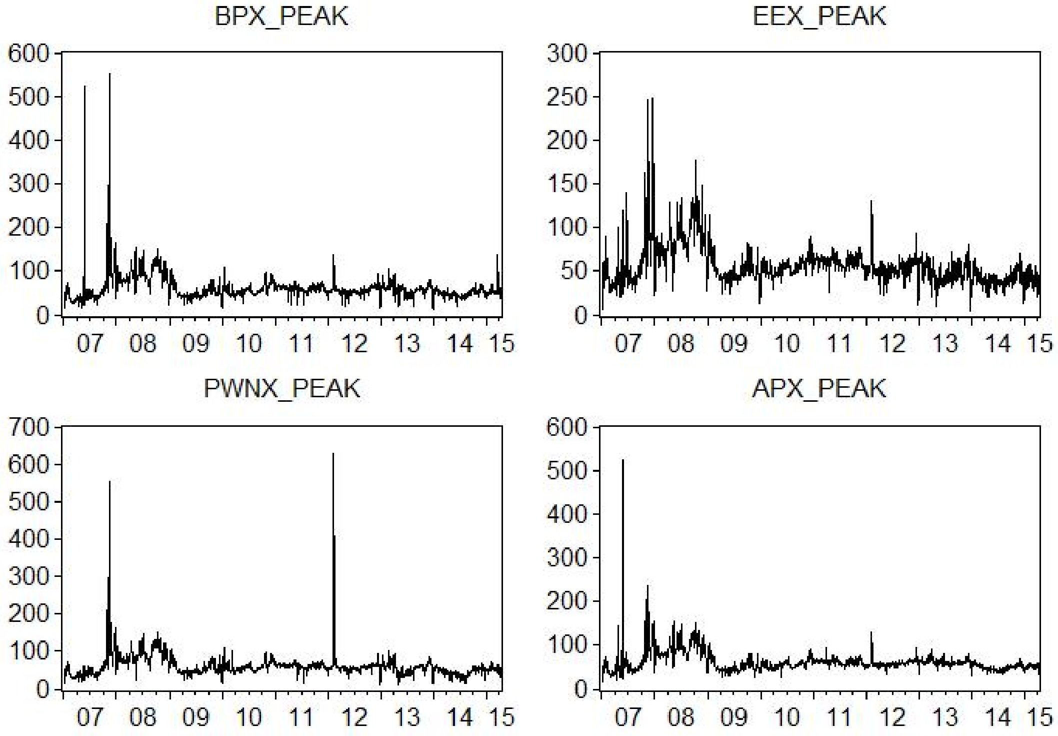

Figure 5.4: Day-ahead spot electricity prices in Euro/MWh (BPX – Belgium, PWNX – France, EEX – Germany, APX – the Netherlands)

neralised Impulse Response Analysis (Pesaran & Shin, 1998) was finally used to enable an investigation of the overall potential impacts of unexpected shocks or innovations on the endogenous variables.

The most general form of the model, VARX, is as follows:

$$Y_t = C + \sum_{i=1}^{p} A_i Y_{t-i} + BX_t + u_t \tag{5.1}$$

where Y_t is the log day-ahead electricity price matrix, C is the constant matrix, A_i and B are coefficient matrices, X_t is the exogenous variable matrix and u_t is the matrix of unobservable error terms. The Schwartz Bayesian criterion (BIC) and the Hannan-Quinn criterion (HQC) were used to determine the lag length of each model in a sequential test procedure through successive estimation, starting with 15 lag models and calculating-down for lower lags. The endogenous variable lags where criteria are minimised are presented in Table 5.1 for the three estimated models. The Breusch-Godfrey test for residual autocorrelation was performed to all models, indicating adjustment of the number of lags used in each model (Lütkepohl, 2005). Also a lag exclusion Wald test was performed to each model, in order to detect lags with non-significant coefficients (Davidson & Mackinnon, 2004). The stability condition of no roots outside the unit circle is satisfied for all equations in the models.

For the first model (VAR Peak), all variables are considered to be endogenous (there were no exogenous variables considered), in order to capture the corresponding inter-relationships, therefore,

$$Y_t^T = (BPX_{peak}, PWNX_{peak}, EEX_{peak}, APX_{peak}, WS_z{\cdot}Wcap_z, HDD_z, WS_z{\cdot}HDD_z)_t.$$

where z is the subscript for Belgium, France, Germany and the Netherlands.

In the second model (VARX Peak), the price inter-relationships and the influence of wind power, heating degree days and wind chill on prices are captured, therefore, the endogenous variable matrix is:

$$Y_t^T = (BPX_{peak}, PWNX_{peak}, EEX_{peak}, APX_{peak})_t,$$

and the exogenous variable matrix is:

$$X_t^T = (WS_z \cdot Wcap_z, HDD_z, WS_z \cdot HDD_z)_t.$$

The third model (VAR Wind Chill) intends to capture the inter-relationships of wind chill alone, therefore, it only considers as endogenous variables,

$$Y_t^T = (WS_z \cdot HDD_z)_t.$$

Table 5.1: Model Lag Length

	VAR Peak			VARX Peak			VAR Wind Chill		
Lag Length Criteria	Lags	BIC	HQC	Lags	BIC	HQC	Lags	BIC	HQC
	2	126.5707	125.6636*	5	-4.856887	-5.083654*	3	34.57369*	34.48436

5.6 Analysis and discussion of results

5.6.1 Wind effects on demand and supply

In the estimated models, we use the product of wind speed and installed wind capacity as a proportional proxy for wind power output, and the product of wind speed and Heating Degree-Days as a proxy for the wind-chill effect. The results in Table 5.2 and Table 5.3 show the relevant coefficients taken from the full VARX modelling:

- Local wind power generation has significant negative effects, as expected, in all four countries. Surprisingly, France and the Netherlands have the most significant negative spillovers into the other countries, whilst Germany and Belgium have no significant effects elsewhere. These are, of course, average effects, but they do suggest that it is not necessarily the case that the largest wind generating country will spread lower prices to its neighbours. Rather a country that is predominantly low cost and exporting (France) may be more influential. The Netherlands appears to be both an importer from Germany and an exporter to Belgium, and so even though it is a small wind producer, its price sensitivity is effective. Belgium, as an importer, does not spillover.

- French wind chill has significant positive influence on its own prices, as expected, given the high sensitivity of demand to cold weather in that country. Furthermore, this positive effect spills over to all other CWE markets. Evidently, the increased demand is met not only by the French internal supply, but also by electricity imports from neighbouring countries. Similar wind-chill effects are not observed in the other countries, as they are not associated with such high intensity of electric heating.

- In Table 5.4 we report endogenous lags to explore the inter-day dynamic spillover of the wind-chill effect. Whilst we expect arbitrage in prices for a coupled market to be contemporaneous, windy weather systems generally move across Europe from West to East. Thus, windy conditions in Belgium, France and the Netherlands would on average precede those in Germany. The results show that all countries have a positive wind-chill relation with their own previous day conditions and that Germany does indeed follow the others. In France, the positive lagged effects are significant for three days, and this is a characteristic of thermal inertia in electric heating systems. Thus, the French price spillover is likely to have a persistent effect on its neighbours.

Table 5.2: VARX Wind power generation proxy

2007 – 2014	$ln(BPX_{PEAK})$	$ln(EEX_{PEAK})$	$ln(PWNX_{PEAK})$	$ln(APX_{PEAK})$
$WS_{BE} \cdot Wcap_{BE}$	0.00000058	-0.0000035	0.00000139	0.00000135
	[0.31913]	[-1.8557]*	[0.77677]	[0.95535]
$WS_{DE} \cdot Wcap_{DE}$	-0.0000001	$-4.08E-07$	$-1.27E-07$	$-7.98E-08$
	[-1.04236]	[-4.09718]***	[-1.35185]	[-1.06850]
$WS_{FR} \cdot Wcap_{FR}$	-0.0000019	-0.00000183	-0.00000199	-0.00000131
	[-2.93603]***	[-2.73242]***	[3.13568]***	[-2.60477]***
$WS_{NL} \cdot Wcap_{NL}$	-0.00000178	-0.0000026	-0.00000318	-0.00000267
	[-1.60586]	[-2.26355]**	[-2.92881]***	[-3.10513]***

Significant at *** 1% ** 5% * 10% significance level.

t-statistics in [ ].

Table 5.3: VARX Wind chill proxy

2007 – 2014	$ln(BPX_{PEAK})$	$ln(EEX_{PEAK})$	$ln(PWNX_{PEAK})$	$ln(APX_{PEAK})$
$WS_{BE} \cdot HDD_{BE}$	-0.000225	0.000209	-0.000582	-0.000326
	[-0.90849]	[0.81248]	[-2.39367]**	[-1.69385]*
$WS_{DE} \cdot HDD_{DE}$	-0.0000123	0.0000657	0.000401	-0.00014
	[-0.04603]	[0.23639]	[1.52524]	[-0.67098]
$WS_{FR} \cdot HDD_{FR}$	0.001354	0.0013	0.001515	0.001797
	[1.82301]*	[1.68903]*	[2.07892]**	[3.11189]***
$WS_{NL} \cdot HDD_{NL}$	0.0000972	-0.000183	0.000229	0.000331
	[0.36224]	[-0.65896]	[0.86800]	[1.58623]

Significant at *** 1% ** 5% * 10% significance level.

t-statistics in [ ].

5.6.2 Impulse Response Analysis

With contemporaneous price arbitrage within the coupled market and various specific demand and supply side weather influences, the net effect of shocks is the sum of complex interactions. We therefore present the impulse response functions within the full VAR Peak model to give an indication of the overall spillover potential and their persistence. In Figure 5.5, we see the spillover potential of the wind power proxy on adjacent electricity peak prices. All impacts are initially significant, negative and the persistence to a one standard deviation shock is about four periods. Similarly, Figure 5.6 shows the impact of cold weather shocks. These tend to increase prices and are more persistent. The combination of wind speed and cold weather is shown in Figure 5.7 in terms of wind-chill. Here, most interestingly, the initial impact is negative (perhaps mainly a supply side effect of wind power) and then positive as the extra heating is required. Finally, for completeness in Figure 5.8 we show the endogenous price interactions. Price shocks transmit across the coupled markets and gradually decay, as expected and as noted by other researchers who have investigated these indications of market integration.

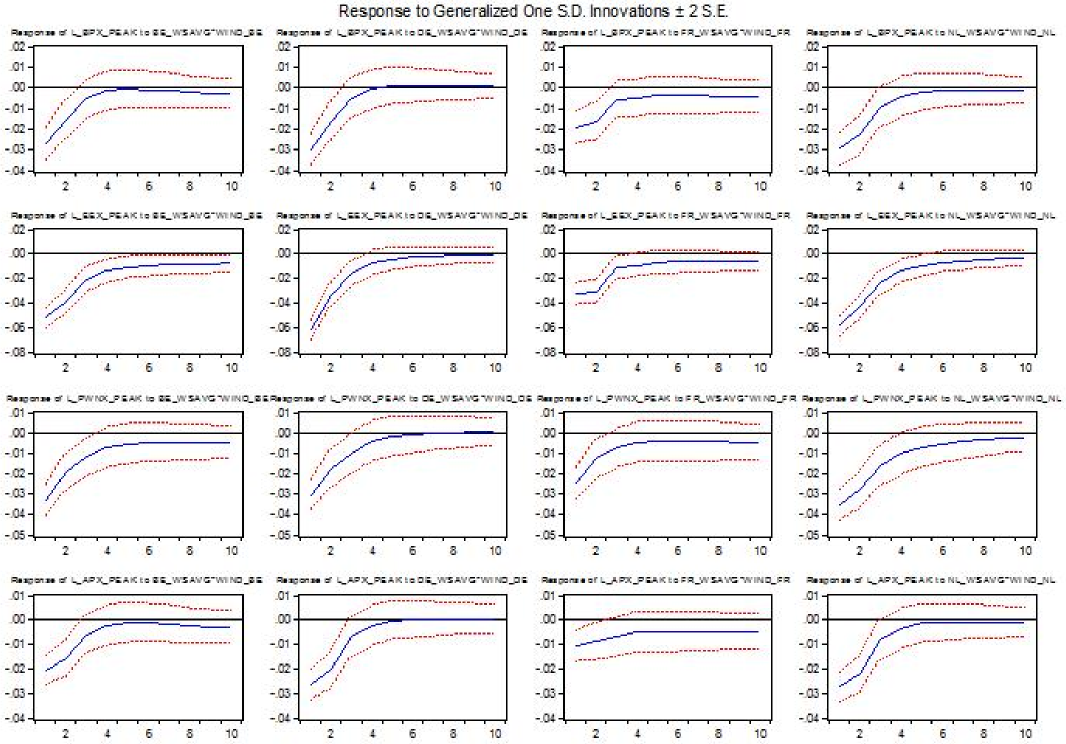

Figure 5.5: Impulse response functions of peak spot electricity prices to wind power proxy shocks

Table 5.4: VAR wind chill - sample 1/1/2007 to 31/12/2014 - 2162 observations.

	$WS_{BE} \cdot HDD_{BE}$	$WS_{DE} \cdot HDD_{DE}$	$WS_{FR} \cdot HDD_{FR}$	$WS_{NL} \cdot HDD_{NL}$
$WS_{BE}(-1) \cdot HDD_{BE}(-1)$	0.445344	0.233903	0.036301	0.135016
	$[14.2342]^{***}$	$[6.82318]^{***}$	$[3.23136]^{***}$	$[3.69104]^{***}$
$WS_{BE}(-2) \cdot HDD_{BE}(-2)$	0.041359	-0.047363	-0.028174	-0.018147
	[1.25384]	$[-1.31046]$	$[-2.37878]^{**}$	$[-0.47053]$
$WS_{BE}(-3) \cdot HDD_{BE}(-3)$	0.072713	-0.01659	0.001843	-0.030263
	$[2.30996]^{**}$	$[-0.48100]$	[0.16307]	$[-0.82231]$
$WS_{DE}(-1) \cdot HDD_{DE}(-1)$	0.028281	0.37225	-0.008171	-0.009178
	[1.15155]	$[13.8339]^{***}$	$[-0.92663]$	$[-0.31965]$
$WS_{DE}(-2) \cdot HDD_{DE}(-2)$	0.035526	0.009246	0.035975	0.053624
	[1.36558]	[0.32435]	$[3.85123]^{***}$	$[1.76299]^{*}$
$WS_{DE}(-3) \cdot HDD_{DE}(-3)$	0.089132	0.165917	0.007541	0.046121
	$[3.68756]^{***}$	$[6.26481]^{***}$	[0.86887]	[1.63204]
$WS_{FR}(-1) \cdot HDD_{FR}(-1)$	0.168532	0.15751	0.342332	0.197716
	$[2.6338]^{***}$	$[2.24658]^{**}$	$[14.8999]^{***}$	$[2.64284]^{***}$
$WS_{FR}(-2) \cdot HDD_{FR}(-2)$	0.075434	0.155153	0.129872	0.160178
	[1.13202]	$[2.12499]^{**}$	$[5.42792]^{***}$	$[2.05596]^{**}$
$WS_{FR}(-3) \cdot HDD_{FR}(-3)$	0.159352	0.093759	0.109908	0.163032
	$[2.50324]^{**}$	[1.34422]	$[4.80846]^{***}$	$[2.19051]^{**}$
$WS_{NL}(-1) \cdot HDD_{NL}(-1)$	0.091282	0.054973	0.023332	0.369898
	$[3.69991]^{***}$	$[2.03362]^{**}$	$[2.63381]^{***}$	$[12.8237]^{***}$
$WS_{NL}(-2) \cdot HDD_{NL}(-2)$	-0.013619	-0.02728	0.012772	0.091357
	$[-0.53114]$	$[-0.97096]$	[1.38721]	$[3.04732]^{***}$
$WS_{NL}(-3) \cdot HDD_{NL}(-3)$	-0.019173	0.017645	0.000371	0.109072
	$[-0.77706]$	[0.65267]	[0.04190]	$[3.78089]^{***}$
C	3.767092	4.048953	1.329848	4.032492
	$[4.82796]^{***}$	$[4.73602]^{***}$	$[4.74671]^{***}$	$[4.42036]^{***}$
$R-squared$	0.623337	0.581325	0.50175	0.564083
$Adj.R-squared$	0.621156	0.5789	0.498864	0.561559
$SchwarzSC$	9.292424	9.475189	7.243893	9.604993

Significant at *** 1% ** 5% * 10% significance level.

t-statistics in [ ].

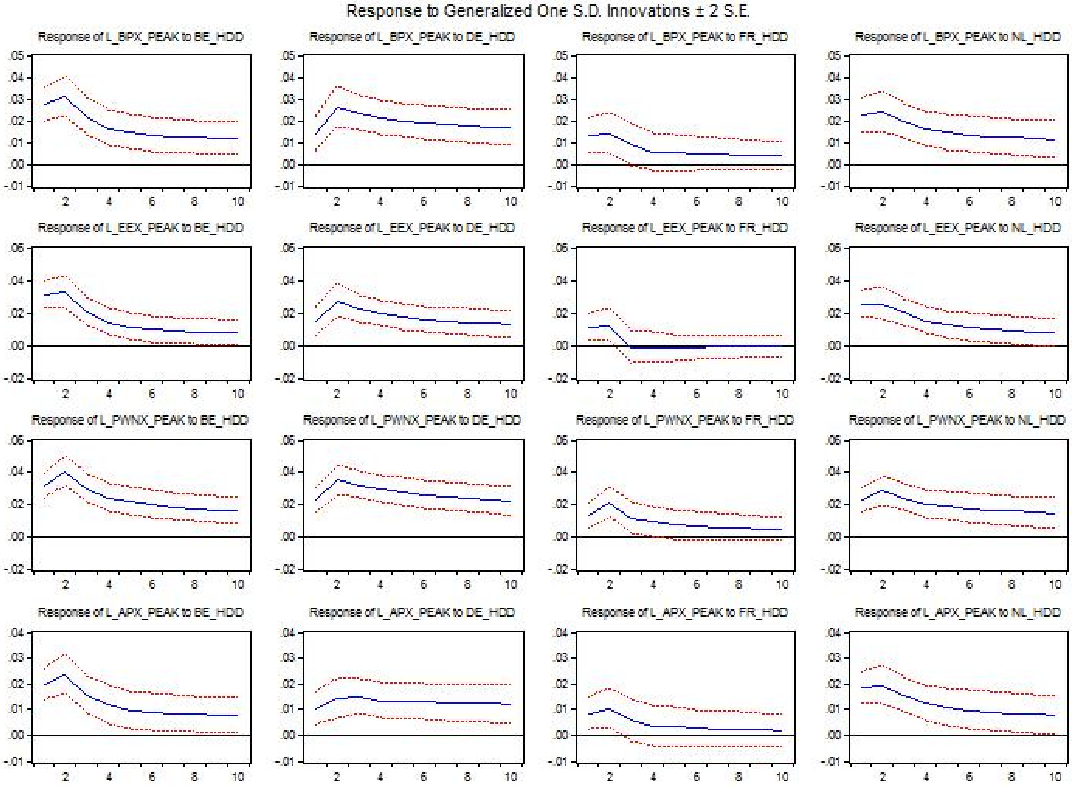

Figure 5.6: Impulse response functions of peak spot electricity prices to HDD shocks

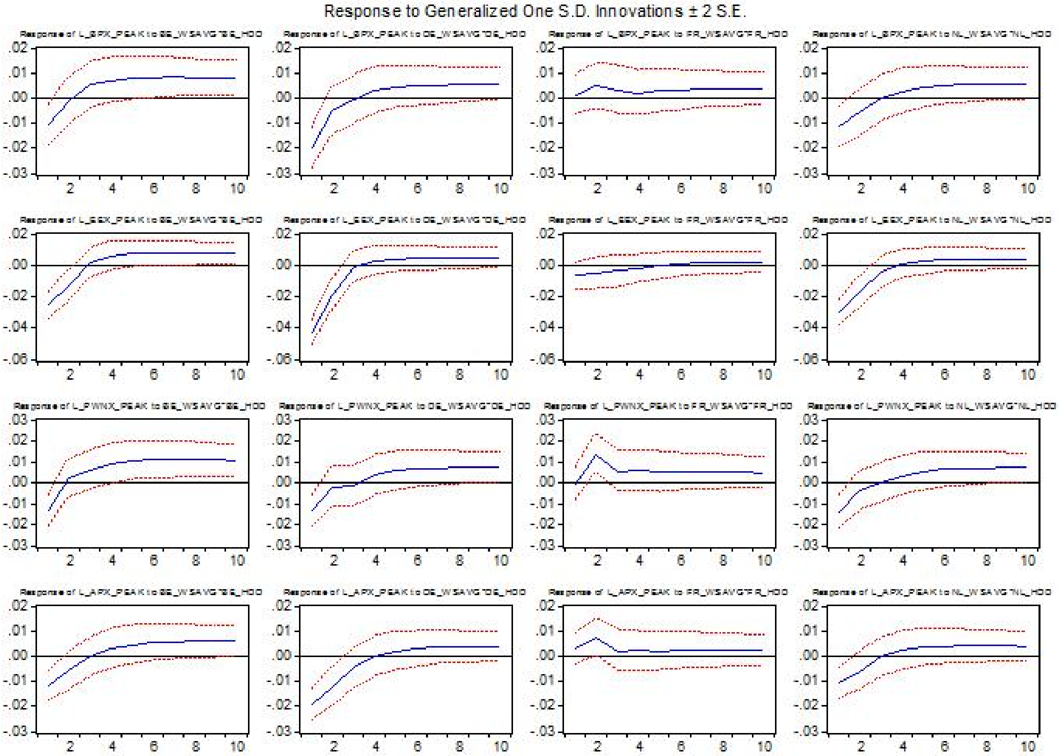

Figure 5.7: Impulse response functions of peak spot electricity prices to wind chill proxy shocks

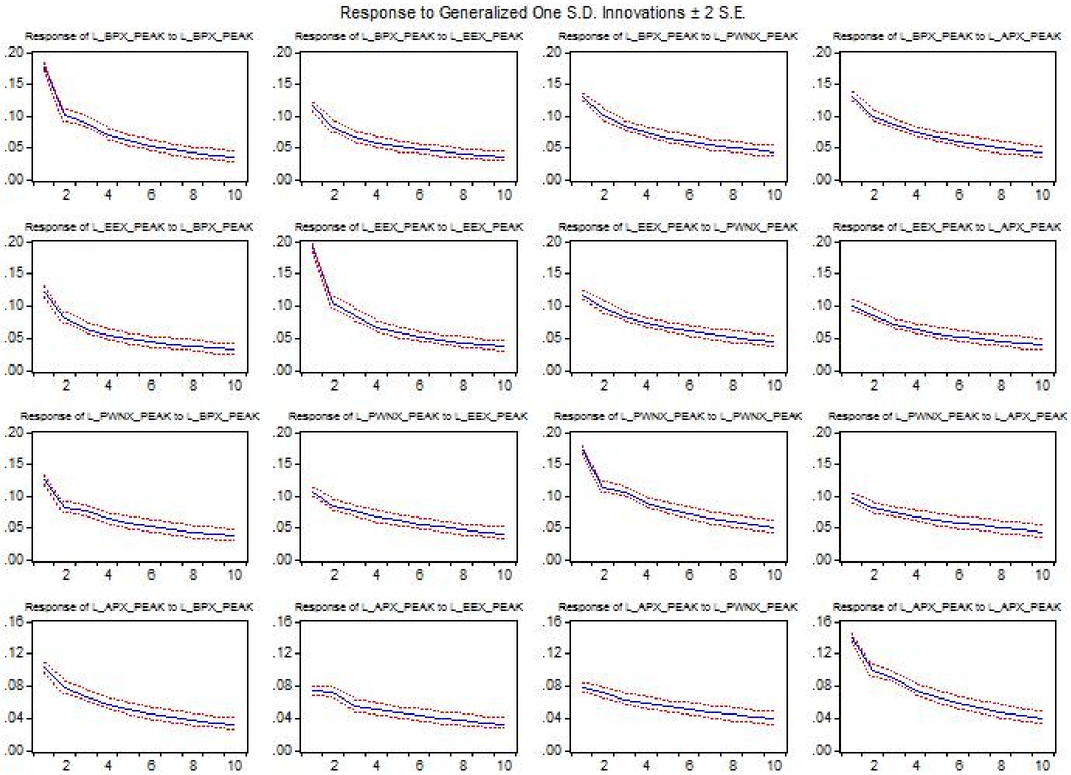

Figure 5.8: Impulse response functions of peak spot electricity prices to price shocks

Chapter 6

Electricity spot price convergence

6.1 Introduction on Electricity Spot Price Convergence

The fast expansion of renewable generation, resulting from the transition to a post carbon society, is creating one of the most demanding challenges to transmission grids and their operation (Carvalho, Bonifacio, & Dechamps, 2011; European Union, 2014; Henriot et al., 2013; Ragwitz et al., 2012; Wiseman, Edwards, & Luckins, 2013). In addition, the integration of the European electricity markets through High Voltage (HV) cross-border interconnections, is a substantial part of the European internal energy policy (ERGEG, 2006; European Union, 2009b), aiming to offer numerous advantages under normal operating conditions, such as optimal power station daily production, increasing opportunities for operation with renewable energies, the promotion of competition and enhancement of supply security. However, cross-border interconnections are limited and congestions can arise in multiple operation conditions.

The single market for electricity is a substantial part of the European internal energy market. After the required unbundling of the electricity sectors, wholesale electricity markets were implemented and then partially joined through regional electricity markets (ERGEG, 2006; Karova, 2011; Meeus & Belmans, 2008). The interaction between electricity markets occurs through HV cross-border interconnections with limited capacity. Several authors have studied electricity market integration, addressing different geographic areas: De Vany and Walls (1999), Park et al. (2006) in the USA regional markets; Worthington et al. (2005), Higgs (2009) in Australia; and Armstrong and Galli (2005), Zachmann (2008), Bosco et al. (2010), Bunn and Gianfreda (2010), Pellini (2012b), Figueiredo and Silva (2012, 2013c) in Europe. Regarding the SWE regional electricity market, composed of France, Portugal and Spain, all studies are unanimous in establishing that there is integration between both Iberian electricity markets (MIBEL) in the period analysed in this study. France has not been found to be integrated with the Iberian markets, as analysed by these authors.

Literature can be found regarding electricity market integration in different geographic areas. USA regional electricity market integration is studied in (De Vany & Walls, 1999; Park et al., 2006), using spot market electricity prices, the first through cointegration and a vector error correction model and the second through a vector auto-regression model. Electricity market integration in Australia is assessed in (Higgs, 2009; Worthington et al., 2005), through the use of MGARCH models, to include time-varying conditional correlation spillovers across electricity markets and better describe price and price volatility inter-relationships. Electricity market integration in Europe was assessed by a significant number of studies and these are unanimous in establishing that there is electricity market integration in the North European regional electricity market, the Nord Pool, which is composed currently by Norway, Sweden, Finland, Denmark, Lithuania, Estonia and Latvia. However, by using Markov switching fractional cointegration, (Haldrup & Nielsen, 2006) found that cointegration exists only when interconnections between bidding areas are not congested in a detailed analysis to the electricity price pairs West Denmark – Norway and East Denmark – Sweden. Furthermore, (Zachmann, 2008) used a Principal Component Analysis (PCA), unit root tests and a convergence test based on filtered pairwise price relations of wholesale electricity prices, demonstrating that convergence between both Danish bidding areas and between East Denmark and Sweden had been achieved. However, (Bosco et al., 2010) through the use of cointegration and unit root analysis, found the Nordic electricity markets not to be integrated with Germany and the Netherlands. In an assessment of European spot electricity markets convergence, (Pellini, 2012b) used a fractional cointegration analysis and a Multivariate GARCH model, to report that Nord Pool is fractionally cointegrated with the remaining analysed electricity markets (Austria, Belgium, Czech Republic, France, Germany, Greece, Ireland, Italy, Poland, Portugal, Spain, Switzerland, the Netherlands and the UK), and that perfect integration had not been achieved.

Also, literature focusing the impact of high penetration of wind power can be found. Highlighted issues in Benatia et al. (2013) are: the importance of adequate interconnection and transmission capacities; the capacity incentives for dispatchable power plants; demand management, reduce electricity trading constraints and further research on energy storage technology. Moreover, Franco and Salza (2011) highlighted the risk of excessive production, the use of energy storage and exports through interconnections to address balancing issues, appropriate system security and ancillary services; and Söder et al. (2007) stressed the importance of enough dispatchable backup capacity with fast response dynamics, system robustness and reserves to cover uncertainty and/or withstand eventual electrical faults, and adequate transmission grid capacities to transport eventual excess renewable generation; the importance of wind power forecasting, allowing for load management and system balancing, is highlighted in Milligan et al. (2009). Furthermore, Amorim et al. (2010), Cruz et al. (2011), Cutler et al. (2011), Gelabert et al. (2011), Jónsson, Pinson, and Madsen (2010), Klessmann et al. (2008), Mauritzen (2010), B. Moreno et al. (2012), Mulder and Scholtens (2013), Sáenz de Miera et al. (2008) and Sensfuß et al. (2008) all reported some level of decrease on the electricity spot market prices due to the increase in the share of RES-E generation. This is explained due to the almost inexistent marginal costs, associated bidding into the spot electricity market and the resulting merit order of power plant dispatch, which displaces higher marginal cost fossil fuel power plants. The influence of the existing high wind power penetration on the behaviour of electricity price differences was studied for the four ERCOT zones of Texas by Woo et al. (2011), through the use of ordered-logit and log-linear regression models, establishing that high wind power loads in west Texas cause interconnection congestion and electricity price differences with the remaining zones. The RES-E influence on interconnection congestion was also analysed by Sapio (2015) for Sicily and the rest of Italy electricity prices, through the use of a time-varying regime switching models and a dynamic probit ruling the transition between regimes, with distinct results as wind power is found to decrease interconnection congestion, which according to the author may be due to wind curtailment practices by the Transmission System Operator (TSO). Moreover, Italy was studied by Ardian et al. (2015) through the use of multinomial logit and three stage least square models, reporting that the probability of interconnection congestion increases with high wind power generation exiting a bidding area and decreases with high wind power generation in the destination bidding area. For Iberia, Figueiredo et al. (2015a) through a non-parametric approach, found that increasing wind power generation, or furthermore, increasing low marginal cost generation has a clear influence on market splitting, increasing its probability.

The electricity generation mix is changing in Europe with the increasing penetration of Renewable Energy Sources Electricity (RES-E). The impact of high penetration of RES-E has been discussed throughout a number of scientific papers and reports. In particular, some of the issues discussed related with the high level growth of wind power installed capacity reported are: the importance of adequate interconnections and transmission capacities to transport excess production, electrical system fault endurance, available and flexible standby generating capacity to accommodate load variability and effective control or curtailment of wind power production (Benatia et al., 2013; Franco & Salza, 2011; Söder et al., 2007). Also wind forecasting is fundamental to allow wind power load management and electrical system balancing (Milligan et al., 2009). Due to the almost inexistent marginal costs of RES-E generation, they are the first in the merit order of power plant dispatch. Therefore, by displacing higher marginal cost electricity generation, one could expect some level of decrease in the electricity spot market prices. This fact is reported by several authors (Amorim et al., 2010; Cruz et al., 2011; Cutler et al., 2011; Gelabert et al., 2011; Jónsson et al., 2010; Klessmann et al., 2008; Mauritzen, 2010; B. Moreno et al., 2012; Mulder & Scholtens, 2013; Sáenz de Miera et al., 2008; Sensfuß et al., 2008) and implies the hypotheses of increasing the cross-border transit of electricity, therefore market splitting.

The integration of the European electricity markets together with the fast expansion of renewable generation is thus creating one of the most demanding challenges to transmission grids and their operation (Henriot et al., 2013; Ragwitz et al., 2012). The large deployment of RES-E, with related increasing electricity flows at particular climate conditions can create congestions, leading to strengthening requirements of transmission grids throughout European Member states. Moreover, cross-border interconnections are increasingly essential for the targeted European electricity market integration, which, with the observed high availability of renewable generation, might not be sufficient for the required commercial electricity transits. Literature is scarce on the assessment of the impacts that high penetration of RES-E generation have on interconnected market behaviour and specifically on market coupling. The only study found addressing this issue was done for the Electricity Reliability Council of Texas (Woo et al., 2011), considering the influence of the existing high wind power penetration on the behaviour of the market coupling arrangement.

6.2 Evaluating the Market Splitting Determinants: Evidence from the Iberian Spot Electricity Prices

This study addresses the market splitting behaviour of the Iberian electricity spot market, through parametric and non-parametric probability response models, using data from the 1st July 2008 until the 31st December 2012. This approach brings a new perspective on the use of non-parametric models in the assessment of electricity markets. Therefore, the research questions are twofold: a) does increasing renewable power generation increase market splitting probability of occurrence?; and b) does empirical data confirm the available cross-border interconnection capacity influence on market splitting?

In Sub-section 6.2 overviews of the EU legislative framework and the Iberian electricity markets are presented. Additionally, an overview of the renewables deployment and cross-border interconnections in Iberia is made. Data and model specification used in this study are presented in Section 2, followed by the obtained results in Section 3. In Section 4 the analysis and discussion of the results is provided. Section 5 concludes with some policy recommendations.

6.2.1 A brief overview of the EU legislative framework

The objectives set for the European energy policies were to: guarantee the supply of electricity, reduce costs, foster competition, ensure security of supply, and protect the environment. The European Directive 96/92/EC established for the first time common rules for the various electricity markets in Europe, based on the liberalisation of the sector without prejudice of the public service required and the access by the generators and consumers to the transmission and distribution grids (Jamasb & Pollitt, 2005). These requirements are guaranteed by regulating authorities established in each country (Silva & Soares, 2008). The adequate integration of national electricity transmission grids and associated increase of electricity cross-border transfers aim to ensure the optimisation of the production infrastructure (Jacottet, 2012). However, different levels of market opening and diverse development stages of interconnectors between electricity transmission grids across European countries are observed. In consequence, Member-States took necessary measures to facilitate transit of electricity between transmission grids in accordance with the conditions laid down in the Directives. In 2006 the European Regulators Group for Electricity and Gas (ERGEG - currently the Agency for the Cooperation of Energy Regulators – ACER) launched seven Electricity Regional Initiatives for the creation of seven regional electricity markets (Karova, 2011; Meeus & Belmans, 2008). The objective for the creation of these regional electricity markets was to provide an intermediate step for the consolidated European Electricity Market (ERGEG, 2006). Almost simultaneously, the European Directive 2001/77/EC, called for the promotion of electricity generation by renewable energy sources (RES) in Europe. The aim was to reduce dependency on imported fossil fuels and to allow a reduction in Green House Gas (GHG) emissions. The large deployment of RES-E generation in Europe was achieved through a programme of strong financial support mechanisms (Amorim et al., 2013; de Jager et al., 2011; Meyer, 2003), like feed-in tariffs, feed-in premia, fiscal incentives, tax exemptions and others. The RES-E generation in Europe was 467,7 TWh in 2013 consisting of 42.4% hydroelectric, 27.4% wind, 10.4% solar, 9,9% biomass and 10% of other renewable technologies (Eurostat, 2015). The RES-E generation technologies are in different stages of development which explain the different shares of deployment achieved in each technology (Brown et al., 2011).

6.2.2 The Iberian electricity market

The agreement reached between the authorities and the electricity companies late in December 1996 (Ministerio de Industria y Energía - Spain, 1996), allowed for electricity sector reform in Spain. The law for the electricity sector was then issued in November 1997, establishing its regulation with the objectives to guarantee the supply, the quality of supply at the minimum possible cost and respect of the environment. Therefore, the existing public service was replaced by the guarantee of supply for all consumers; the electrical sector was privatised on the generation and commercialisation sides and regulated on the transmission and distribution sides (Boletín Oficial del Estado - Spain, 1997). The transmission system was assigned to Red Eléctrica de España (REE) as a regulated monopoly, and in January 1998 an electricity spot market was introduced in Spain (OMEL). In Portugal, Decree-law 7/91 of the 8th January established the conversion of the existing public electricity company Electricidade de Portugal (EDP) into a private company, however still owned by the state. This allowed the unbundling of the Portuguese electricity sector and later its re-privatisation. The re-privatisation of EDP in 1997, after the issue of Decree-law 56/97 of the nth14 March, determined on the first phase the sale of 29.99% of its capital and was followed by several other phases, the last one being in 2012. The transmission system operation was assigned to Redes Energéticas Nacionais (REN), created in 1994, as a regulated monopoly, under the ownership of EDP. By the end of the year 2000, the Portuguese state had acquired 70% of REN from EDP and only in 2007 did the initial phase of REN's privatisation take place (Redes Energéticas Nacionais, 2012c). Currently EDP still owns a 5% share in REN (Redes Energéticas Nacionais, 2012a). The Portuguese regulator for the energy sector (ERSE) was created in 1995 by Decree law 187/95 of 27th July (Diário da República Portuguesa, 1995) and has since then been amended through several other laws related to the energy sector and EU requirements (Silva, 2007). The Iberian electricity market only became a reality in July 2007 after several years of preparation and negotiation between the Portuguese and the Spanish states. MIBEL is composed by a spot (OMIE) and a bilateral (OMIP) electricity markets (Conselho de Reguladores do MIBEL, 2009). It started operation in July 2007 and by 2008 the corresponding spot electricity market was already trading 88% of the total demand (Zachmann, 2008). In 2014, trading in MIBEL achieved 81% of the total demand (OMIE, 2013). Additional details on the Spanish electricity market can be found in Crampes and Fabra (2005), Furió and Lucia (2009), Garrué-Irurzun and López-García (2009) and on the Portuguese electricity market in Amorim et al. (2010). In Iberia, wind power installed generation capacity increased substantially as can be observed in Table 6.1. Furthermore, and with respect to renewables, solar generation in Portugal did not have a similar growth to the one observed in Spain, where it achieved 7 GW of installed capacity. Portugal did not pursue the deployment of solar power generation and, in addition to the already large hydro power share, it concentrated mainly on wind power for the further development of renewable energy sources. Nuclear power has only been developed in Spain. Thermal power increased in Spain after 2002 and until 2010, mainly due to the installation of new combined cycle power plants. The installation of new combined cycle power plants was also done in Portugal, but at a later stage and to a lesser extent. Both in Spain and Portugal a slight decrease can be observed after 2011.

6.2.3 Overview of Renewables and Cross-border Interconnections

The leading hypothesis considered in this study is that increasing renewable power generation and available cross-border interconnection capacity are the main drivers for market splitting. The following sub-sections provide a brief overview of these two drivers.

6.2.3.1 Renewables deployment in Iberia

The large deployment of RES-E generation and namely of wind power in Europe was achieved by strong financial support mechanisms, including feed-in tariffs, fiscal incentives and tax exemptions (Amorim et al., 2013; de Jager et al., 2011; Meyer, 2003). This poses new challenges, both in the technical sense and in the market design. Electricity systems needs restructuring to accommodate RES-E intermittency, namely by increasing the availability of standby and balancing services (Lynch et al., 2012; Mauritzen, 2010). Policy design has to reflect the required market integration of these technologies, knowing that price volatility is prone to increase (Batlle, Pérez-Arriaga, & Zambrano-Barragán, 2012; Benatia et al., 2013). In Iberia, both the Portuguese and the Spanish wind power sectors were successfully developed (Batlle, 2011; Gelabert et al., 2011; F. Moreno & Martínez-Val, 2011; Ruiz Romero, Colmenar Santos, & Castro Gil, 2012), following the European Union (EU) targets for the promotion of RES-E, aiming to reduce dependency on imported fossil fuels and allowing for the reduction in greenhouse gas emissions (European Union, 2009a, 2001). Comparing the hourly demand profile with the wind power installed capacity evolution in Iberia, to the adequate climate conditions, wind power can supply a large share of electricity to the system. It is also noticeable that the share of wind power installed capacity over total installed generation capacity is approximately the same. Therefore, Iberia stands as an ideal case-study, where the high level deployment of wind power is observed, together with the early implementation of the market splitting arrangement between both spot electricity markets.

6.2.3.2 Cross-border interconnections

The Transmission System Operators (TSOs) are mostly ruled through the implementation of national regulations. These have been progressively adapted towards a single set of rules pushed by the European Union, aiming for an efficient integrated market. The key responsibility to manage cross-border interconnections constraints is specifically ruled by European Union Regulation 1228/2003/EC of 26 June 2003, which was later repealed by European Union Regulation 714/2009 of 13 July 2009 (European Union, 2009d, 2003c), aiming to enhance competition, establish a compensation mechanism for cross-border flows of electricity, setting principles on cross-border transmission charges and allocating available capacities. Since then, the European Network of Transmission System Operators (ENTSO), created under the so called third legislative package, has been commissioned by the Agency for the Cooperation of Energy Regulators (ACER) to prepare a set of network codes, in order to harmonise rules across TSOs, thereby guaranteeing an efficient transmission network management. Amongst these, the Network Code on Capacity Allocation and Congestion Management will establish uniform interconnection capacity allocation methods to be applied in all European markets, in order to allow consistent trade and supply of electricity across borders. ACER has recommended the adoption of this code by the European Commission on 26 May 2014 (ACER, 2014a) and is currently with the Electricity cross-border Committee. The transmission and cross-border interconnection costs determination play an important role in market design. Cost allocation methods are usually either Flat Rate based or Flow-based. Flat rate methods, which are simple to calculate and implement, are however, unfair to generators that use less capacity and extent of the transmission lines (Galiana et al., 2003). On the other hand, flow-based costs are most commonly used due to their dependence on the capacity and extent used by each generator of the transmission lines. Explicit auctioning, where interconnector capacity is sold to the highest bidder or implicit auctioning, which integrates electricity and transmission markets and also called *"Market Splitting"/"Price Coupling"*, are both used across Europe (Coppens & Vivet, 2006). To join electricity markets, several methodologies for cross-border interconnection congestion management were used in different REM. In Europe consensus has recently been achieved concerning implicit auctioning through market coupling/splitting[1] (J.-M. Glachant, 2010). Initially implemented in the Nordic countries in 1996, it was then implemented in 2006 between Belgium, France and the Netherlands, the so called trilateral market coupling (Figueiredo & Silva, 2013c). In July 2007, the Iberian spot electricity market started operation, implementing a market splitting implicit auctioning process between Portugal and Spain, which is the subject of the present study. The trilateral market coupling was then extended to Germany and Luxembourg in November 2010, creating the Central West Europe regional

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[1] In Weber et al. (2010) the distinction between market coupling and market splitting is clarified:

- Market splitting – markets operated by a single power exchange
- Market coupling – markets managed through co-operation of multiple power exchanges

Both have a similar welfare optimisation algorithm behind. Therefore, the main difference is that the market coupling algorithm needs the additional complexity of a Market Coupler receiving information from multiple power exchanges (Biskas et al., 2013; EPEX, Apx-endex, & BelPEX, 2010; Nord Pool, 2015a; OMIE, 2015).

electricity market. The market coupling arrangement allows the coordination of different price zones through an implicit auctioning process, increasing overall welfare in the coupled markets (Jacottet, 2012). With this arrangement, markets with lower prices export electricity to markets with higher prices through limited capacity cross-border interconnections (Meeus et al., 2009). If the interconnection capacity is large enough to accommodate the exported electricity flows (without congestion), then the price is the same in both markets otherwise, market splitting occurs and two regional market prices are cleared (EPEX et al., 2010). The basis of this arrangement is the calculation of the Available Transfer Capacity (ATC), which is made by the TSOs taking into account the safety and reliability of the electrical system, together with an allowable safety margin (Turvey, 2006). Therefore, import and export ATC can have different values depending on loop flows and technical constraints (Luna & Martínez, 2011). In the case of Iberia, subject of this study, the EUPHEMIA algorithm for the market coupling arrangement is implemented (OMIE, 2014). For the analysed period there was no market coupling/splitting implemented across the French-Spanish interconnection (implemented in May 2014).

The literature is vast on the discussions of the merits and issues of market splitting/market coupling. Hobbs, Rijkers, and Boots (2005) analysed the introduction of market coupling between Belgium and the Netherlands through a Cournot-Nash model, reaching the conclusion that market coupling would improve social surplus depending on existing market power of market players. Furthermore, in this same region, de Jonghe et al. (2008) found a sharp decrease of the hourly price differences after the introduction of the Trilateral Market Coupling between Belgium, France and the Netherlands, in spite of this, a reduction on price volatility could only be found in the Netherlands. Kristiansen (2007) through an empirical analysis assessed the introduction of the market coupling arrangement between East Denmark and Germany (the Kontek cable), finding a relatively low level of market splitting. Genesi, Marannino, et al. (2008), Genesi, Rossi, et al. (2008) showed that market coupling would achieve an efficient cross-border interconnection capacity allocation through the solution of a set of linear programing problems. Barth et al. (2009) found that market coupling reduced the total system operation costs and the electricity prices, considering a high level of wind power deployment, through the use of a deterministic input/output model. Further models to evaluate market coupling were developed by Waniek et al. (2009) based on the simulation of the market by aiming for the maximisation of economic welfare, Kurzidem (2010) modelling imperfect competition in electricity and transmission markets, Oggioni and Smeers (2010, 2013) and Oggioni et al. (2012) with a Generalised Nash Equilibrium applied to different organisations of counter-trading activities and assuming different zonal decomposition (nodal pricing and market coupling). Meeus et al. (2009) discussed the use of locational marginal prices and the importance of price coordination, through the minimisation of the congestion rents, in order to avoid distortion of network development incentives. The options of volume coupling versus price coupling and centralised versus decentralised approach were discussed by J.-M. Glachant (2010), reaching the conclusion that decentralised price coupling, or market coupling, would be the most feasible solution. In the Italian electricity market, Pellini (2012a) found a welfare increase with the introduction of the market coupling arrangement. Biskas et al. (2013), through a Mixed-integer Linear Programming model, found better welfare gains with the implementation of a market splitting versus a market coupling arrangement. The introduction of demand side participation in the electricity markets is refered by Caramanis, Foster, and Goldis (2010) as a means to contribute to system stability, considering renewable generation intermittency. A study performed by Salic and Rebours (2011) did not address directly the market coupling/splitting arrangement, but assessed the contribution of day-ahead wind power generation forecasts for Germany on the net transfer capacity from Germany to France. Findings establish negative relations between the day-ahead wind power generation forecast and the day-ahead net transfer capacity. These results can suggest that with less net transfer capacity, the ATC calculated is also smaller, thus increasing market splitting probability. The initiative denominated Price Coupling of Regions (PCR) was launched at the Florence Regulatory Forum in 2009 by three power exchanges: Nordpool, EPEX and MIBEL (Europex, 2009), to be implemented by the end of 2012. In the meantime additional members joined the initiative, APX-Endex, BPX and Gestore dei Servizi Energetici (GME), reaching the 2860 TWh/year of potential electricity trading (Europex, 2011) and to be fully implemented by the end of 2014. In May 2014 market coupling between Iberia, Central West Europe and Nordpool was achieved, which was one of the main objectives of the Price Coupling of Regions initiative. Finally, on 24 February 2015 market coupling was implemented between Italy, Austria, France and Slovenia. Consequently, 19 countries are now linked improving integration of the European electricity market.

6.2.4 Methods

Market splitting occurs when there is congestion of cross-border interconnection. The amount of electricity flowing through a cross-border interconnection with creating congestion, thus market splitting, will depend on its capacity available for commercial trades. Moreover, if congestion occurs, then the electricity flowing across the cross-border interconnections will be constant during the duration of this same congestion. A consequence of this congestion is the separation of the spot electricity prices. To model market splitting behaviour, the explored options were: a) to establish a probability of occurrence, therefore assuming a binary dependent variable, or b) to model the price difference between spot electricity markets. This latter model might have specification problems due to the large number of hourly periods where the spot electricity price difference is zero. Therefore, the models pursued were based on the probability of market splitting occurrence. Logit and nonparametric models are estimated to express the probability response of day-ahead spot electricity prices market splitting (the binary variable of market splitting occurrence assumes the value 1 if the difference of the hourly Iberian spot electricity prices is not zero and assumes the value 0 otherwise), as a function of the explanatory variables: wind, hydro, nuclear and thermal power generation, together with ATC and electricity demand. Solar power generation is negligible in Portugal, and in Spain its size is approximately the same as nuclear power. Solar power is mostly available connected to the distribution grid, indicating an absence of online remote metering. Therefore, given its small relative share and the absence of reliable hourly data, this technology was not included in our study. Therefore, the inputs to the model are: the wind, hydro, thermal and nuclear power generation shares, the ATC in both directions and demand in both electricity markets. The model will then provide, as an output, the probability of market splitting occurrence. In the following sub-sections, data, logit and non-parametric model specifications are described. The use of non-parametric models in the assessment of market splitting provides a novel approach in the analysis of interconnected electricity markets.

6.2.4.1 Data

Hourly data for the day-ahead spot electricity prices in Euro/MWh and for the ATC in MW were extracted from OMIE (2013), for Portugal and Spain, from 1 July 2008 until 31 December 2012. From the Transmission System Operators of both countries, hourly demand and generating data were extracted (Red Eléctrica de España, 2014; Redes Energéticas Nacionais, 2014). Additionally, wind power installed capacities in both Iberian countries were obtained from Eurostat (2015).

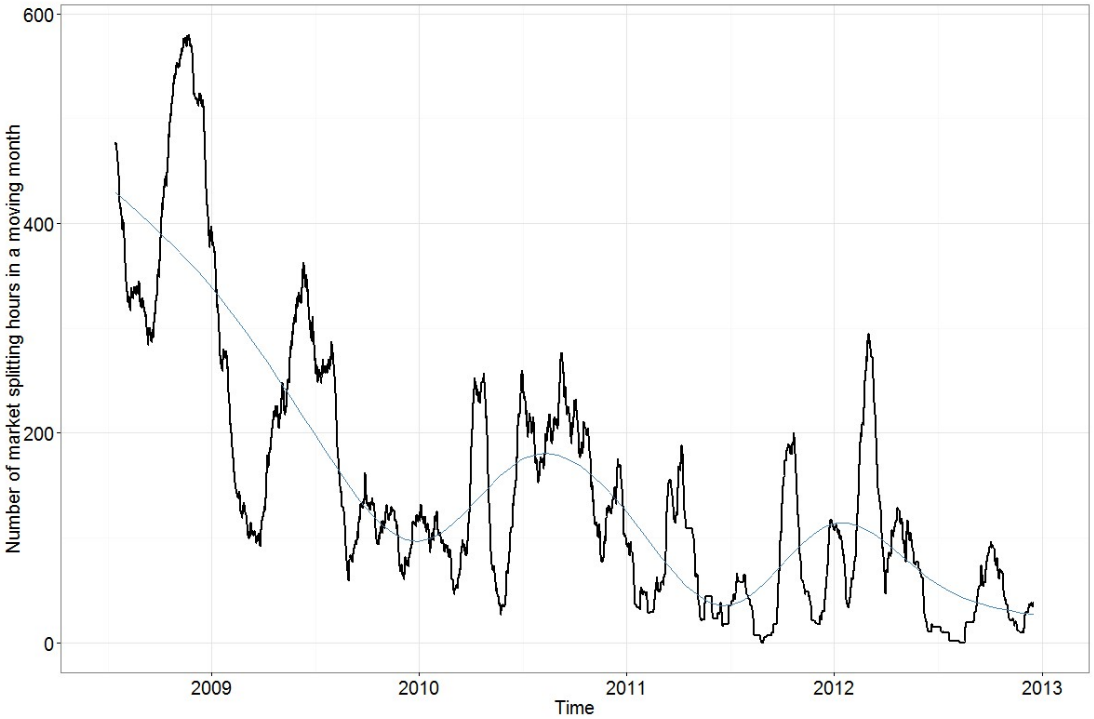

Figure 6.1: Iberian market splitting evolution

Market integration in Iberia has been demonstrated in several other studies (Figueiredo & Silva, 2013b). However, market splitting occurred in 19.1% of the observed hours within the complete data set. A similar pattern of market splitting is reported in Woo et al. (2011), between the North and West zones of Texas. In these zones, the development of wind power is equally relevant. It is to highlight that, with the renewable-energy credit trading program target for 2015 (5.88 GW) already surpassed, wind power generation installed capacity achieved 7.5 GW in 2009. In Iberia, as shown in Figure 6.1, the share of market splitting in a moving month has, somehow, decreased over time presenting oscillations with a maxima in 2012 of 294 hours in a moving month. Specifically, peaks observed in 2012 and 2013 occur in March, typically a month with high availability of wind and hydro generation. The Portugal-Spain electrical interconnection currently consists of eight HV lines with a maximum interconnection capacity of 2400 MW (Red Eléctrica de España, 2012). A new interconnection line between Tavira and P. Guzman is being constructed (to be concluded by REE on the Spanish side) and another new line is forecast to be in service in 2015 between V. Fria and O Covelo, which with several other internal line reinforcements will allow the completion of the interconnection capacity between Portugal and Spain of 3000 MW, essential for the joint Iberian electricity market MIBEL (Redes Energéticas Nacionais, 2013). The existing maximum interconnection of 2400 MW is 2.7% of the Spanish and 12.7% of the Portuguese total installed capacities, or 5.4% of the Spanish and 25.5% of the Portuguese maximum demand. Concerning the ATC (Figure 6.2), the increase in interconnection capacity between the two Iberian countries is visible, with the last improvement being observed in mid-2012. It is also of note that ATC limitations are more often observed in the direction from Spain to Portugal. A possible explanation is that the calculation of the ATC made by REE includes safety factors resulting from the relative larger size of the Spanish electricity system, taking into account network security constraints.

Wind power generation has significant variability in both Iberian countries, without any evident seasonal pattern, meaning that wind power generation might be present throughout all weather seasons. This is not the case with hydro power generation, where some seasonality can be found. It is of note that in spite of the larger size generation in Spain, Portugal has higher shares of both wind power and hydro power generation. Both thermal power generation and respective shares are larger in Spain, with a slight tendency to decrease with time. Again, the different

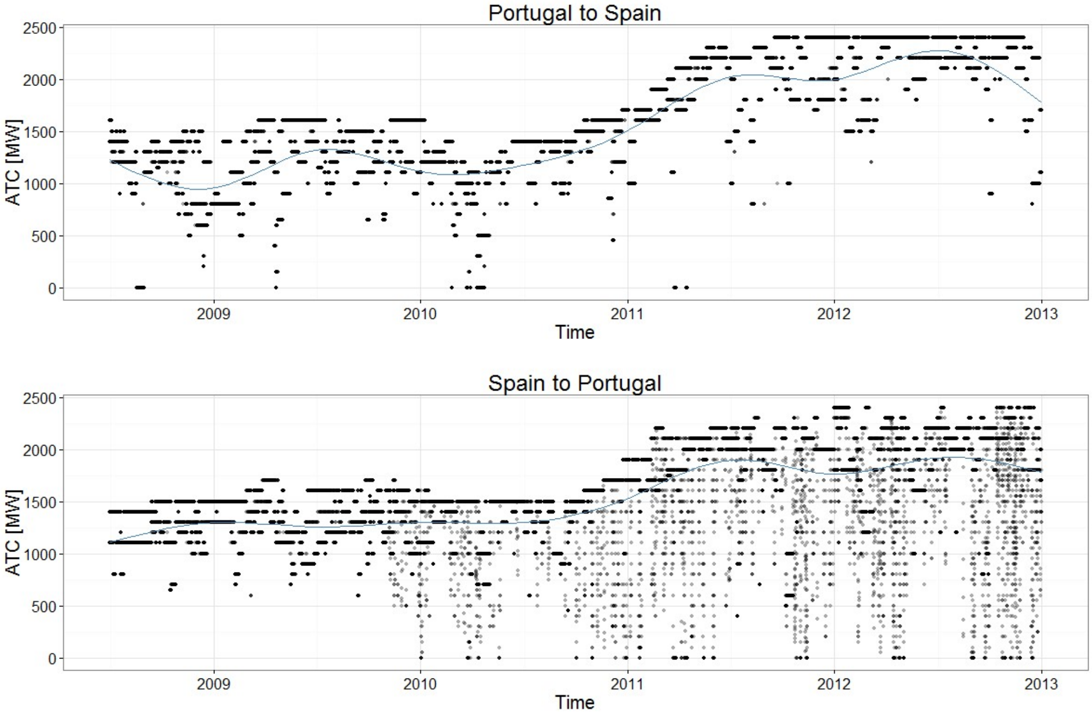

Figure 6.2: Available Transfer Capacities in Iberia

scales of the Portuguese and Spanish electricity markets are a natural consequence of the countries asymmetric dimensions. Nuclear generation is only present in Spain, evidencing both stable installed capacity and generation share, within the period herein considered. Currently, no plans exist for new nuclear power capacity, apart from some plant upgrades and life extension. There are seven nuclear power plants operating, three of them licensed up to 2020, another three up to 2021 and the last up to 2024 (World Nuclear Association, 2015c). Summary statistics for the time series are presented in Table 6.2. Skewness and kurtosis values indicate that all price time-series have non-normal distribution, which is confirmed by Jarque-Bera statistic rejection of the null for normal distribution testing.

6.2.4.2 Logit Model Estimation

The estimated models aim to provide indications about the behaviour of the market splitting arrangement in the Iberian spot electricity markets, considering the mix of the main available generation technologies, ATC and Demand in these same markets. The market splitting probability model used is:

$$P(Y = 1|X) = P(Split^{*} > 0|X) = P(X\beta + e > 0|X), \qquad (6.1)$$

where X is a matrix of explanatory variables and e is the error term that is an independently distributed variable independent from X following the standard logistic distribution[2], from which we obtain,

$$P(e > -X\beta|X) = 1 - P(e \leq -X\beta|X) = 1 - \Lambda(-X\beta) = \Lambda(X\beta), \qquad (6.2)$$

where

$$\Lambda(X\beta) = \frac{exp(X\beta)}{1 + exp(X\beta)}$$

The probability of market splitting is modelled as a function of explanatory variables representing thermal, nuclear, hydro and wind power generation. The other explanatory variables used consist of the demand of each country and the ATC between both spot electricity markets. The former expresses the ability of the country to consume the electricity produced and the latter expresses the ability to export the electricity generated. Following the concept of wind power penetration level or generation share (Jónsson et al., 2010), we have expanded it to the remainder of the generation technologies considered in the model. The estimated model associated to the *Split* latent variable is then:

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[2] The option was to apply the logit model as a binary response model, due to the fact that the probit model latent error does not follow a normal distribution (Jeffrey M. Wooldridge, 2003)

$$Split^{*} = \beta_0 + \beta_1 \frac{W_{PT}}{D_{PT}} + \beta_2 \frac{W_{ES}}{D_{ES}} + \beta_3 \frac{H_{PT}}{D_{PT}} + \beta_4 \frac{H_{ES}}{D_{ES}} + \beta_5 \frac{T_{PT}}{D_{PT}} + \beta_6 \frac{T_{ES}}{D_{ES}} + \beta_7 \frac{N_{ES}}{D_{ES}}$$

$$+ \beta_8 ATC_{PT-ES} + \beta_9 ATC_{ES-PT} + \beta_{10} D_{PT} + \beta_{11} D_{ES} + e, \quad (6.3)$$

where W_{PT} and W_{ES} are the hourly wind power generation in Portugal and Spain, respectively; H_{PT} and H_{ES} are the hourly hydro power generation in Portugal and Spain, respectively; T_{PT} and T_{ES} are the hourly thermal power generation in Portugal and Spain, respectively; N_{ES} is the hourly nuclear power generation in Spain; ATC_{PT-ES} and ATC_{ES-PT} the hourly ATC for both directions of the interconnections between Portugal and Spain; and D_{PT} and D_{ES} the hourly electricity demand in Portugal and Spain, respectively.

6.2.4.3 Non-parametric Model Estimation

Non-parametric models do not require parametric assumptions for the underlying data generation process (Pagan & Ullah, 1999). Moreover, data has the required information allowing for the model estimation through kernel methods, consisting simply of a weighting function. Non-parametric models are an alternative to parametric models, where specification issues are found to reject or at least to question such a model. Bandwidth choice is crucial in these methods and the data-driven bandwidth choice can present a quite demanding computational challenge, due to the nature of the kernel methods (Racine, 2007). With the evolution of computer processing speed, this situation is improving and namely the use of parallel processing presents as the most viable solution when using large datasets, as it is the case in this study. Further detailed information about non-parametric models can be found in Hayfield and Racine (2008) and Racine (2007). Our non-parametric models were developed in R (The R Foundation for Statistical Computing, 2014) using the *"np"* package for non-parametric kernel estimation (Hayfield & Racine, 2008). The non-parametric models developed further expand on the indications provided by the logit models. These are expected to provide additional performance and details on the behaviour of the market splitting arrangement in the Iberian spot electricity markets, avoiding the specification issues described. Models were implemented in R: (i) without parallel processing, using the *“rule of thumb”* for bandwidth selection, and (ii) with parallel processing, using *“likelihood cross-validation”*, taking advantage of the *npRmpi* routines for bandwidths calculation and model estimation. Depending on the type of variable considered, different types of univariate kernels are used to obtain the generalised product kernels. The continuous variables were modelled by using a second-order Gaussian kernel function:

$$K(z) = \frac{e^{(-(\frac{X_i - x}{h})^2/2)}}{\sqrt{2\pi}}, \tag{6.4}$$

and the categorical variables are modelled by using the kernel function proposed by Aitchison and Aitken (1976):

$$l(X_i, x, \lambda) = \begin{cases} 1-\lambda, & \text{if } X_i = x \\ \frac{\lambda}{c-1}, & \text{otherwise} \end{cases}, \tag{6.5}$$

where c is the number of outcomes in x and $\lambda \in [0,(c-1)/c]$. Both h and λ are the bandwidths respectively for the continuous variables and for the categorical variables kernel functions. Being the most crucial aspect of non-parametric modelling, model bandwidths were calculated through several different methods in order to compare and select the most adequate for the intended purpose (Okumura & Naito, 2004). For the models expressing the probability of market splitting, two methods for bandwidth selection were used:

- *”Rule of Thumb”*

  $$h = 1.06\sigma n^{-1/(2P+l)} \tag{6.6}$$

  where σ is the $min(\hat{\sigma}, interquartilerange/1.349)$, n is the number of observations, P is the order of the kernel and l the number of continuous variables;

- *"Likelihood cross-validation"*

$$\mathcal{L} = \sum_{i=1}^{n} log \left[\frac{1}{(n-1)h} \sum_{j=1, j \neq i}^{n} K \left(\frac{X_j - x}{h} \right) \right] \tag{6.7}$$

  where h is selected by maximizing the log likelihood function.

Similar to the logit models specified, the explanatory variables are the wind, hydro, thermal and nuclear power generation shares, together with the ATC and demand in each market, all of them continuous variables. The variable representing market splitting is categorical. Models were estimated with bandwidths calculated with both selection methods, considering the same data set from 1$^{\text{st}}$ July 2008 until 31$^{\text{st}}$ December 2012. In Table 6.4 results for the bandwidth calculation and model performance are presented for both estimated models.

6.2.5 Results

Results and performance of the logit and non-parametric models are described in the following sub-sections. The use of non-parametric models is demonstrated to provide better model performance as shown below in Section 6.2.5.2.

6.2.5.1 Logit Model Results

In the estimated model all coefficients are statistically significant ($p < 0.01$) with the exception of the hydro generation share in Spain (Table 3). The "Neglected Heterogeneity" specification issue might have an influence on the coefficient estimates causing an underestimation of the effects. However relative effects of the explanatory variables can still be extracted (Mood, 2009; Wooldridge, 2010). An accuracy of 0.8257 was found for the considered model, with a McFadden pseudo R-square of 0.240 (Table 6.3). Another specification issue present in the estimated model is the heteroskedasticity of the error term, as found according to the Breusch-Pagan test performed (Table 6.3). In this case the error term does not have a constant variance and following Davidson and Mackinnon (2004), even if the model used is the logit, it is reasonable to consider the alternative specification:

$$P(Split = 1|X) = \Lambda\left(\frac{X\beta}{exp(X'\gamma)}\right), \tag{6.8}$$

where X' is a matrix of explanatory variables belonging to the original information set and γ a vector of parameters to be estimated. The market splitting probability is then not only dependent on the original regression function, but also on a skedastic function. The heteroskedasticity correction variables for the skedastic function were selected according to model performance. As seen in Table 6.3, the coefficients for the selected variables in the skedastic function (wind and hydro power generation shares, both in Portugal and Spain) are all statistically significant ($p < 0.01$). The heteroskedasticity corrected model achieved a better McFadden pseudo R-squared (0.275) and a slightly better accuracy, sensitivity and specificity (Table 6.3). For simplicity, other estimated models are not herein presented.

These results lead to the necessity of deepening our analysis about market splitting behaviour, through the estimation of non-parametric model as presented in the following Section.

6.2.5.2 Non-parametric Model Results

With higher accuracy, sensitivity and specificity, the non-parametric models herein estimated have better performance than the logit and do not suffer from related specification issues, as the ones described in Section 6.2.4.2. In particular, the performance of the estimated model with the bandwidth selected by likelihood cross-validation is quite superior to all other estimated models, as seen in Table 6.4. With a sensitivity of 0.9135 and a specificity of 0.9900 the likelihood cross-validation non-parametric model outperforms all other estimated models. The likelihood cross-validation bandwidth calculation method obtains in general smaller bandwidths, which will create more complex shapes as is later shown in Section 6.2.6.

The better performance of the non-parametric model is also observed in Figure 6.3, where the observed and the fitted number of market splitting hours are shown for a rolling month in the considered period, for both the heteroskedasticity corrected logit model and the non-parametric model with the bandwidth selected by likelihood cross-validation.

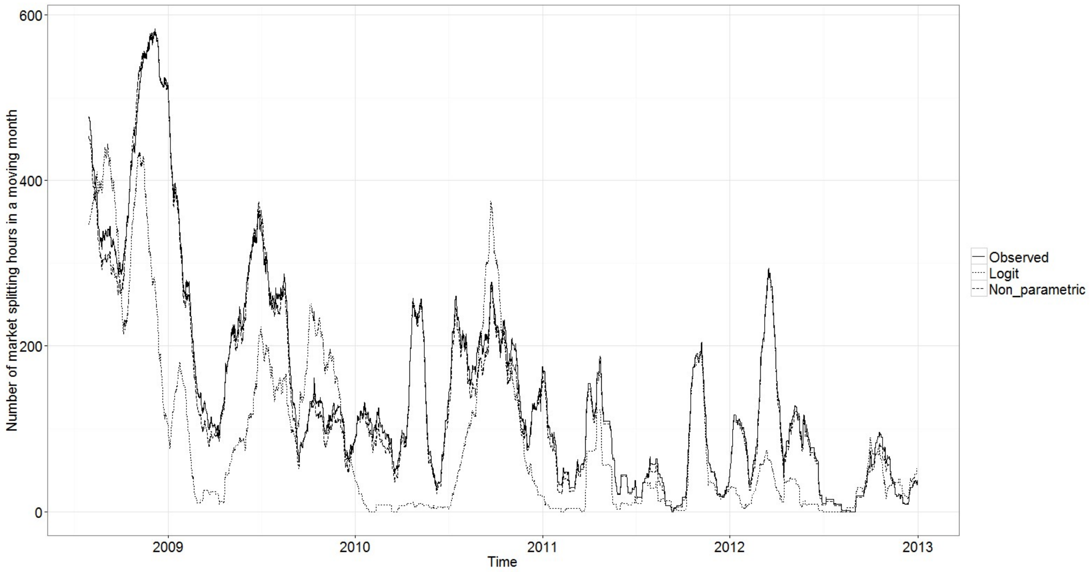


Figure 6.3: Iberian market splitting evolution

6.2.6 Discussion

In Table 6.3 the reader can find marginal effects for both logit models. Between the logit models, in-sample performance was slightly better with the heteroskedasticity correction. However, as already described, non-parametric models outperform logit, both with better performance and without the known specification issues (Table 6.4). In order to ease interpretation, 3D probability plots are shown and analysed for all estimated models, as follows.

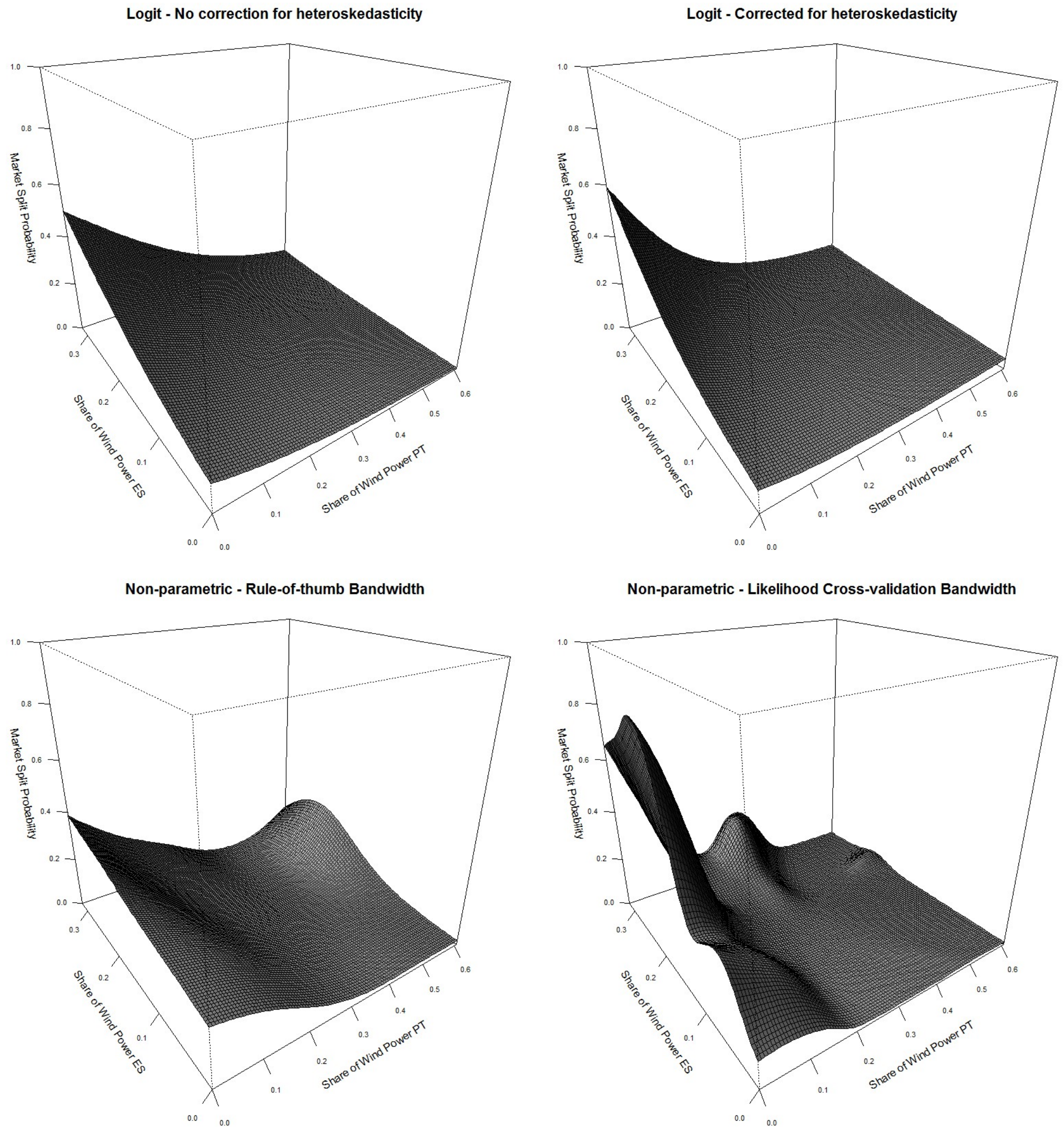
6.2.6.1 Wind power generation

Results from the models express that market splitting probability increases generally when there is an increase of wind power generation share. Market splitting probability is more responsive to the Spanish wind power generation share, whilst there is almost no influence of the Portuguese wind power generation share (Figure 6.4). This can be explained by having low marginal cost electricity available to flow across the border, mainly from Spain to Portugal due to the larger installed capacity available of wind power generation in this country. The non-parametric model provides the additional information that there is a slight market splitting probability increase when both the Spanish and Portuguese wind power generation shares are high. This fact can occur not only due to the congestion of the interconnections with low marginal cost electricity (there is low marginal cost electricity on both sides of the border), but also due to some degree of decrease in ATC calculated by the TSOs for grid security reasons; thus increasing market splitting probability. This market splitting probability increase changes when the bandwidth decreases, obtaining a better fit in the case of likelihood cross-validation as seen in Table 6.4.

In the case of increasing wind power generation in Spain, but not in Portugal, the market splitting probability is dramatically high. Available low price electricity in Spain congests the interconnections, however with increasing wind power generation in Portugal there is a system balance decreasing market split probability. The asymmetry between the Portuguese and Spanish probability response behaviour is here evident due to the difference in wind power installed capacities.

6.2.6.2 Hydro power generation

As previously described, there is a significant share of hydro power installed generation in Portugal, which if unavailable due to a dry year and in the absence of a stable low price electricity such as nuclear, creates a significant internal supply shortage. This will then be supressed by electricity import flows from Spain, creating interconnections congestion, thereby explaining the increasing market splitting probability (Figure 6.5). This behaviour is not observed in Spain in the logit models, but in the non-parametric models the additional information provided shows a similar behaviour, however not as steep, probably due to its bigger electrical system size and available nuclear power generation, which supplies a base of low price electricity. Furthermore, the existing hydro pump storage capacities improves the transmission grid balancing ability and allows the use of surplus renewable generation, thus decreasing cross-border transmission congestion and market splitting probability.



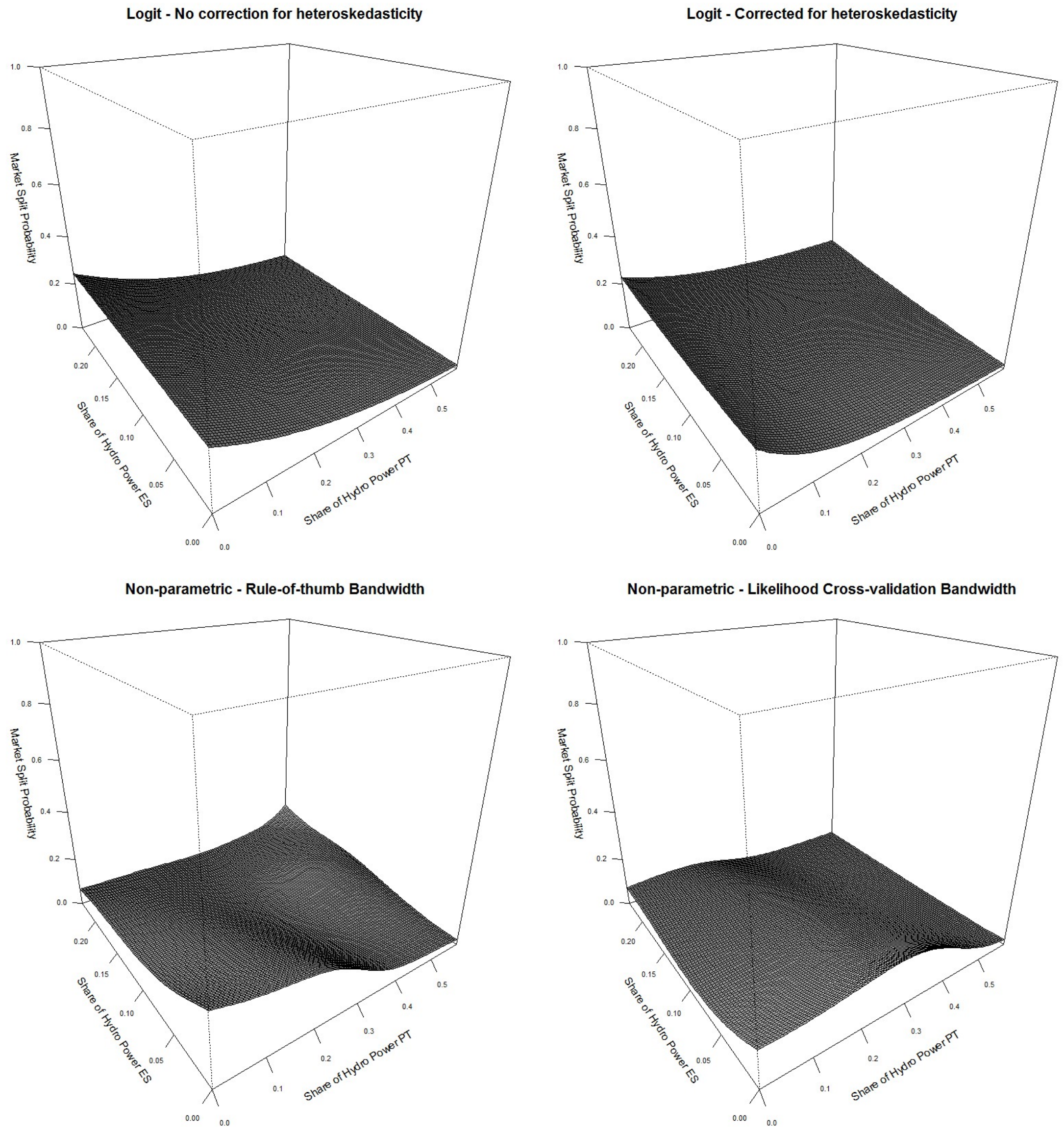
Logit - No correction for heteroskedasticity

Logit - Corrected for heteroskedasticity

Non-parametric - Rule-of-thumb Bandwidth

Non-parametric - Likelihood Cross-validation Bandwidth

Figure 6.4: Iberian market splitting evolution



Logit - No correction for heteroskedasticity

Logit - Corrected for heteroskedasticity

Non-parametric - Rule-of-thumb Bandwidth

Non-parametric - Likelihood Cross-validation Bandwidth

Figure 6.5: Predicted probability response to hydro power generation share

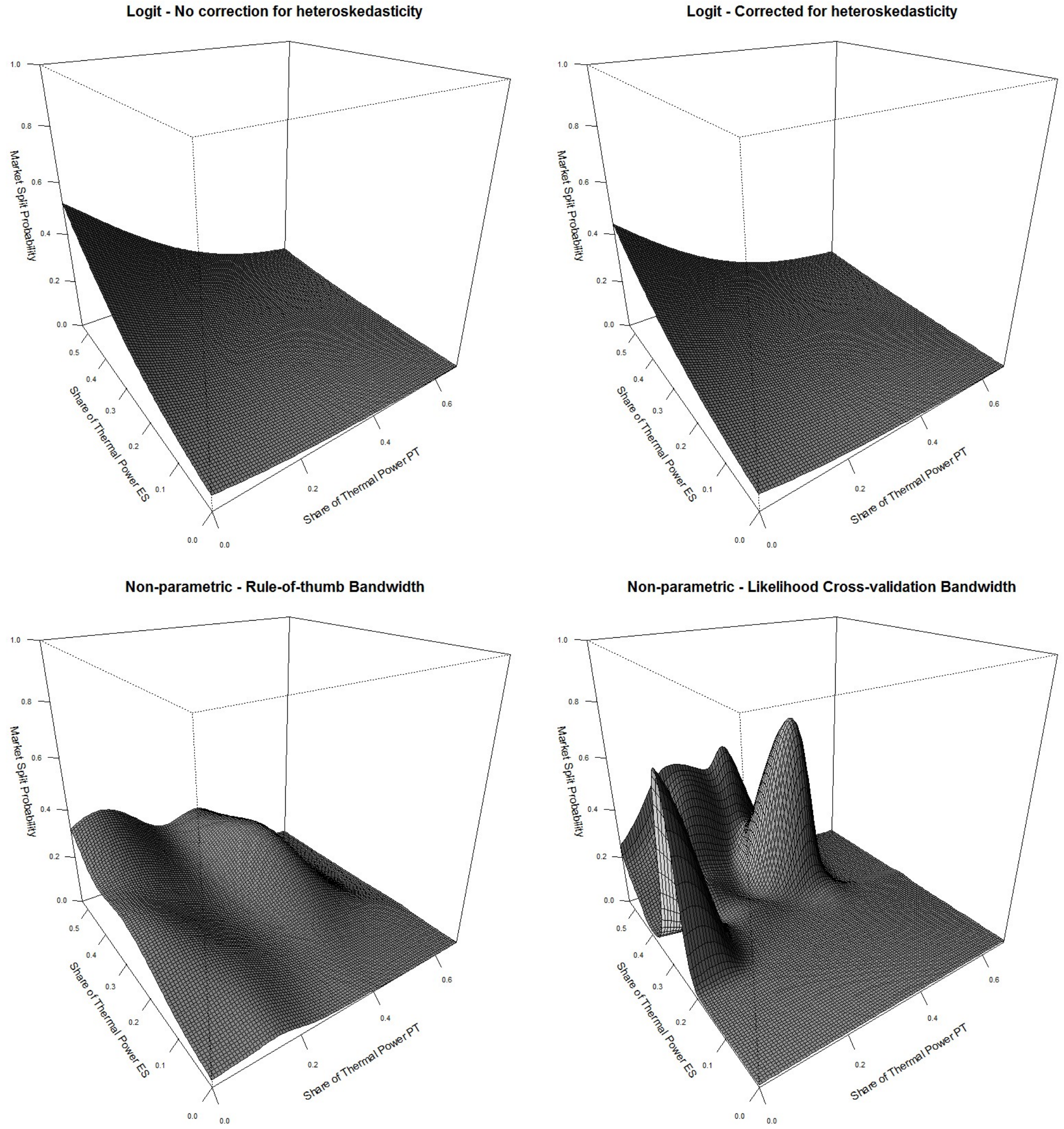
6.2.6.3 Thermal power generation

Decreasing thermal power generation share in Portugal might occur when there is a high availability of renewable resources, having high shares of wind and hydro power generation. This can create a scenario of low marginal cost electricity export from Portugal to Spain, with the increasing probability of interconnection congestion, thus market splitting. It is more evident when the thermal power generation share in Spain is high, due to its relative high marginal cost, thereby creating arbitrage between markets (Figure 6.6). The peaks observed in the likelihood cross-validation bandwidth non-parametric model do not have a clear explanation, but are in the nature of these models due to the use of smaller bandwidths, capturing additional detail and allowing for better model performance (Table 6.4).

With increasing renewable generation share, thermal generation will be driven out of the merit order, having the remaining role of reserve capacity for balancing and system stability purposes. Therefore, the influence of thermal power generation on market splitting probability will remain low.

6.2.6.4 Nuclear power generation

Nuclear power generation is bid into the spot electricity markets at low marginal costs due to its inflexible operational characteristics. It is normal for nuclear power generation to be at the base of the generation mix, together with other low marginal cost technologies, like renewables or combined heat and power (CHP) plants. Therefore, with a higher share of nuclear power generation, more expensive technologies like combined cycle power plants, currently last in the merit order, will be driven out of the market and the spot electricity price will decrease. In Iberia, nuclear power generation is only present in Spain, which will tend to increase exporting electricity flows to Portugal, increasing market splitting probability. In this case the lower likelihood cross-validation bandwidth applied to the non-parametric model, changes the shape of the probability response to nuclear power generation, maintaining however the same overall increasing tendency (Figure 6.7). Depending on the policy followed, nuclear power in Spain might decrease after the decommissioning of the existing operating plants. This might occur after 2020 unless licences are extended and life extension programmes are performed. There-


Logit - No correction for heteroskedasticity

Logit - Corrected for heteroskedasticity

Non-parametric - Rule-of-thumb Bandwidth

Non-parametric - Likelihood Cross-validation Bandwidth

Figure 6.6: Predicted probability response to thermal power generation share

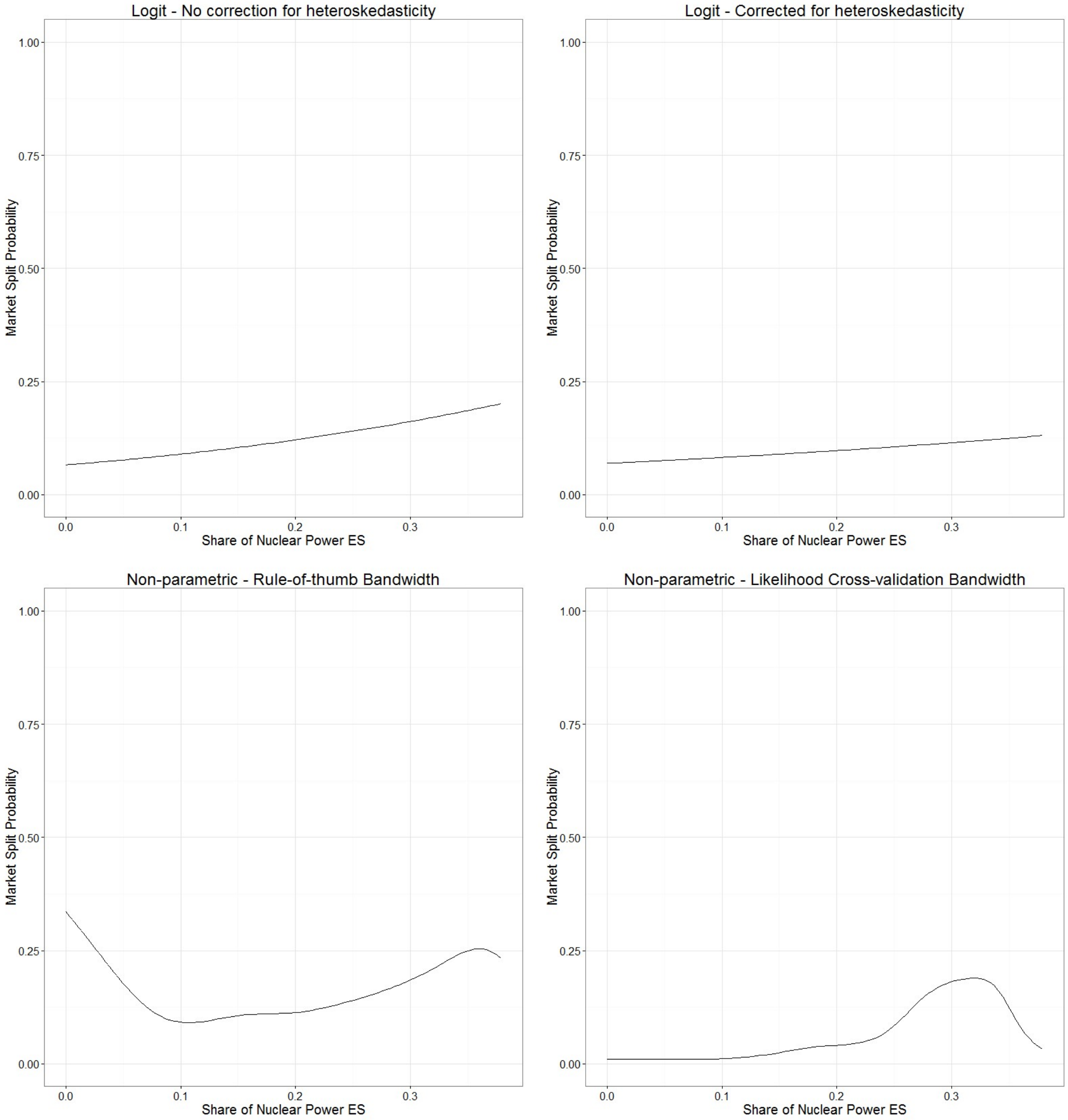


Figure 6.7: Predicted probability response to nuclear power generation share

fore, the contribution of nuclear power for market splitting in the future should be reduced.

6.2.6.5 Available Transfer Capacity

Market splitting probability is seen to decrease with increasing ATC (allowing higher flows of electricity between markets), as one could expect by the definition of the market splitting concept (Figure 6.8). Increasing ATC means that more electricity can flow through the interconnection and, consequently, saturation or congestion of the interconnection is harder to achieve. Furthermore, market splitting probability decreases. This behaviour is shown with both logit and non-parametric models, however the characteristics of the latter give a more complex probability response shape. The complex shape captured by the non-parametric models, in spite of the difficulty in explaining it, gives detailed information and a better model performance is observed (Table 6.4). The increase in sensitivity to 0.91 is notable in the likelihood cross-validation bandwidth model. In particular, the bandwidth for the variable ATC in the direction Portugal to Spain decreases dramatically from 287.7 to 46.6 in the ATC PT-ES (Table 6.4); creating the additional complexity in the shape for the probability response plot (Figure 6.8). A smoother shape is obtained with higher bandwidths in the *"rule-of-thumb"* non-parametric model. Nevertheless, the same tendency of increasing market splitting probability with lower ATC can be observed in all plots (Figure 6.8). Considering the existing level of market splitting probability, we can conclude that the existing cross-border interconnection is adequate for the required electricity market integration, bearing in mind that it is actually higher (currently 25.6%) than the EU recommendation of 10% of the peak demand of the smaller interconnected market (Amorim et al., 2014). Moreover, in order to maintain this reasonable market splitting probability level and spot electricity markets integration, the requirements for cross-border interconnection capacity should increase with increasing available wind power. This will allow further generation optimisation and security of supply, giving TSOs additional possibilities to balance the electrical grid. Otherwise, additional internal reserve capacities should be in place and available for the required grid balancing and system security, with the associated costs to the system. With increasing renewables without the adequate cross-border interconnection, thus increasing market splitting probability, these reserve capacities will normally be outside the dispatch merit order. A capacity payment mechanism might be necessary in order to have reserve power plants ready to be dispatched when required.

6.2.6.6 Demand

The different size of the electrical system between both Iberian countries also determines the market splitting behaviour. In general, lower demand in Spain creates importing electricity flows into Portugal thereby increasing market splitting probability. This is explained by the congestion of the interconnections due to the higher amounts of low marginal cost electricity available in Spain (including nuclear power due to its lack of flexibility). With high electricity demand in Spain, the increase in market splitting probability with increasing demand in Portugal is minimal. This is explained by the low marginal cost electricity being completely consumed internally and high marginal cost electricity dispatched, typically thermal power (Figure 6.9). Future demand in Iberia is dependent, not only on the economic performance, but also on policies that impact the electricity sector on the demand side. Policies for energy efficiency can control the growth of electricity demand, whilst the demand side response might create additional instruments for grid balancing and system security. Both avoid increasing cross-border transits of electricity, therefore decreasing market splitting probability.

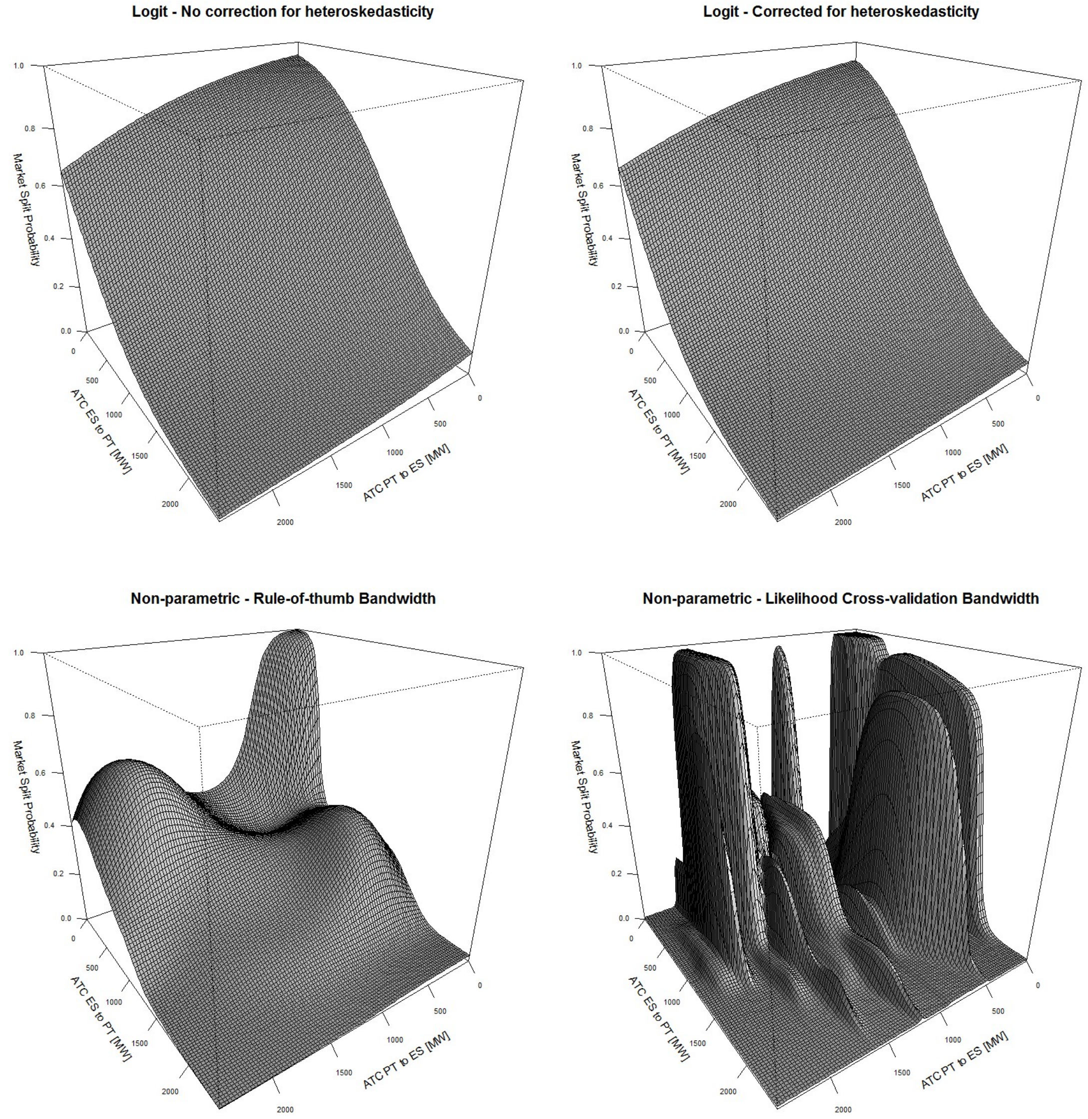
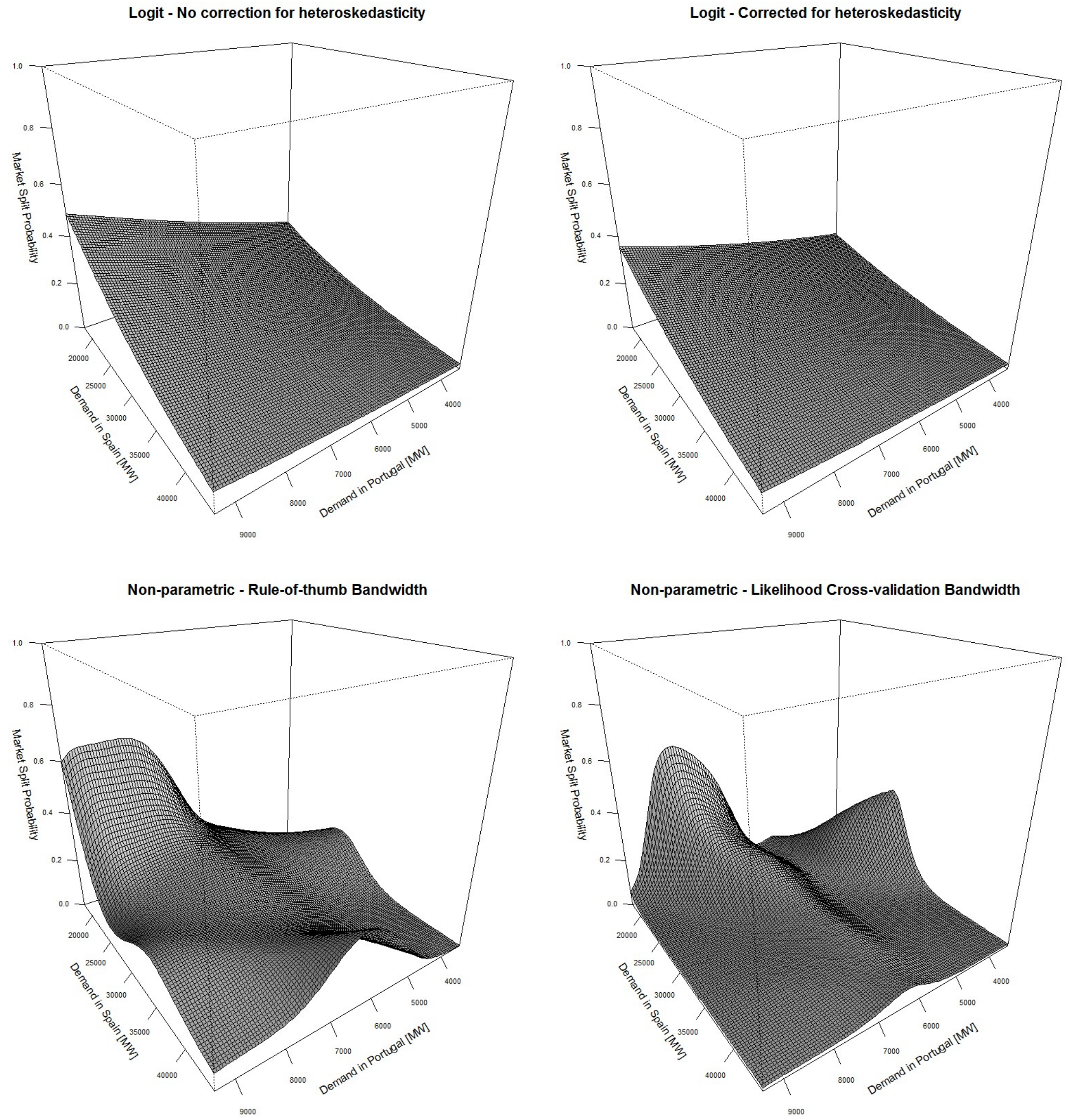


Figure 6.8: Predicted probability response to ATC at mean power generation mix


Logit - No correction for heteroskedasticity

Logit - Corrected for heteroskedasticity

Non-parametric - Rule-of-thumb Bandwidth

Non-parametric - Likelihood Cross-validation Bandwidth

Figure 6.9: Predicted probability response to demand at mean power generation mix

Table 6.1: Iberian installed generation capacities [MW] (Eurostat, 2015)

Portugal

Year	Thermal	Nuclear	Hydro	Wind	Solar	Total
2000	6275	0	4535	83	1	10894
2001	6291	0	4560	125	1	10977
2002	6448	0	4583	190	1	11222
2003	6749	0	4583	268	2	11602
2004	7292	0	4831	553	2	12678
2005	7277	0	5017	1064	2	13360
2006	7685	0	5053	1681	3	14422
2007	7692	0	5061	2201	24	14978
2008	7767	0	5058	2857	59	15741
2009	8846	0	5091	3326	115	17378
2010	9871	0	5106	3796	134	18907
2011	9936	0	5535	4256	172	19899
2012	9360	0	5717	4412	238	19727
2013	8308	0	5666	4610	296	18880

Spain

Year	Thermal	Nuclear	Hydro	Wind	Solar	Total
2000	26243	7503	17960	2206	12	53924
2001	26915	7519	18032	3397	16	55879
2002	29941	7577	18068	4891	20	60497
2003	37310	7581	18043	5945	27	68906
2004	35477	7577	18167	8317	37	69575
2005	40799	7577	18220	9918	60	76574
2006	43659	7365	18318	11722	180	81244
2007	47412	7365	18372	14820	750	88719
2008	47832	7365	18451	16555	3450	93653
2009	47760	7365	18505	19176	3770	96576
2010	50457	7450	18535	20693	4653	101788
2011	49786	7450	18540	21529	5501	102806
2012	49736	7450	18550	22789	6646	105171
2013	49786	6984	19094	22958	7016	105838

Table 6.2: Time series summary statistics

	$Price_{PT}$ [$Euro/MWh$]	$Price_{ES}$ [$Euro/MWh$]	$\Delta Price_{PT-ES}$ [$Euro/MWh$]	ATC_{PT-ES} [MW]	ATC_{ES-PT} [MW]	$Demand_{PT}$ [MWh]	$Demand_{ES}$ [MWh]
Mean	46.68658	45.54854	1.138048	-1542.638	1528.993	5749.859	29165.64
Median	46.4	45.91	0	-1500	1500	5734.602	29311.83
Maximum	180.3	145	136.3	0	2400	9383.98	44273.83
Minimum	0	0	-47.46	-2400	0	3406.955	17687
Std. Dev.	15.78929	15.48229	4.448196	550.1416	461.4037	1078.157	5227.109
Skewness	-0.003616	-0.143803	3.982872	0.177799	-0.379035	0.258378	0.118456
Kurtosis	4.019719	3.957801	61.21812	2.614746	3.195486	2.286221	2.114621
Jarque-Bera	1709.909	1644.498	5677558	451.9792	1007.788	1276.854	1381.278
Probability	0	0	0	0	0	0	0
Observations	39464	39464	39464	39464	39464	39464	39464

	$Wind.gen_{PT}$ [MWh]	$Wind.gen_{ES}$ [MWh]	$Hydro.gen_{PT}$ [MWh]	$Hydro.gen_{ES}$ [MWh]	$Thermal.gen_{PT}$ [MWh]	$Thermal.gen_{ES}$ [MWh]	$Nuclear.gen_{ES}$ [MWh]
Mean	974.3427	4672.579	924.6938	2466.898	1402.33	11213.7	6347.269
Median	775.3975	4137.833	763.825	2257	1438.3	11075	6404.667
Maximum	3715.67	16469.17	3904.475	11398.67	3731.75	25323.5	8028.833
Minimum	5.3125	0	-1038.7	-3381	-31.5	0	0
Std. Dev.	752.585	2743.402	943.4651	2251.771	589.6106	4443.246	878.2405
Skewness	0.964183	0.799007	0.642897	0.499848	0.072625	0.170796	-0.618126
Kurtosis	3.254006	3.15797	2.80143	3.104692	3.12601	2.562856	2.774229
Jarque-Bera	6220.696	4240.083	2783.354	1661.358	60.80157	506.0926	2596.882
Probability	0	0	0	0	0	0	0
Observations	39464	39464	39464	39464	39464	39464	39464

Table 6.3: OMIE market splitting logit model

Dependent variable: Market Split

Data: 1 of July 2008 to 31 of December 2012

Coefficients (binomial model with logit link):

	No het. Correction		Het. Correction	
c	3.157	***	7.12	***
Wind share PT	-5.028	***	-13.36	***
Wind share ES	6.588	***	12.66	***
Hydro share PT	-4.925	***	-12.91	***
Hydro share ES	0.2876		-6.683	***
Thermal share PT	-4.744	***	-8.901	***
Thermal share ES	5.343	***	8.089	***
Nuclear share ES	3.367	***	3.272	***
ATC PT to ES	-0.000979	***	-0.001415	***
ATC Es to PT	-0.002207	***	-0.004095	***
Demand PT	0.0002289	***	0.0003794	***
Demand ES	-0.00008922	***	-0.0001247	***

Latent scale model coefficients (with log link):

Wind share PT			1.5167	***
Wind share ES			-0.7004	***
Hydro share PT			1.1257	***
Hydro share ES			3.2242	***

Studentized Breusch-Pagan test

data: ms.logit

BP = 6096.314, df = 11, p-value ¡ 2.2e-16

	No het. Correction	Het. Correction
McFadden pseudo R-squared:		
	0.2403994 (*df* = 12)	0.2745606 (*df* = 16)
Accuracy (CCR)	0.8257	0.8332
Sensitivity (TPR)	0.3613	0.3993
Specificity (SPC)	0.9496	0.9489

***Significant at 1% level

Note: Confusion matrices are available from authors upon request. A confusion matrix is a performance measure used to evaluate probability response models. It compares for the binary dependent variable the observed values with the predicted results from the model. Further description of this performance measure can be found in Bontemps, Racine, and Simioni (2011)

Table 6.4: OMIE market splitting non-parametric model

Dependent variable: Market Split		
Bandwidth Type: Fixed		
Conditional density data (39464 observations, 12 variable(s))		
(1 dependent variable(s), and 11 explanatory variable(s))		
Data: 1 of July 2008 to 31 of December 2012		
Unordered Categorical Kernel Type: Aitchison and Aitken		
Bandwidth Selection Method:	Rule of Thumb	Likelihood cross-validation
	Bandwidth:	Bandwidth:
Market Split	0	0.009525335
Wind share PT	0.06602877	0.04218351
Wind share ES	0.05050762	0.02516179
Hydro share PT	0.07660497	0.09979179
Hydro share ES	0.03462729	0.03768847
Thermal share PT	0.05096986	0.03847238
Thermal share ES	0.06278519	0.0230787
Nuclear share ES	0.02663741	0.02196849
ATC PT to ES	287.7722	46.59403
ATC Es to PT	232.6589	164.1666
Demand PT	563.9704	423.8871
Demand ES	2734.236	2419.506
Continuous Kernel Type: Second-Order Gaussian		
Bandwidth Selection Method:	”Rule-of-Thumb”	”Cross-validation”
Accuracy (CCR)	0.905787553213055	0.97387492398135
Sensitivity (TPR)	0.60839749759384	0.913498556304139
Specificity (SPC)	0.98513739085773	0.989984591679507

Note: Confusion matrices are available from authors upon request

6.3 It is windy in Denmark: does market integration suffer?

One of the best case studies, considering the high level deployment of wind power and with a long history of electricity market integration through market splitting, is Denmark. Its support to research and technological development of wind power, resulted in a strong player in the wind power turbine market, supplying about one third of the world demand for this technology (International Energy Agency, 2011, 2013).

Therefore, this research aims to assess the influence of high availability of wind power on the market splitting behaviour of the Danish bidding areas in the Nord Pool electricity spot market, taking into account cross-border electricity flows. The leading hypothesis considered in this study is that, in spite of the multiple existing interconnections and associated cross-border flows, wind power generation still influences market splitting in Denmark.

Following Figueiredo et al. (2015a), expanded to a new multi-interconnected electricity market, logit and non-parametric models are herein used to express the probability response for market splitting of day-ahead spot electricity prices as a function of wind power generation share, electricity demand, interconnection cross-border flows and market splitting of adjacent bidding areas. Logit models contribute with preliminary indications on market splitting behaviour, in spite of the known specification limitations. These limitations are subsequently overcome with the use of non-parametric models as demonstrated in Figueiredo et al. (2015a).

In Sub-section 6.3.1 the Danish electricity market characterisation is presented, consisting of a survey of the EU legislative framework and Danish energy policy, an overview of the renewables deployment in Denmark and a brief explanation of the Danish electricity market as part of the Nordic electricity market. Data and model specification used in this study are presented in Sub-section 6.3.2, followed by the presentation of the model results in Sub-section 6.3.3 and the respective analysis and discussion in Sub-section 6.3.4.

6.3.1 Danish Electricity Market Characterisation

6.3.1.1 EU and the Danish Energy Policy

The absence of energy natural resources together with the oil crisis of the 1970's drove Denmark into a path of extensive efforts in Research and Development (R&D) of endogenous energy sources. Within the period until 1990, Denmark developed oil and natural gas production in the North Sea, decreasing its dependency on oil imports. Additionally, energy security of supply was achieved by replacing oil consumption by coal and natural gas, and on the demand side by implementing a challenging energy saving programme (Danish Energy Agency, 2012; Lund & Clark, 2002).

Bearing in mind that oil and gas resources are scarce and following the Kyoto accords to reduce CO_2 emissions, Danish energy policy turned into the development of renewable energy sources. Nonetheless, the formerly existing Danish energy policy was deemed to be insufficient to achieve the established target of 20% CO_2 emissions reduction by 2005 compared with 1988, which created the need for the so called *"Green Energy Plan"*, instigating the official *"Energy 21"* adopted in 1996. This plan comprised of the following measures: switching from electric heating to central heating, improving insulation and low-temperature district heating, utilisation of natural gas in district heating, diffusing the use of biomass, deployment of wind turbines (3000 MW by 2015), further stakeholder training and energy conservation (Lund, 1999). These measures intended to attain the main objective of CO_2 reduction by also setting the following sub-targets: 20% improvement of energy conservation compared with 1994 and 12% to 14% share of electricity consumption generated from renewable sources. Additionally, the chief goal of achieving 50% CO_2 reduction by 2030 compared with 1998, would be accomplished by increasing energy conservation to 55% above 1994 levels and 35% share of electricity consumption generated from renewable sources (Lund & Clark, 2002).

In 2005, the *"Energy Strategy 2025"* established the vision of total independence from fossil fuels. Targets were established to achieve a reduction of 15% for fossil fuel usage and keep a static overall energy consumption. Further specific targets were set for energy efficiency (1.25% annual growth), renewable energy (30% renewable energy share consumption by 2025) and more efficient new energy technologies (R&D support of new energy technologies). This strategy also depended on efficient markets and specifically on the electricity market where the expansion of transmission networks is fundamental for the supply reliability (Danish Energy Authority, 2007). Danish energy policy for the years 2008 to 2011 expanded on previous policies by setting intermediate targets of 20% consumption share from renewable energy sources (RES) by 2011 and development of offshore wind by 2012 (International Energy Agency, 2011).

"Energy Strategy 2050" was launched in 2011, setting the same overall goal of fossil fuel independence, though giving it the deadline of 2050. The renewable energy share consumption of 30% was advanced to 2020, supporting and exceeding the EU target of 20%. Furthermore, measures like the electrification of heating systems, industry and transport, or the development of smart grids are part of this strategy. The Energy Agreement reached in March 2012 finally extended and brought Denmark closer to its strategy goals: 35% consumption share from RES; 50% electricity demand share from wind power; and 34% reduction in Greenhouse Gas (GHG) emissions compared to 1990 (Danish Energy Agency, 2012; Danish Ministry of Climate Energy and Building, 2013).

Danish energy policies were always aligned, if not a step ahead of EU own policies. The release of the Council Directive 96/61/EC established common rules for pollution control and prevention and the EU Directive 2003/87/EC established the GHG emission allowance trading scheme. Almost simultaneously, in order to reduce dependency on imported fossil fuels and to allow the reduction in GHG emissions, the EU Directives 2001/77/EC and 2009/28/EC called for the promotion of electricity generation by renewable energy sources. On the electricity market side, the EU Directives 96/92/EC, 2003/54/EC and 2009/72/EC established common rules for the various electricity markets in Europe.

6.3.1.2 Renewables deployment in Denmark

As referred in the above Section, Danish and EU policies for emissions reduction and energy security, together with the related aim to decrease the dependence from fossil fuels, led to the development of RES-E generation. Given the limited hydro power potential, the R&D was mainly focused on wind power and Combined Heat and Power (CHP) (Lund, 2007). Almost non-existent in 1972, wind power share grew to 20% in 2008 (Lund, 2010), with some municipalities in West Denmark (DK1) fully supplied by wind power (Lund et al., 2013). The main source of renewable electricity generation in Denmark is nowadays wind power, with a share of 51.1% of the electricity demand in 2014 (Nord Pool, 2015b).

Wind power R&D was enhanced through the establishment of a partnership between public and private institutions, aiming to keep Denmark as a major world player in wind power technology at competitive prices (Danish Energy Authority, 2007). Additionally, wind power generation development in Denmark has been supported through strong financial support mechanisms, initially by price premiums paid to wind turbine owners and later after 1999 by feed-in tariffs. From 2004 onwards, subsidies were given as supplements to the electricity market price. These subsidies were later increased in 2008 and were limited to a maximum number of full-load operating hours, after which wind power is paid at electricity market prices (Danish Parliament, 2008). A gradual reduction of subsidies to wind power is expected, due to its increasing technological competitiveness and the subsidy expiration of older units (Danish Ministry of Transport and Energy, 2007). Additional details about wind power financing can be found in Lund et al. (2013), Munksgaard and Morthorst (2008).

New concerns and challenges of high shares of RES-E are reported both in the technical sense and in the market design. On the technical sense: generation variability and uncertainty, adequate transmission capacity, flexibility and standby of dispatchable generation, electrical system regulation and frequency control, demand side response, RES-E curtailment, energy storage, adequate transmission grid and cross-border interconnections (O. Edenhofer et al., 2011; Lynch et al., 2012; Mauritzen, 2010; Nicolosi, 2010); and in the market design: electricity market integration, transmission grid and cross-border interconnections cost allocation, intraday and reserve power markets, RES-E financial support schemes and capacity support mechanisms (Batlle et al., 2012; Benatia et al., 2013; MIT Energy Initiative, 2011; Nicolosi, 2010).

As seen in Figure 6.10, thermal power generation capacity share is decreasing since 2000, with a steeper fall in 2011, whilst wind power generating capacity share steadily increased during the same period. Therefore, thermal generation was gradually being replaced with wind generation. The absence of hydro and nuclear power generation in Denmark is noteworthy: the former due to the absence of geographic conditions, and the latter, by a parliament resolution not to build nuclear power plants in the country (World Nuclear Association, 2015a). By the end of 2013, wind power generation capacity reached 4820 MW in Denmark, which is equivalent to a 34.9% share of installed capacity. Solar power generation capacity share slightly start to increase after 2011.

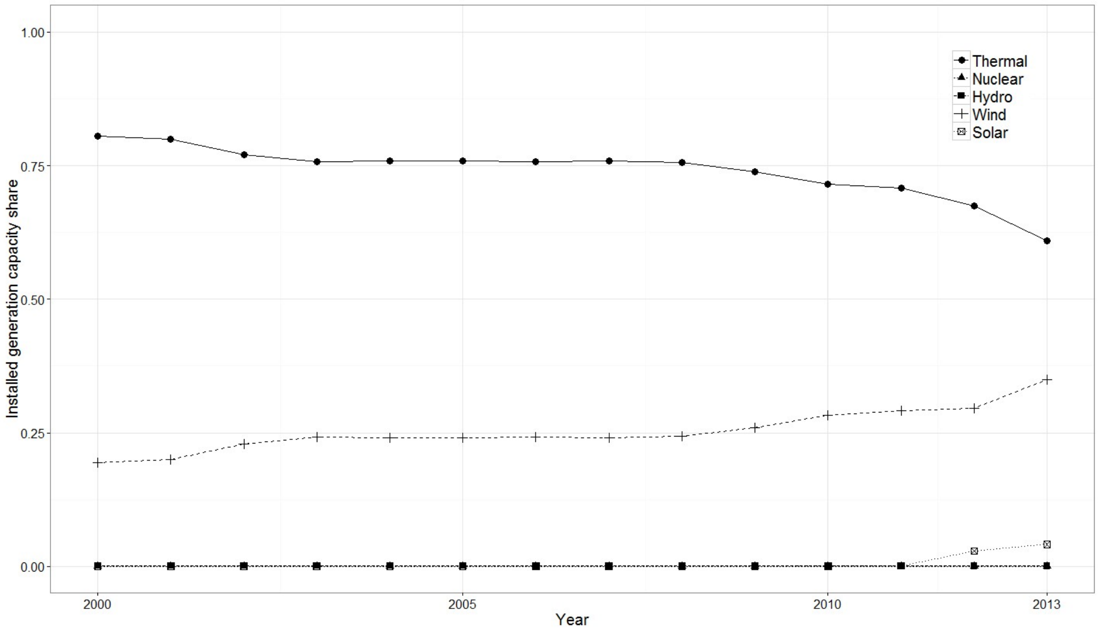


Figure 6.10: Installed generation capacity shares of total installed capacity in Denmark (Eurostat, 2015)

When analysing the extracted hourly data, wind power generation share of demand has been, surprisingly in more than a few hourly periods, above 1 in West Denmark (DK1). This means that not only wind generation was able to supply the complete electricity demand in West Denmark (DK1), but also that there was a surplus exported through the existing interconnections. This is not the case for East Denmark (DK2). However, wind power generation share is still quite high, frequently achieving values above 0.5 (Nord Pool, 2015b).

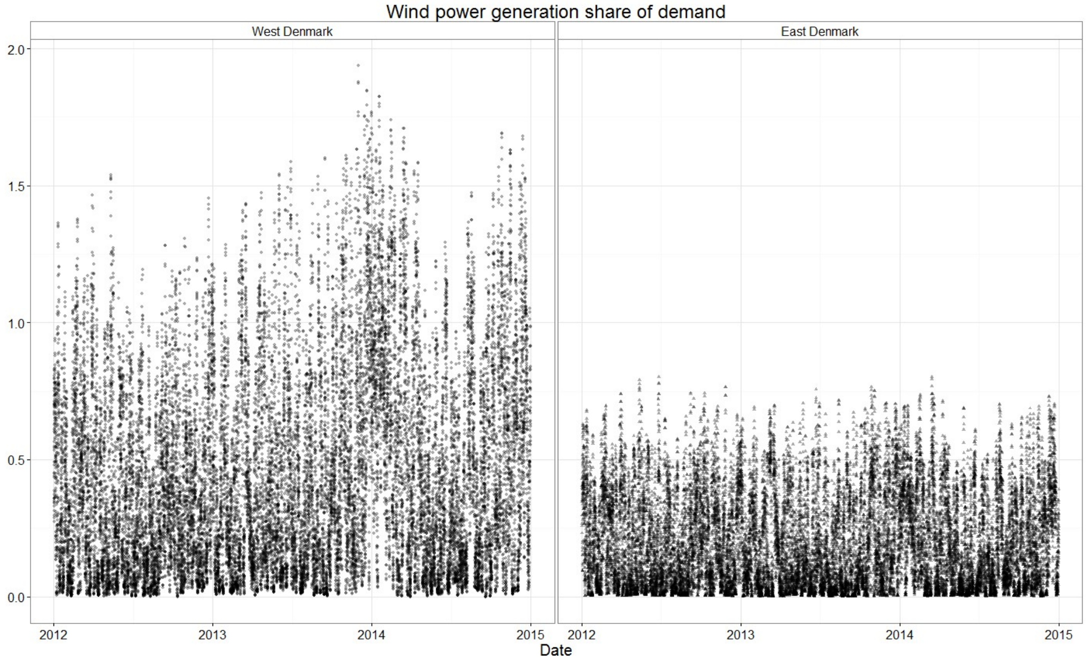


Figure 6.11: Wind power generation share of demand in Denmark

6.3.1.3 Denmark in the Nordic electricity market

The Nordic electricity market, the Nord Pool, is composed by Norway, Sweden, Finland, Denmark, Estonia, Latvia and Lithuania. These countries are then subdivided by bidding areas, taking into account transmission system capacities and constraints. The Nord Pool was established in 1996 with a joint Norwegian-Swedish power exchange, after the deregulation of the Norwegian electricity market in 1991. To complete the adhesion of the northern European countries, Finland joins Nord Pool in 1998 followed by Denmark in 2000. Consequently, Nord Pool is the oldest electricity market in Europe where a market splitting mechanism is implemented.

Elspot (Nord Pool's spot electricity market) calculates day-ahead prices for every hour and for each bidding area by establishing a balance between supply and demand bids. It also takes into account available transmission capacities (ATC) between the bidding areas. The congestion of interconnections between bidding areas creates the market splitting, with the electricity spot prices diverging. Bidding areas with lower prices export electricity to areas with higher prices through these limited capacity interconnections (Meeus et al., 2009). If the ATC is large enough to accommodate the exported electricity flows (no congestion), then the price is the same in both bidding areas. Therefore, this mechanism is supported on the calculation of the ATC, which is made by each TSO taking into account the safety and reliability of the electrical system. Depending on loop flows and technical constraints imposed by TSOs, import and export ATC can have different values (Luna & Martínez, 2011).

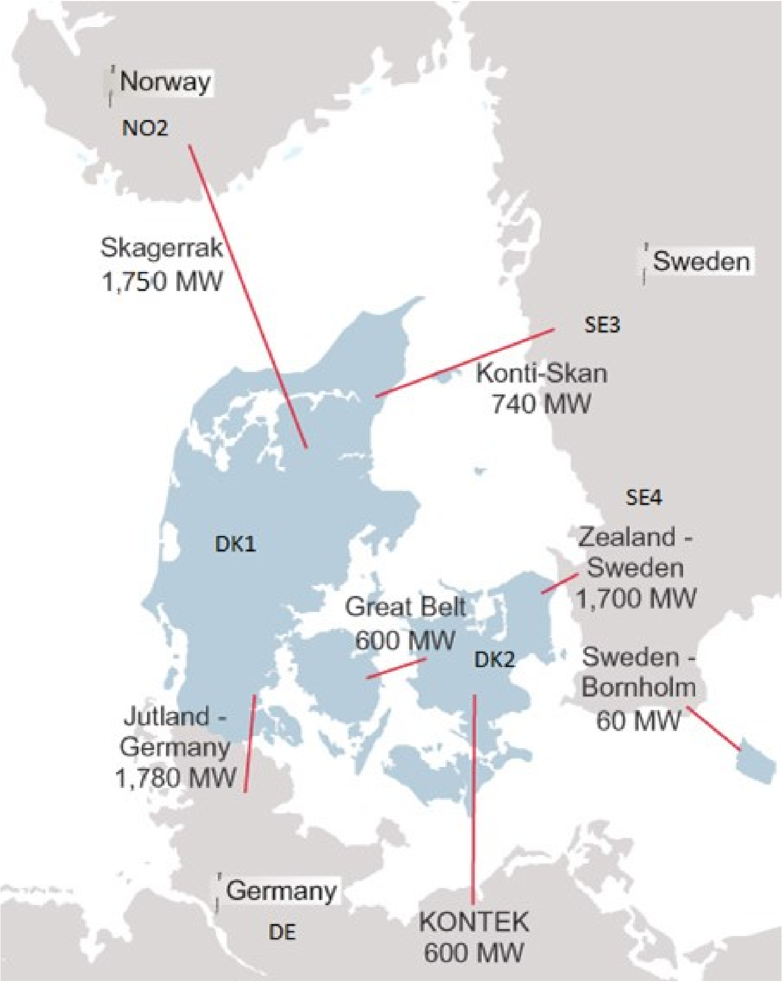


Figure 6.12: Denmark's bidding areas and interconnections (Energinet, 2015)

Denmark is divided into two bidding areas, interconnected through the HV electricity grid. Moreover, Denmark is also interconnected with Norway and Sweden in the north and Germany (DE) in the south. The interconnection capacity between the two Danish bidding areas is 600 MW through a HV Direct Current cable. The interconnection capacities and bidding areas are shown in Figure 6.12. Interconnections capacity between the considered areas are higher than the current EU recommended level of 10% of the peak demand of the smaller interconnected market (Amorim et al., 2014). Denmark has already surpassed this value reaching 23.8% between West and East Denmark (DK1-DK2), 15.9% between West Denmark (DK1) and Sweden bidding area 3 (SE3), 64.5% between East Denmark (DK2) and Swedish bidding area 4 (SE4), 23.8% between East Denmark (DK2) and Germany (DE) and 38.3% between West Denmark (DK1) and Germany (DE), all of the peak demand observed in the period considered in this study.

6.3.2 Data and Methods

Following the methodology described in Figueiredo et al. (2015a), expanded to a new multi-interconnected electricity market, market splitting behaviour was modelled through logit and non-parametric models estimating the probabilities of its occurrence. In the estimated models the introduction of electricity flows and market splitting binary variables of surrounding interconnected bidding areas introduce an additional complexity in relation to the models used in Figueiredo et al. (2015a), where the interconnection between Spain and France was not considered. In the estimated models the probability response for market splitting of day-ahead spot electricity prices is expressed as a function of wind power generation shares, electricity demands, five interconnection electricity flow shares and five market splitting binary variables. These variables correspond to the two Danish bidding areas, the Swedish bidding areas 3 and 4, the Norwich bidding area 2 and Germany (DE), which are all adjacent. By imposing a parameter approach, logit models provide a general indication of the effects of each variable (*"ceteris paribus"*), which might change with others. Additionally, logit models present known specification restrictions, such as:

- The *"Neglected Heterogeneity"* specification issue, where the coefficient estimates may cause an underestimation of the effects – extraction of explanatory variables relative effects can still be of use (Mood, 2009; J. Wooldridge, 2010);

- Heteroskedasticity of the error term – A correction can be used according with Davidson and Mackinnon (2004) and Zeileis, Koenker, and Doebler (2013).

Yet, logit models can provide some preliminary indications about the model behaviour. The non-parametric models, herein used, do not require parametric assumptions for the underlying data generation process, therefore the logit specification limitations are avoided. One of the main set-backs of non-parametric modelling is the required computer processing resources when using large datasets, as it is inhere the case where the model estimation took several days to run, even with parallel processing. Furthermore, the *"Curse of Dimensionality"*, related with the number of continuous explanatory variables, might deteriorate the convergence rate of the kernel functions, nevertheless models remain consistent (Racine, 2007). In our models the sample size overcomes this issue.

6.3.2.1 Data

Day-ahead spot electricity prices in Euro/MWh, interconnection flows in MWh, Demand in MWh and Wind Power Generation in MWh, for each hour from the 2nd of January 2012 until the 31st of December 2014, were extracted from the Nord Pool Spot ftp server (Nord Pool, 2015b) and from EPEX (2016), for both Danish and adjacent bidding areas. This consists in a sample of 26281 hours. The demand of the Danish electricity market has a peak of 6.5 GWh, which is comparably small with the demand in Norway, with a peak of 24.2 GWh, and the demand in Sweden, with a peak of 26.6 GWh. However, when these electricity markets are divided into bidding areas, the only bidding area that stands out is the Swedish bidding area 3 with a demand peak of 17.5 GWh (Nord Pool, 2015b). Germany (DE) with its 77.2 GWh of peak demand is by large the biggest connected electricity market (ENTSO-E, 2015b).

By using a rolling window procedure for the number of market splitting hours in a month, a trend is established and can be plotted. Therefore, a price convergence can be observed in the case of reducing number of market splitting hours in a rolling month. Between West and East Denmark, the number of market splitting hours in a moving month remains low, with an exception during a small period in the end of 2013 and 2014 (Figure 6.13). Furthermore, it seems that there

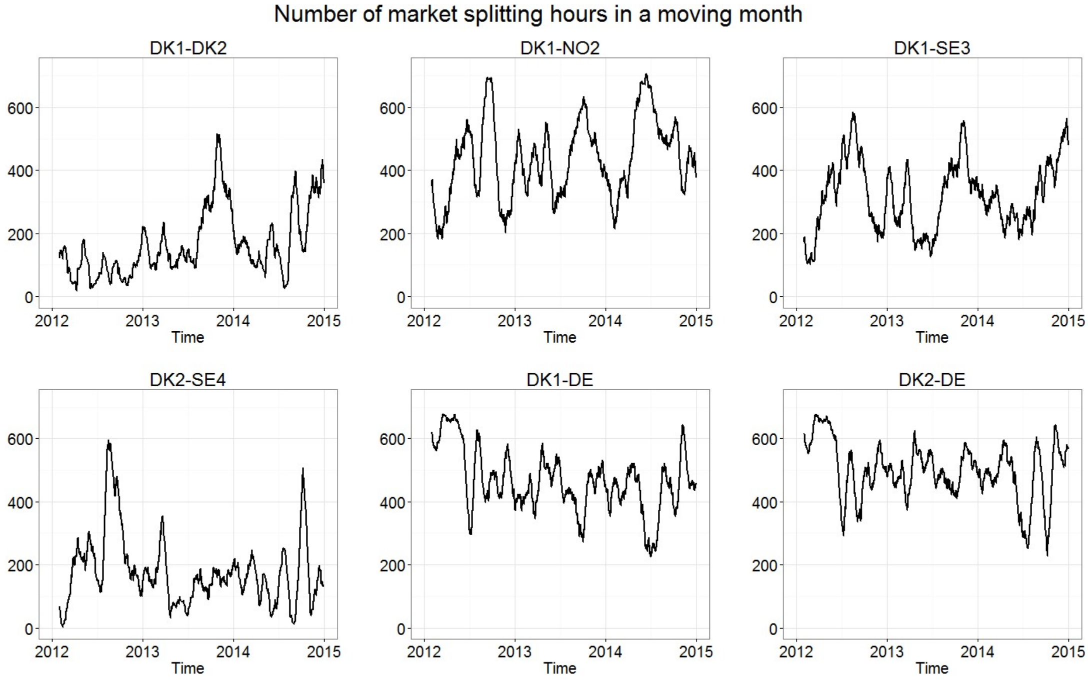


Figure 6.13: Market splitting evolution

is a higher integration level between both Danish bidding areas and between East Denmark (DK2) and Sweden bidding area 4 (SE4). In this period, market splitting between both Danish biding areas occurred in 23.3% of the total 26281 hours considered in our sample. Likewise, market splitting occurred 60.4% between West Denmark (DK1) and Norway bidding area 2 (NO2), 44.3% between West Denmark (DK1) and Sweden bidding area 3 (SE3), 24.3% between East Denmark (DK2) and Sweden bidding area 4 (SE4), 64.8% between West Denmark (DK1) and Germany (DE) and 69.5% between East Denmark (DK2) and Germany (DE), of the total sample.

Figure 6.14 plots the spot electricity price differences between West Denmark (DK1) and East Denmark (DK2), showing that multiple market splitting hours occurred in the period herein considered. It is also observed that there are more data points below zero, which means that prices in East Denmark (DK2) are frequently higher than the ones in West Denmark (DK1).

In Figure 6.15 the interconnection cross-border flows between Denmark and

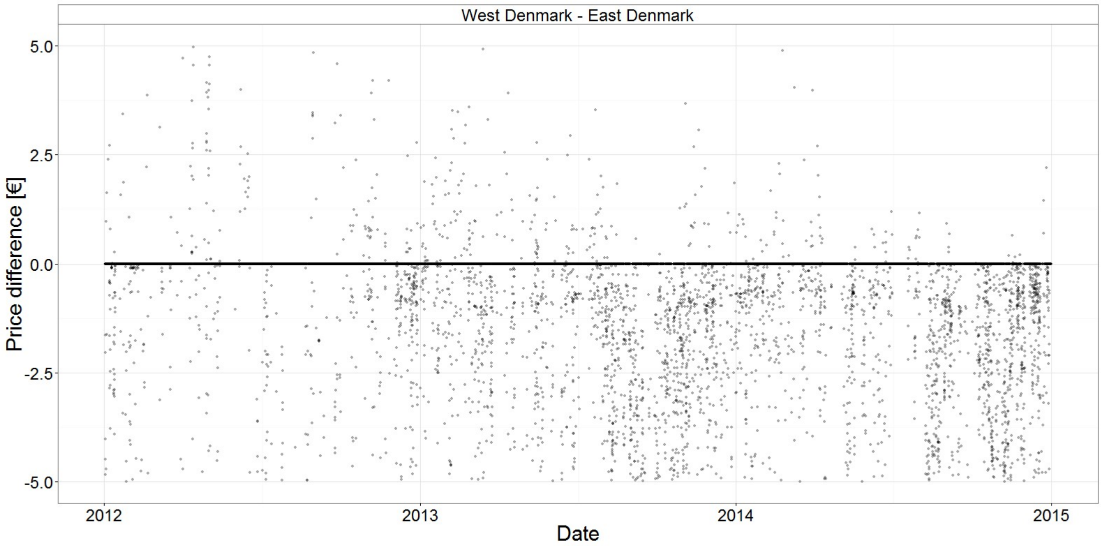


Figure 6.14: Spot electricity price differences between Danish bidding areas

the Nord Pool adjacent areas are plotted. The interconnection transfer flows plot between both Danish bidding areas reveals that, most of the time the electricity flow direction is from West to East Denmark. This is consistent with the lower prices observed in West Denmark (Figure 6.14). The interconnection transfer flows between East Denmark and Sweden have a slight tendency to be predominantly in the direction from Sweden to East Denmark, indicating lower prices in Sweden bidding area 4 (SE4). No significant asymmetries are observed in the remaining interconnection flow plots, which indicate that there is no evident preferred direction for the cross-border flows.

In Table 6.5 the summary statistics are presented for the considered time series. All price time-series have non-normal distributions, as determined by the rejection of the null for the Jarque-Bera normal distribution test.

6.3.2.2 Logit Model Estimation

Following the logit specification in Figueiredo et al. (2015a), the estimated market splitting probability model expresses the probability of occurring different prices, thus interconnection congestion, between both Danish bidding areas. The

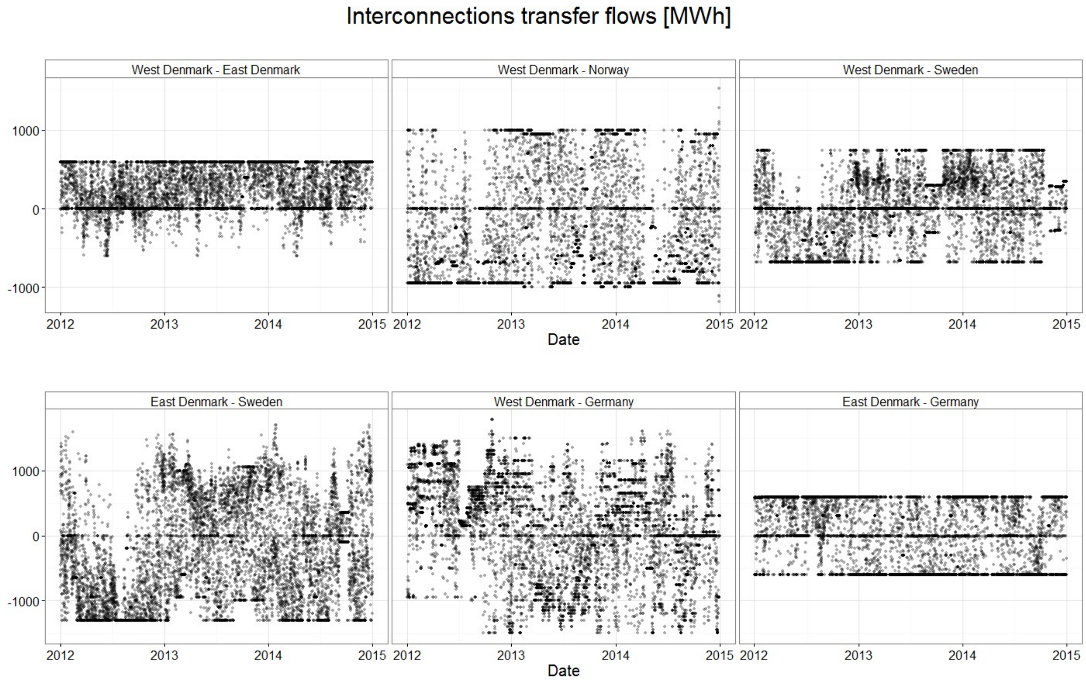


Figure 6.15: Interconnection cross-border flows with Danish adjacent bidding areas

model specification used is:

$$P(Y = 1|X) = P(Split^* > 0|X) = P(X\beta + e > 0|X), \tag{6.9}$$

$$P(e > -X\beta|X) = 1 - P(e \leq -X\beta|X) = 1 - \Lambda(-X\beta) = \Lambda(X\beta), \tag{6.10}$$

where

$$\Lambda(X\beta) = \frac{exp(X\beta)}{1 + exp(X\beta)}$$

$Split$ is the binary dependent variable, X a matrix of explanatory variables and

Table 6.5: Time series summary statistics

	Price DK1 [Euro/MWh]	Price DK2 [Euro/MWh]	Price NO2 [Euro/MWh]	Price SE3 [Euro/MWh]	Price SE4 [Euro/MWh]	Price DE [Euro/MWh]
Mean	35.377	36.482	37.956	31.501	31.258	37.732
Median	33.85	34.815	36.325	31.76	31.725	36.51
Maximum	2000	253.92	300.01	234.38	210	210
Minimum	-200	-200	1.38	0.59	0.59	-221.99
Std. Dev.	29.639	14.162	14.194	10.518	9.702	16.707
Skewness	50.852	0.598	3.741	2.744	1.832	-1.062
Kurtosis	3280.827	39.475	41.154	35.534	21.624	25.136
Jarque-Bera	1.17E+10	1.45E+06	1.65E+06	1.19E+06	3.92E+05	5.39E+05
Probability	0	0	0	0	0	0
Observations	26146	26146	26146	26146	26146	26146

	Demand DK1 [MWh]	Demand DK2 [MWh]	Demand NO2 [MWh]	Demand SE3 [MWh]	Demand SE4 [MWh]	Demand DE [MWh]
Mean	2290.037	1541.256	3902.668	9907.371	2785.675	54633.017
Median	2238	1535	3799	9688	2732	54290.5
Maximum	4647	2520	6702	17466	5163	79120
Minimum	1159	829	2327	5057	1085	29201
Std. Dev.	495.104	328.932	760.786	2286.445	685.998	10351.346
Skewness	0.242	0.191	0.450	0.401	0.408	-0.005
Kurtosis	2.111	2.288	2.447	2.606	2.656	1.954
Jarque-Bera	1.12E+03	7.11E+02	1.21E+03	8.70E+02	8.54E+02	1.19E+03
Probability	0	0	0	0	0	0
Observations	26146	26146	26146	26146	26146	26146

	Cross-border flow DK1-NO2 [MWh]	Cross-border flow DK1-SE3 [MWh]	Cross-border flow DK2-SE4 [MWh]	Cross-border flow DK1-DE [MWh]	Cross-border flow DK2-DE [MWh]	Wind power DK1 [MWh]	Wind power DK2 [MWh]
Mean	-258.825	-5.938	-304.489	128.510	47.800	986.547	311.342
Median	-451.3	0	-382.4	150	0	770	234
Maximum	1632	740	1700	1780	585	3517	1032
Minimum	-1232	-680	-1300	-1500	-600	-2	2
Std. Dev.	683.133	436.225	781.972	708.107	497.014	794.581	266.154
Skewness	0.634	-0.066	0.318	-0.315	-0.210	0.822	0.701
Kurtosis	2.048	2.104	1.905	2.376	1.384	2.758	2.331
Jarque-Bera	2.74E+03	8.93E+02	1.75E+03	8.57E+02	3.04E+03	3.01E+03	2.63E+03
Probability	0	0	0	0	0	0	0
Observations	26146	26146	26146	26146	26146	26146	26146

Notes: DK1 - West Denmark; DK2 - East Denmark; NO2 - Norway bidding area 2; SE3 - Sweden bidding area 3; SE4 - Sweden bidding area 4; DE - Germany

e is the independently distributed error term independent from X and following the standard logistic distribution. The $Split^*$ latent variable is then expressed as follows:

$$Split^{*} = \beta_0 + \beta_1 \frac{W_{DK1}}{D_{DK1}} + \beta_2 \frac{W_{DK2}}{D_{DK2}} + \beta_3 D_{DK1} + \beta_4 D_{DK2} + \beta_5 D_{NO2} + \beta_6 D_{SE3} + \beta_7 D_{SE4}$$

$$+ \beta_8 D_{DE} + \beta_9 Flow_{DK1-NO2} + \beta_{10} Flow_{DK1-SE3} + \beta_{11} Flow_{DK2-SE4} + \beta_{12} Flow_{DK1-DE}$$

$$+ \beta_{13} Flow_{DK2-DE} + \beta_{14} Split_{DK1-NO2} + \beta_{15} Split_{DK1-SE3} + \beta_{16} Split_{DK2-SE4}$$

$$+ \beta_{17} Split_{DK1-DE} + \beta_{14} Split_{DK2-DE} + e, \quad (6.11)$$

where W_{DK1} and W_{DK2} are the hourly wind power generation in West and East Denmark, respectively; D_{DK1}, D_{DK2}, D_{NO2}, D_{SE3}, D_{SE4} and D_{DE} are the hourly electricity demand in West Denmark, East Denmark, Norway bidding area 2, Sweden bidding area 3, Sweden bidding area 4 and Germany, respectively; $Flow_{DK1-NO2}$, $Flow_{DK1-SE3}$, $Flow_{DK2-SE4}$, $Flow_{DK1-DE}$ and $Flow_{DK2-DE}$ are the hourly interconnection cross-border flow shares between West Denmark – Norway bidding area 2, West Denmark – Sweden bidding area 3, East Denmark – Sweden bidding area 4, West Denmark – Germany and East Denmark – Germany, respectively; and $Split_{DK1-NO2}$, $Split_{DK1-SE3}$, $Split_{DK2-SE4}$, $Split_{DK1-DE}$ and $Split_{DK2-DE}$ are the hourly binary variables representing market splitting between West Denmark – Norway bidding area 2, West Denmark – Sweden bidding area 3 East Denmark – Sweden bidding area 4, West Denmark – Germany and East Denmark – Germany electricity markets, respectively.

6.3.2.3 Non-parametric Model Estimation

As described in Figueiredo et al. (2015a) the underlying data generation process is not required for non-parametric models, avoiding specification issues that can question parametric models (Pagan & Ullah, 1999). Model estimation is performed through kernel methods with the information provided by the data. An introduction to non-parametric modelling can be found in Hayfield and Racine (2008) and Racine (2007).

Therefore, by using the *"np"* package for non-parametric kernel estimation (Hayfield & Racine, 2008) developed in *R* (The R Foundation for Statistical Computing, 2014), the models inhere used overcome the logit specification issues. With the required information from the data, model estimation is done through kernel methods and the associated bandwidth (Li & Racine, 2007). Parallel processing was used due to the large datasets analysed in this study.

The market splitting probability is estimated by the conditional probability density function (PDF) expressing the probability of occurring different prices between both Danish bidding areas, conditional on the considered explanatory variables. The conditional PDF is then:

$$\hat{f}(y^d|x^d, x^c) = \frac{\hat{f}(y^d, x^d, x^c)}{\hat{f}(x^d, x^c)}, \tag{6.12}$$

where $\hat{f}(y^d, x^d, x^c)$ is the joint PDF, $\hat{f}(x^d, x^c)$ the marginal PDF, y^d the discrete dependent variable, x^d the discrete explanatory variables and x^c the continuous explanatory variables. As described in Section 6.3.2.2 the variables used are: y^d is the binary variable *Split* expressing market splitting between both Danish bidding areas; x^d are the binary variables representing market splitting $Split_{DK1-NO2}$, $Split_{DK1-SE3}$, $Split_{DK2-SE4}$, $Split_{DK1-DE}$ and $Split_{DK2-DE}$; and x^c are the wind power generation variables W_{DK1} and W_{DK2}, the electricity demand variables D_{DK1}, D_{DK2}, D_{NO2}, D_{SE3}, D_{SE4} and D_{DE}, and the interconnection cross-border flow variables $Flow_{DK1-NO2}$, $Flow_{DK1-SE3}$, $Flow_{DK2-SE4}$, $Flow_{DK1-DE}$ and $Flow_{DK2-DE}$.

The joint PDF can then be estimated by:

$$\hat{f}(y^d, x^d, x^c) = \frac{1}{n}\sum_{i=1}^{n} L_{\lambda_y, Y_i^d, y^d} \cdot L_{\lambda_x, X_i^d, x^d} \cdot W_{h_x, X_i^c, x^c}, \tag{6.13}$$

and the marginal PDF by:

$$\hat{f}(x^d, x^c) = \frac{1}{n}\sum_{i=1}^{n} L_{\lambda_x, X_i^d, x^d} \cdot W_{h_x, X_i^c, x^c}, \tag{6.14}$$

where $L(\cdot)$ and $W(\cdot)$ are product kernel functions for discrete and continuous variables, respectively.

For discrete variables:

$$L_{\lambda_x, X_i^d, x^d} = \prod_{s=1}^{r_{x,d}} l(X_{i,s}^d, x_s^d, \lambda_{x,s}), \tag{6.15}$$

$$l(X_{i,s}^d, x_s^d, \lambda_{x,s}) = \begin{cases} 1-\lambda_{x,s}, & \text{if } X_{i,s}^d = x_s^d \\ \frac{\lambda_{x,s}}{c_s - 1}, & \text{otherwise} \end{cases}, \tag{6.16}$$

where $l(\cdot)$ is the discrete univariate kernel function proposed by (Aitchison & Aitken, 1976), $r_{x,d}$ the number of discrete explanatory variables, c_s the number of outcomes in x_s and $\lambda_{x,s}$ the bandwidth, with $\lambda_{x,s} \in [0, (c_s - 1)/c_s]$.

For continuous variables:

$$W_{h_x, X_i^c, x^c} = \prod_{s=1}^{r_{x,c}} \frac{1}{h_{x,s}} w\left(\frac{X_{i,s}^c - x_s^c}{h_{x,s}}\right), \tag{6.17}$$

$$w\left(\frac{X_{i,s}^c - x_s^c}{h_{x,s}}\right) = \frac{e^{\left(-\left(\frac{X_i - x_s^c}{h_{x,s}}\right)^2/2\right)}}{\sqrt{2\pi}}, \tag{6.18}$$

where $w(\cdot)$ is the continuous univariate Second-order Gaussian kernel function, $r_{x,c}$ the number of continuous explanatory variables and $h_{x,s}$ the bandwidth of variable s.

Bandwidth selection is a fundamental part of non-parametric estimation, therefore two methods were considered: the *"rule of thumb"* and *"likelihood cross-validation"*. The *"rule of thumb"* bandwidth is given by:

$$h = 1.06 \cdot \sigma \cdot n^{-1/(2P+l)} \tag{6.19}$$

where σ is the $min(\hat{\sigma}$, interquartile range/1.349), n the number of observations, P the order of the kernel and l the number of continuous variables.

The *"likelihood cross-validation"* method selects the bandwidth (h) by maximizing the following log likelihood function:

$$\mathcal{L} = \sum_{i=1}^{m} log \left[\frac{1}{(n-1)h} \sum_{j=1, j \neq i}^{n} K \left(\frac{X_j - x}{h} \right) \right] \tag{6.20}$$

Finally, the most adequate method was then selected according to model performance (Okumura & Naito, 2004).

By using the same explanatory variables as in the logit model, the non-parametric models were estimated with bandwidths calculated with both selection methods and considering the same data set.

6.3.3 Results

In the following Sections 4.1 and 4.2 results and performance are presented for both logit and non-parametric models.

6.3.3.1 Logit model results

All coefficients are statistically significant ($p < 0.01$) in the estimated model, with the exception of demand Norway area 2 (NO2) and demand Sweden area 3 (SE3), both significant at least to 10%, and the binary variables representing market splitting between West Denmark (DK1) – Sweden area 3 (SE3) and East Denmark (DK2) – Sweden area 4 (SE4) are not significant (Table 6.6). An attempt to correct the heteroskedasticity of the error term (Breusch-Pagan test in Table 6.7) was performed (Figueiredo et al., 2015a), but with little or no improvement on model performance. For this model an accuracy of 0.9360 and a McFadden pseudo R-square of 0.634 were found (Table 6.7). The coefficients for the introduced correction variables in the skedastic function are significant ($p < 0.01$) with the exception of the cross-border flow share from West Denmark to Norway area 2 (NO2) (significant to 10%) and the cross-border flow share from East Denmark (DK2) to Germany (DE) (Table 6.6). Moreover, notwithstanding the “Neglected

Heterogeneity" specification issue of the logit models, extraction of the relative effects can be made (Mood, 2009; J. Wooldridge, 2010).

6.3.3.2 Non-parametric model results

In Table 6.8 confusion matrices for both estimated models are presented and in Table 6.9 the results for the bandwidth calculation are shown. Non-parametric models are revealed to have improved performance, in addition to the absence of the specification issues of the logit models. An accuracy of 0.9965 is obtained with the bandwidth selected by likelihood cross-validation, the highest amongst all estimated models.

In Figure 6.16 the observed and the fitted number of market splitting hours in a rolling month are shown in the sample period, for the measured data, for the heteroskedasticity corrected logit model and for the likelihood cross-validation non-parametric model. As demonstrated, the performance of the non-parametric model is clearly better than the one obtained by the logit model.

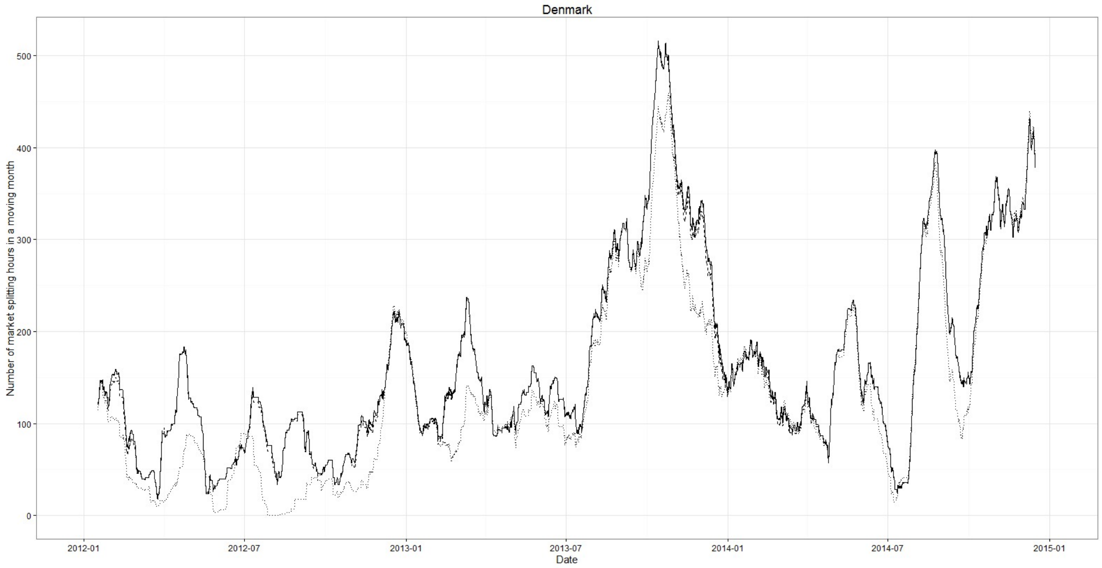


Figure 6.16: Danish market splitting evolution (dotted - logit, dashed – non-parametric, solid - measured)

6.3.4 Discussion

For clarification purposes, when market splitting probability is referred to, it means the probability of market splitting occurrence between West and East Denmark (the Danish splitting: DK1-DK2). No other market splitting probability is estimated in this study. Considering the results of the logit models and their marginal effects (Table 6.6), together with the 3D plots of the non-parametric models, it is possible to unveil the complex behaviour of the Danish electricity market splitting as observed in Figure 6.17 and Figure 6.18. Given that the *"likelihood cross-validation"* non-parametric model has the highest performance amongst all estimated models, the following interpretations are based on this model.

Figure 6.17 shows (from top to bottom and left to right) the behaviour of market splitting probability response as a function of wind power generation in West and East Denmark: a) given market splitting occurrence between Denmark and all adjacent bidding areas (Denmark isolated); b) given market splitting occurrence between Denmark and all adjacent bidding areas with the exception of West Denmark (DK1) to Norway bidding area 2 (NO2); c) given market splitting occurrence between Denmark and all adjacent bidding areas with the exception of West Denmark (DK1) to Sweden bidding area 3 (SE3); d) given market splitting occurrence between Denmark and all adjacent bidding areas with the exception of East Denmark (DK2) to Sweden bidding area 4 (SE4); e) given market splitting occurrence between Denmark and all adjacent bidding areas with the exception of West Denmark (DK1) to Germany (DE); and f) given market splitting occurrence between Denmark and all adjacent bidding areas with the exception of East Denmark (DK2) to Germany (DE). Figure 6.18 shows (from top to bottom and left to right) the behaviour of market splitting probability response as a function of wind power generation in West and East Denmark: a) given no market splitting occurrence between Denmark and all adjacent bidding areas (absence of congestions, therefore it is expected a null probability of market splitting); b) given no market splitting occurrence between Denmark and all adjacent bidding areas with the exception of West Denmark (DK1) to Norway bidding area 2 (NO2); c) given no market splitting occurrence between Denmark and all adjacent bidding areas with the exception of West Denmark (DK1) to Sweden bidding area 3 (SE3); d) given no market splitting occurrence between Denmark and all adjacent bidding areas with the exception of East Denmark (DK2) to Sweden bidding area 4 (SE4); e) given no market splitting occurrence between Denmark and all adjacent bidding areas with the exception of West Denmark (DK1) to Germany (DE); and f) given no market splitting occurrence between Denmark and all adjacent bidding areas with the exception of East Denmark (DK2) to Germany (DE).

The results obtained from the models express that, generally speaking, market splitting probability between both Danish bidding areas is sensitive to the wind power generation share in Denmark, nevertheless with distinct behaviour according to the congestion of interconnections with other bidding areas. The simplistic interpretation that can be done with the obtained logit marginal effects does not suffice. For example, the decreasing probability with increasing wind power in East Denmark can only be related with the situation when Denmark is isolated, with the exception of the interconnection West Denmark (DK1) – Sweden bidding area 3 (SE3) (Figure 6.17 bottom left), and the situation when Denmark is not isolated, with the exception of West Denmark (DK1) – Germany (DE) (Figure 6.18 center right). The former can be associated with wind power from West Denmark (DK1) being able to be exported to Sweden and not to East Denmark (DK2), with the sudden drop of the West Danish electricity price (DK1) caused by the high wind power generation share originating a detour of the electricity flow into Sweden bidding area 3 (SE3), and releasing some cross-border transmission capacity between West and East Denmark. The latter can be associated with increasing wind power in East Denmark (DK2) stopping incoming interconnection electricity flows from West Denmark (DK1), which can not flow into Germany. These findings expand on Ardian et al. (2015), Figueiredo et al. (2015a), Sapio (2015), Woo et al. (2011) and unveil a more complex behaviour of multiple interconnected electricity markets.

In the case that Denmark is isolated from the adjacent electricity markets (Figure 6.17 top left), market splitting probability between West and East Denmark (DK1-DK2) increases when there is an increase of wind power generation share in both West and East Denmark. The shown behaviour can be explained by the asymmetric availability of low marginal cost electricity generated by the extensive existing wind power capacity in West Denmark (DK1), which is exported to East Denmark (DK2) with associated congestion of the Danish interconnection.

The non-existence of market splitting between West Denmark (DK1) and Norway bidding area 2 (NO2) (Figure 6.17 centre left) does not change significantly the market splitting response behaviour from the market configuration when Denmark is isolated (Figure 6.17 top left). This demonstrates that the interconnection between West Denmark (DK1) and Norway bidding area 2 (NO2) plays a limited role in the influence that wind power has on the behaviour of the Danish market splitting, perhaps due to the unnecessary import of electricity by Norway, which already has low cost electricity generation mainly from hydro power.

In the case that Denmark is not isolated from the adjacent electricity markets (Figure 6.18 top left), the market splitting probability between West and East Denmark is null and the wind power generation share does not influence it. This behaviour can be explained by the ability of having all surplus electricity exported through the available cross-border interconnections and also not requiring external electricity infeed. Moreover, assuming Denmark not isolated from adjacent bidding areas with the exception of only one of the interconnections with an adjacent bidding area, the probability response of the Danish splitting is also null. The available surplus of low cost electricity can always be exported through the available interconnections. As described above, with Denmark not isolated from adjacent bidding areas, with the exception of the interconnection West Denmark (DK1) – Germany (DE) (Figure 6.18 centre right), the probability response for the Danish splitting is high, even with low wind power generation, decreasing drastically with high wind power generation share in East Denmark (DK2). Thus, increasing wind power in East Denmark (DK2) may render unnecessary incoming interconnection electricity flows from West Denmark (DK1), which can not flow into Germany (DE).

Table 6.6: Market splitting logit model

Dependent variable: Market Split

Data: 2nd January 2012 to 31st December 2014

Coefficients (binomial model with logit link):

	No het. Correction		Het. Correction	
c	-8.397	***	-11.09	***
Wind share West Denmark	1.503	***	1.794	***
Wind share East Denmark	-3.044	***	-4.582	***
Demand West Denmark	0.001141	***	0.001629	***
Demand East Denmark	0.001268	***	0.002057	***
Demand Norway area 2	0.0002367	*	0.0003545	**
Demand Sweden area 3	-0.0001325	**	-0.000129	*
Demand Sweden area 4	-0.00103	***	-0.00174	***
Demand Germany	0.00002086	***	0.00003408	***
Cross-border flow share West Denmark to Norway area 2	-2.617	***	-3.036	***
Cross-border flow share West Denmark to Sweden area 3	3.704	***	4.844	***
Cross-border flow share East Denmark to Sweden area 4	2.636	***	4.33	***
Cross-border flow share East Denmark to Germany	-1.256	***	-1.142	***
Cross-border flow share West Denmark to Germany	2.467	***	4.209	***
Market splitting West Denmark to Norway area 2	-0.6398	***	-0.7943	***
Market splitting West Denmark to Sweden area 3	-16.85		-52.93	
Market splitting East Denmark to Sweden area 4	22.12		59.12	
Market splitting West Denmark to Germany	0.2171	***	0.282	***
Market splitting East Denmark to Germany	1.821	***	2.302	***

Latent scale model coefficients (with log link):

Wind share West Denmark			-0.33522	***
Wind share East Denmark			0.99027	***
Cross-border flow share West Denmark to Norway area 2			-0.15551	*
Cross-border flow share West Denmark to Sweden area 3			-0.72765	***
Cross-border flow share East Denmark to Sweden area 4			-0.77236	***
Cross-border flow share East Denmark to Germany			-0.02228	
Cross-border flow share West Denmark to Germany			-0.68878	***

*** Significant at 1% level, ** Significant at 5% level, * Significant at 10% level

Table 6.7: Market splitting logit model performance

		No het. Correction		Het. Correction	
McFadden pseudo R-squared:					
		0.6046877 (df=19)		0.6339591 (df=26)	
Studentized Breusch-Pagan test					
data: ms.logit					
$BP = 6837.368$, $df = 18$, $p - value < 2.2e - 16$					
In-sample performance					
Data: 2^{nd} of January 2012 to 31^{st} of December 2014					
Confusion Matrices		Predicted		Predicted	
		0	1	0	1
Observed:	0	19396	703	19570	529
	1	988	5047	1144	4891
Accuracy (CCR)		0.9353		0.9360	
Sensitivity (TPR)		0.8363		0.8104	
Specificity (SPC)		0.9650		0.9737	

Table 6.8: Market splitting non-parametric model performance

Continuous Kernel Type: Second-Order Gaussian					
No. Continuous Explanatory Vars.: 13					
Unordered Categorical Kernel Type: Aitchison and Aitken					
No. Unordered Categorical Explanatory Vars.: 5					
No. Unordered Categorical Dependent Vars.: 1					
In-sample performance					
Data: 2^{nd} of January 2012 to 31^{st} of December 2014					
		”Rule-of-Thumb”		*”Cross-validation”*	
Confusion Matrices		Predicted		Predicted	
		0	1	0	1
Observed:	0	20081	18	20087	12
	1	305	5737	80	5955
Accuracy (CCR)		0.9876		0.9965	
Sensitivity (TPR)		0.9495		0.9867	
Specificity (SPC)		0.9991		0.9994	

Table 6.9: Market splitting non-parametric bandwidth

Dependent variable: Market Split DK1-DK2

Bandwidth Type: Fixed

Conditional density data (26146 observations, 19 variable(s))

(1 dependent variable(s), and 18 explanatory variable(s))

Data: 2nd of January 2012 to 31st of December 2014

Bandwidth Selection Method:	Rule of Thumb	Likelihood cross-validation
	Bandwidth:	Bandwidth:
Market Split DK1-DK2	0	0.0005861131
Wind share DK1	0.205831	0.2665511
Wind share DK2	0.09888924	0.08285425
Demand DK1	288.2946	306.5095
Demand DK2	191.5344	279.4728
Demand NO2	442.999	131.7723
Demand SE3	1331.377	722.8817
Demand SE4	399.4506	207.3693
Demand DE	6027.501	4565.185
Cross-border flow share DK1-NO2	0.1675775	0.1798814
Cross-border flow share DK1-SE3	0.118219	0.08754338
Cross-border flow share DK2-SE4	0.3212651	0.07702665
Cross-border flow share DK1-DE	0.1818036	0.1684009
Cross-border flow share DK2-DE	0.2038545	0.1028271
Market split DK1-NO2	0	7.853852e-08
Market split DK1-SE3	0	4.398261e-07
Market split DK2-SE4	0	0.1336549
Market split DK1-DE	0	4.344162e-10
Market split DK2-DE	0	1.369426e-06

Continuous Kernel Type: Second-Order Gaussian

No. Continuous Explanatory Vars.: 13

Unordered Categorical Kernel Type: Aitchison and Aitken

No. Unordered Categorical Explanatory Vars.: 5

No. Unordered Categorical Dependent Vars.: 1

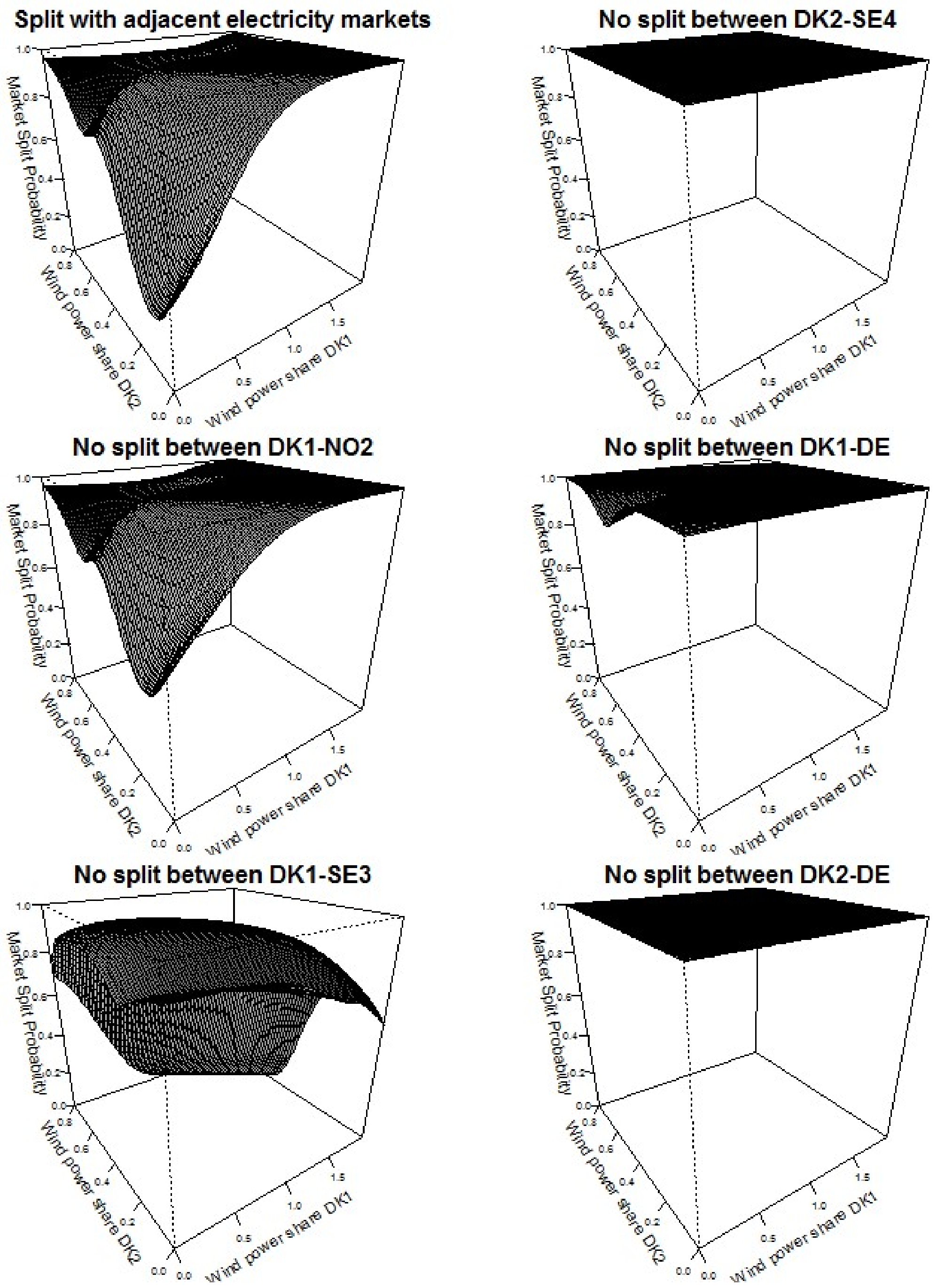
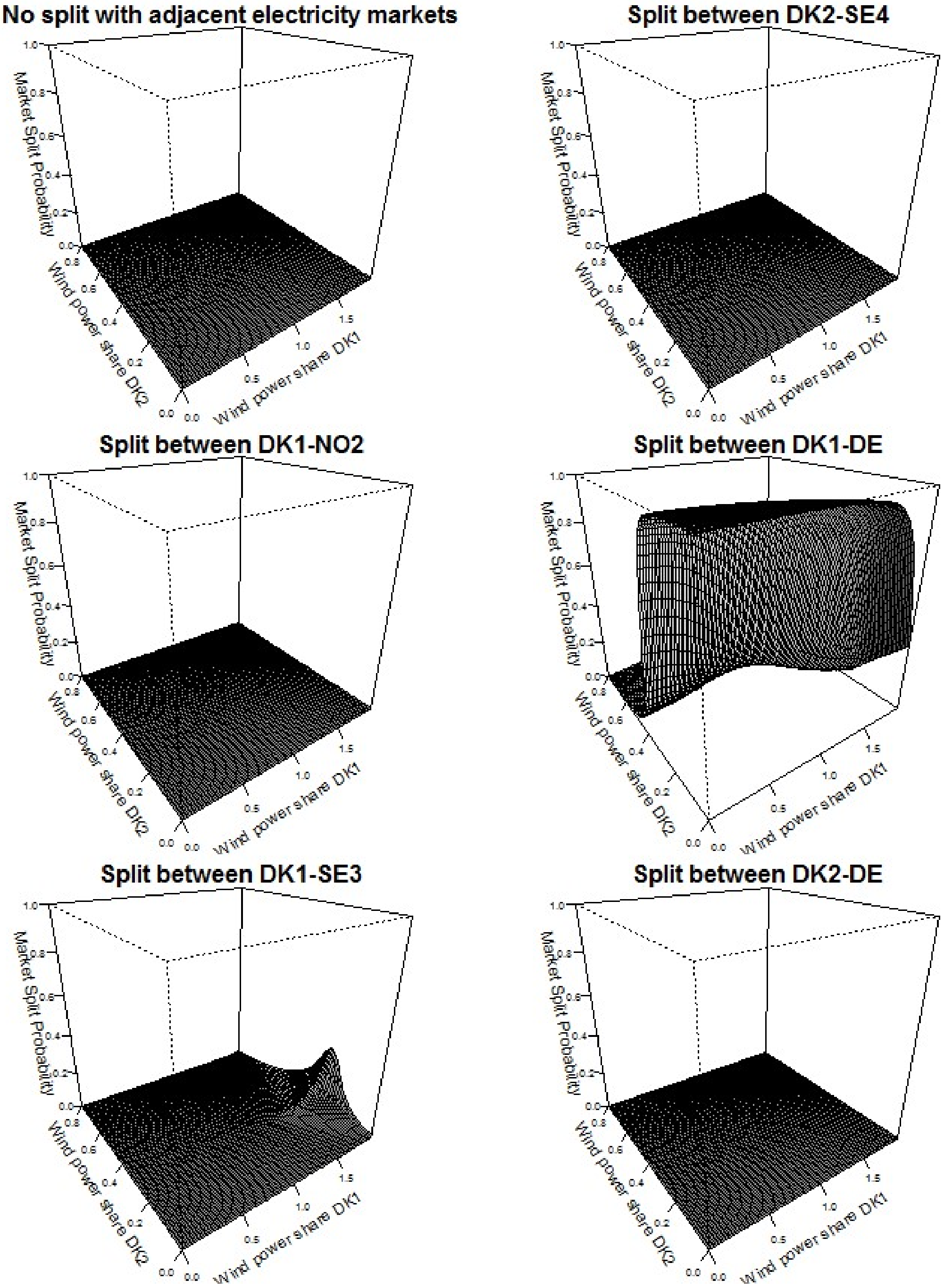


Figure 6.17: Predicted probability response of market splitting between West and East Denmark to wind power generation share


No split with adjacent electricity markets

Split between DK2-SE4

Split between DK1-NO2

Split between DK1-DE

Split between DK1-SE3

Split between DK2-DE

Figure 6.18: Predicted probability response of market splitting between West and East Denmark to wind power generation share

Chapter 7

Renewables Integration in Energy-Only Markets

The introduction of RES-E generation went through a global programme of incentives. This was seen mainly in Europe, but was also observed in Australia and the USA, with wind based generation having the highest growth from 18 GW in 2000 to 238 GW in 2011 of global installed capacity (Agency, 2012). Simultaneously, electricity markets and related liberalization is also observed in some regions of the world. Regional electricity markets are created and then integrated in order to achieve the desirable objectives of efficient competition, security of supply, respect for the environment and reduction of costs. Policy makers aim to regulate the above effectively; however difficulties come to light in face of the dynamics involved.

The high penetration of RES-E, which is now being achieved in some world regions, associated with the integration of electricity markets, poses new problems needing detailed study. As we can see the literature is quite poor in addressing these issues simultaneously. Appropriate econometric modelling can be developed to allow the evaluation of the key determinants of electricity market integration, considering this high penetration of RES-E, including new exogenous variables which can be used to explain renewable generation in function of climate data (rather than climate data to explain demand). The results extracted from the modelling will be essential to provide the required information to generators, TSOs, electricity retailers, consumers and policy makers, in order to guide investment priorities, establish risks, provide guidance in policy design and regulatory framework.

7.1 Introduction

The promotion of Renewable Energy Source for Electricity (henceforth referred to as RES-E) by the European Union (EU) aims to reduce dependency on imported fossil fuels and in Greenhouse Gas (GHG) emissions, resulting in the successful deployment of RES-E generation in Europe (European Union, 2009a). This has been achieved through a set of energy policies, comprising, among others, strong financial instruments, like feed-in tariffs, feed-in premia, fiscal incentives or tax exemptions (Meyer, 2003; de Jager et al., 2011).

The changes in the European electricity systems are profound and on going. New challenges arise from the high level penetration of RES-E, both in the technical sense and in the market design, due to the known RES-E intermittency and non-dispatchability (Benatia et al., 2013).

Simultaneously, electricity markets in Europe are being restructured in face of a number of European policies intending to guarantee the supply of electricity, reduce costs, foster competition, ensure security of supply and protect the environment (European Union, 2009b). Alongside, unbundling and privatisation of the electricity supply industry has been achieved in most of the EU Member States, together with the creation of independent national regulatory agencies, and introducing competition at the different market levels (Silva, 2007). Energy-only markets remunerate electrical energy, based on the traded volume and price. Therefore, increasing RES-E create a depression in spot electricity prices, due to the merit-order effect of zero marginal cost bidding, and diminishes the available load for the remaining non-zero bidding technologies (Traber & Kemfert, 2011). The size of this residual load (Henriot & Glachant, 2013) sets the electricity spot market price and provides the main income to electricity suppliers. Thus, one of the fundamental issue affecting electricity markets is the integration of RES-E and the associated impact on price signals for investment in the electricity system. In parallel, the European Union Emissions Trading Scheme (EU ETS), based on the 'cap-and-trade' principle, emerged to be at the cornerstone of the European Union's policy to combat climate change and its key tool for reducing industrial GHG cost effectively (Freitas & Silva, 2015). Among the several industries covered by the scheme, the electricity sector is the largest one. Launched in 2005, implementation of the EU ETS was set to run in three phases: the first (pilot phase) ranging from 2005 to 2007, the second from 2008 to 2012 and now in its third phase, running from 2013 to 2020. Nevertheless, the collapse of the CO_2 price weakens the link between the carbon market and the electricity market, consequently putting at risk the policy goals associated with carbon pricing (Silva et al., 2016; Silva, Moreno, & Fonseca, 2015; B. Moreno & Silva, 2016), and, thus, leaving increased relevance for the role of RES-E.

In this chapter an analysis of the main concerns in integrating RES-E into the spot electricity markets is provided. The influence of high level RES-E in *"energy-only"* electricity markets is discussed, highlighting its optimization through market integration. In Section 7.2 an overview of the experienced growth in RES-E generation is delivered, followed in Section 7.3 by the description of two main concerns of high RES-E penetration, currently in the mind of many stakeholders in the electricity sector. In Section 7.4, the analysis of the issues, challenges and strategies that European electricity sector faces with the integration of high levels of RES-E is presented and discussed. The RES-E optimisation through regional market integration is then highlighted in Section 7.5, as it is considered one of the most important items in RES-E market integration and consequent optimisation.

7.2 The growth of RES-E

The world demand for energy calls for increasing sustainable energy systems. *"Sustainable"* meaning, in this context and accordingly to Brundtland's report (World Commission on Environment and Development, 1987), energy that does not jeopardise future generations, a reality that can be accomplished through renewable energy sources. In line with this, the development of renewable energy technologies aims to improve energy security, decrease the dependency on fossil fuels and reduce greenhouse gas emissions.

Europe's ambitious target of 20% renewable energy sources in 2020 (or 33%

renewable energy sources for electricity) prompted several member states to propose highly attractive support mechanisms. Denmark, Germany, Portugal, Spain, Italy, Ireland and Belgium, for example, have seen their share of renewable energy sources, mainly in wind and solar, increase drastically in a few years.

Among all renewable energy sources, wind and solar were the ones subject to the strongest research and development, based on clusters established in some regions of Europe. All these efforts required financial instruments like feed-in tariffs, feed-in premia, fiscal incentives, tax exemptions and other (Meyer, 2003; de Jager et al., 2011; Amorim et al., 2013; Klessmann et al., 2008). These financial instruments provided an initial incentive to invest in non-mature RES-E technologies. However, with time, wind and solar power became mature and investment costs decreased to levels where these instruments are obsolete. In fact, the financial burden of RES-E incentive policies is significant and RES-E incentive policies are being reviewed in Europe. Germany and Spain, for instance, took actions reducing RES-E financial support (F. Moreno & Martínez-Val, 2011; Diekmann, Kemfert, & Neuhoff, 2012).

One of the most successful examples of RES-E incentive policies can be found in Denmark, where a partnership between public and private institutions was established (Danish Energy Authority, 2007). By 1972 Denmark did not have significant wind power, which after a strong energy policy shift managed to reach 20% RES-E share in 2008 (Lund, 2010; Lund et al., 2013). Since then, RES-E share in Denmark continued to rise, reaching, in 2015, 41.4% of wind power and 13.8% of essentially biomass (Figure 7.1). This level of RES-E is possible due to the cross-border interconnections that allow electricity trading in the Nord Pool and smooths production profiles with the use of neighbouring pumped storage hydro plants. The Danish 50% target for wind power production can only be achieved with strong interconnected electricity markets (Benatia et al., 2013).

Other European countries also pursued the same route of RES-E deployment. Both Iberian countries had an outstanding increase in wind power, whilst only in Spain there was significant development in solar power. Furthermore, hydropower generation share is historically high in Iberia as seen in Figure 7.2 and Figure 7.3 below. *"Energiewende"* in Germany is the policy shift that prescribed the nuclear phase-out and the replacement of fossil generation with RES-E. Figure 7.4 will illustrate that this policy has been quite successful in deploying wind, solar

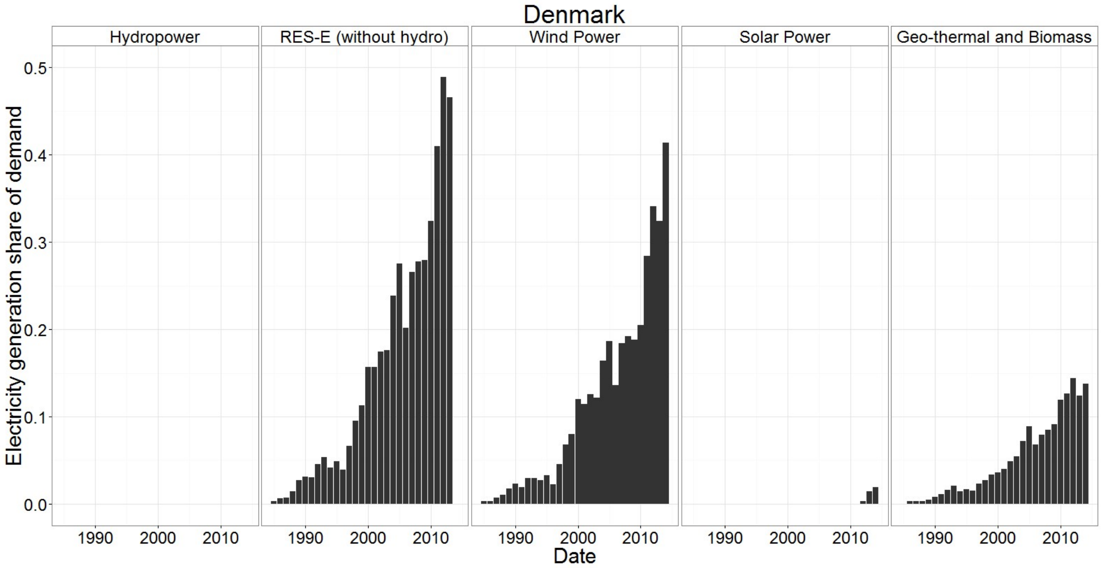


Figure 7.1: Hydropower, RES-E, wind, solar and geo-thermal/biomass electricity generation shares evolution in Denmark (British Petroleum, 2015)

and biomass: Germany has currently the largest wind and solar power in Europe with 40.5 GW and 38.2 GW of installed capacity, respectively (British Petroleum, 2015). Similar RES-E developments are scheduled throughout Europe, depending on country-specific energy policies and financial incentives available. For example, as shown in Figure 7.5, in the UK wind power generation share grew to 9.4% however, without significant solar power development.

The EU 2030 targets a RES-E share increase to 45%, revealing that RES-E still needs to grow, displacing technologies with higher greenhouse gas emissions, and, thus contributing for its desired reduction. Impacts of this high level of RES-E penetration on electricity markets are discussed in the next sections, starting with the effects on the existing energy-only markets and related influence on utility business, followed by some strategies to facilitate the transition to a more sustainable electricity system.

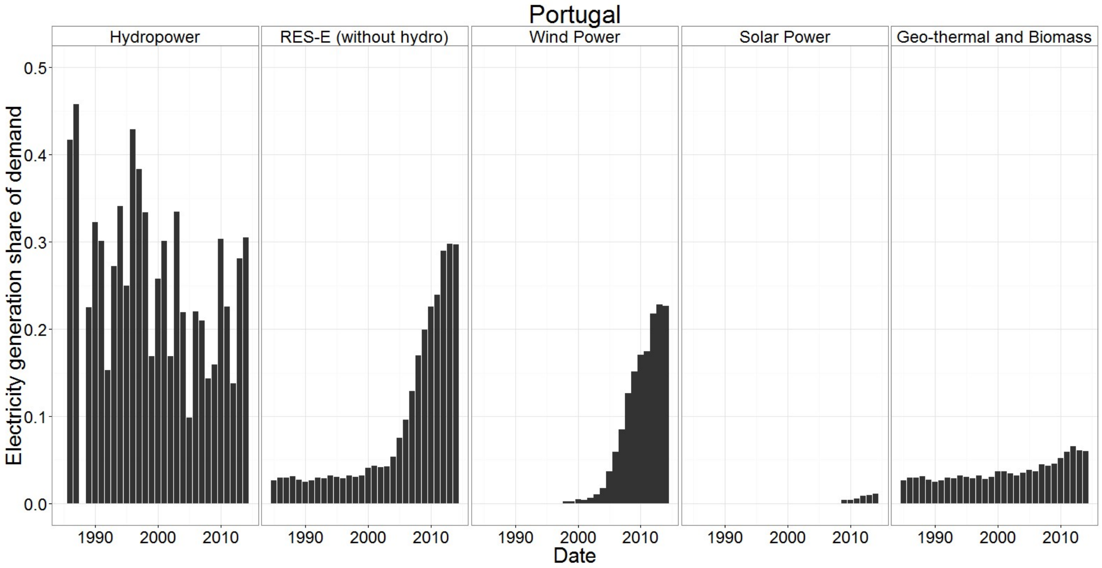


Figure 7.2: Hydropower, RES-E, wind, solar and geo-thermal/biomass electricity generation shares evolution in Portugal (British Petroleum, 2015)

7.3 The *"merit-order effect"* and the *"missing money problem"*

Electricity trading in Europe is currently based on several types of markets: exchanges or spot markets, bilateral and over-the-counter markets, ancillary services markets, and retail markets. Presently, electricity exchanges in Europe trade volumes of electricity at a clearing price, matching supply and demand. All market agents bidding lower than the clearing price trade their bidding volumes at that price. These exchanges have day-ahead sessions for each of the day period (usually for each of the 24 hours) and intraday sessions to provide a first level for the electrical system balance. The electricity market price clearance is done for a specific geographical area, which depends not only on national borders, but also in some cases on internal transmission capacity, reflecting electricity flow constraints and allowing for distinct price signals in each area (e.g. Sweden with four bidding areas). In Europe, spot electricity markets bidding areas are then joined through a market coupling/splitting mechanism where bidding areas with lower prices ex-

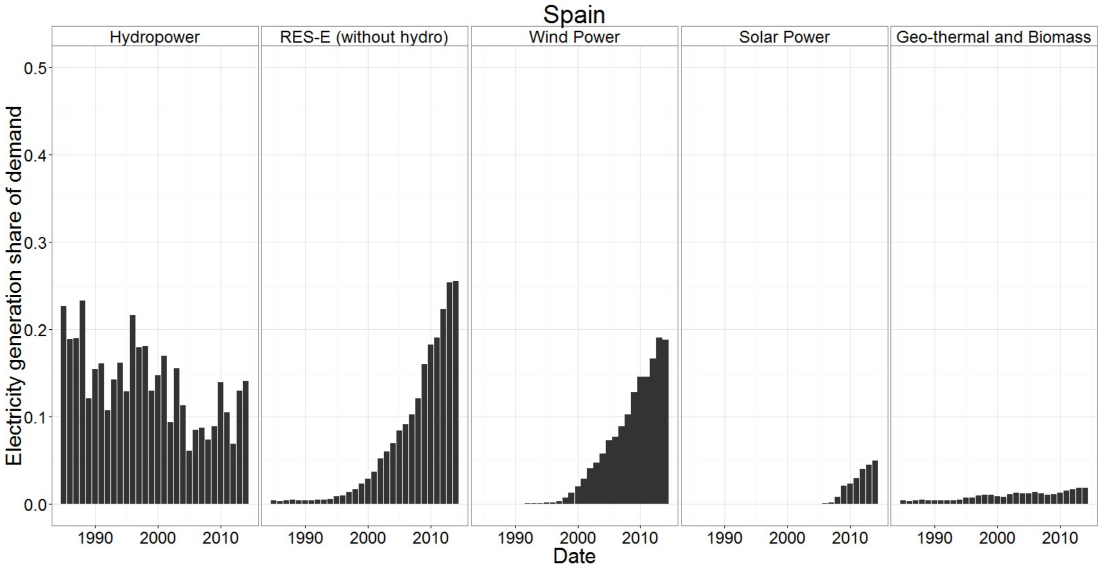


Figure 7.3: Hydropower, RES-E, wind, solar and geo-thermal/biomass electricity generation shares evolution in Spain (British Petroleum, 2015)

port electricity to markets with higher prices through the interconnections. If the interconnection capacity is large enough to accommodate the exported electricity flows (without congestion), then the price is the same in both markets, otherwise market splitting occurs and two regional market prices are cleared (EPEX et al., 2010).

On the supply side, the so-called *"merit-order"* of generators depends on marginal costs of each market agent bidding in the spot electricity market. These marginal costs of market agents depend mainly on the generation technology in their electricity production portfolio and related operational costs (Eydeland & Wolyniec, 2003). Each generating plant operational cost presents several components like fuel, variable consumables, variable maintenance, emissions and transmission costs. Generally, in the bottom of the supply curve one can find market agents bidding electricity produced with low marginal cost technologies, like nuclear or hydro. This is the also the case of renewable generation technologies with high capital costs and small operational costs, which will produce as much electrical energy as the applicable renewable resource available (Klessmann et al., 2008).

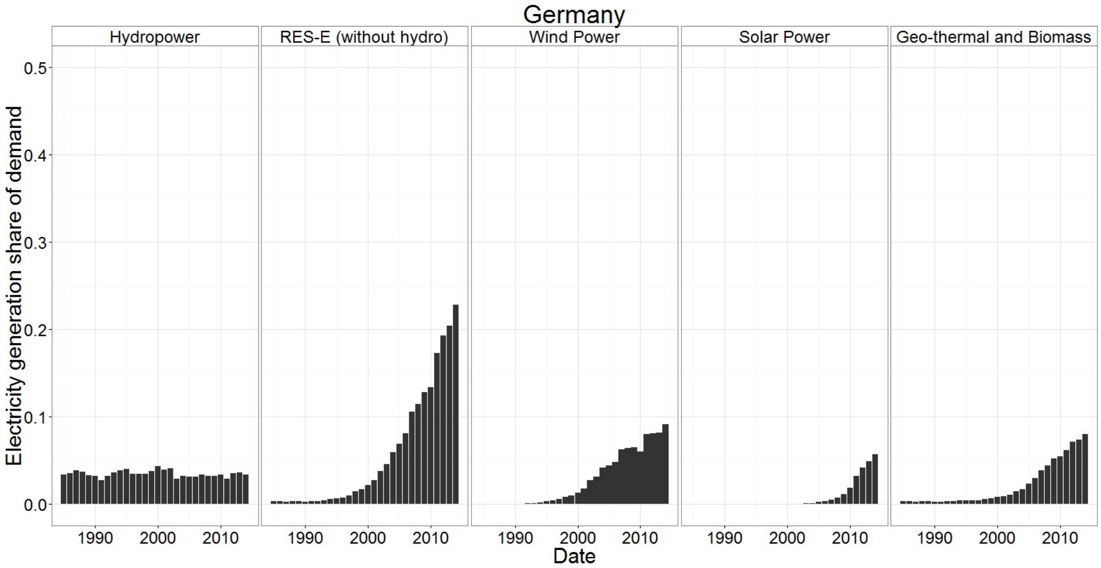


Figure 7.4: Hydropower, RES-E, wind, solar and geo-thermal/biomass electricity generation shares evolution in Germany (British Petroleum, 2015)

Therefore, electricity spot prices are significantly dependent on the available renewable electrical energy in the market, given that renewable power comes first in the merit-order, lowering spot electricity prices and potentially causing zero, or even negative, price periods in the case when demand is fully covered (Schaber et al., 2012; Felder, 2011).

Confirmation of the above is obtained through the analysis of data extracted from the Iberian electricity spot market (OMIE), from the 1st of July 2008 to the 15th of March 2014, where the volume of bids at zero price is found to be positively correlated with the available RES-E power generation, as seen in Figure 7.6. Clearly, the spot electricity price is also correlated with the volume of bids at zero price; however, negatively, with significant amount of market periods with zero spot electricity price (Figure 7.7), confirming the statements of Schaber et al. (2012), Felder (2011) and Ottmar Edenhofer et al. (2013).

Renewable power bids shift the aggregated supply curve to the right and displace high marginal cost generation out of the merit-order. This, as above-mentioned, is the so-called *"merit-order effect"*, causing a reduction in the spot electricity price

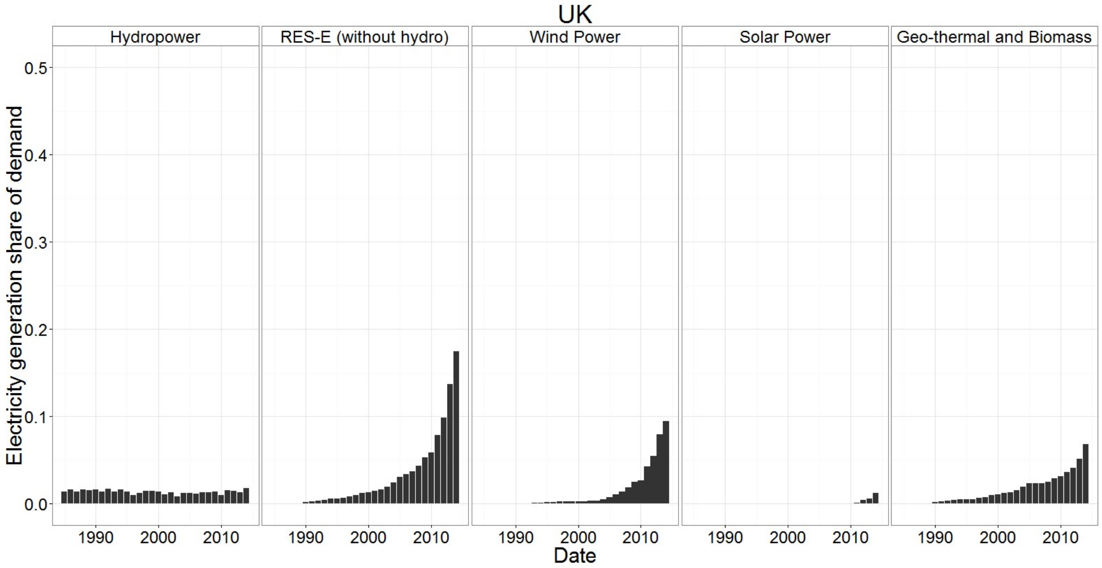


Figure 7.5: Hydropower, RES-E, wind, solar and geo-thermal/biomass electricity generation shares evolution in the UK (British Petroleum, 2015)

and reducing the load available for conventional power, or the so-called *"residual load"* (Sensfuß et al., 2008; Felder, 2011; Henriot & Glachant, 2013). The residual load is positively correlated with the spot electricity price, as observed for the OMIE in Figure 7.9. In Figure 7.8 we can detect that the hour with the highest RES-E generated in Iberia in the data sample extracted from the OMIE was the 28th January 2014, hour 20. Considering the aggregated supply curves with, and without, the RES-E bids, it is possible to compute the merit-order effect, which for this hour alone amounted to 2.1 million Euros.

Felder (2011) actually stated that by providing incentives to *"out-of-market"* technologies, such as most renewables, spot electricity prices would fall to zero. Lower spot electricity prices [1] are often used to justify the incentives provided to RES-E; however, they create a number of challenges related with the investment signals and capital cost recovery. Additionally, wealth fails to shift from producers to consumers (Sensfuß et al., 2008; Würzburg et al., 2013; Gelabert et al., 2011), as in most cases, savings are not obtained by consumers due to the inclusion of

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[1] For example, for each GWh of RES-E predicted in German-Austria, Würzburg et al. (2013) reported 1 Euro/MWh decrease in spot electricity price.

renewable incentives in their electricity bills.

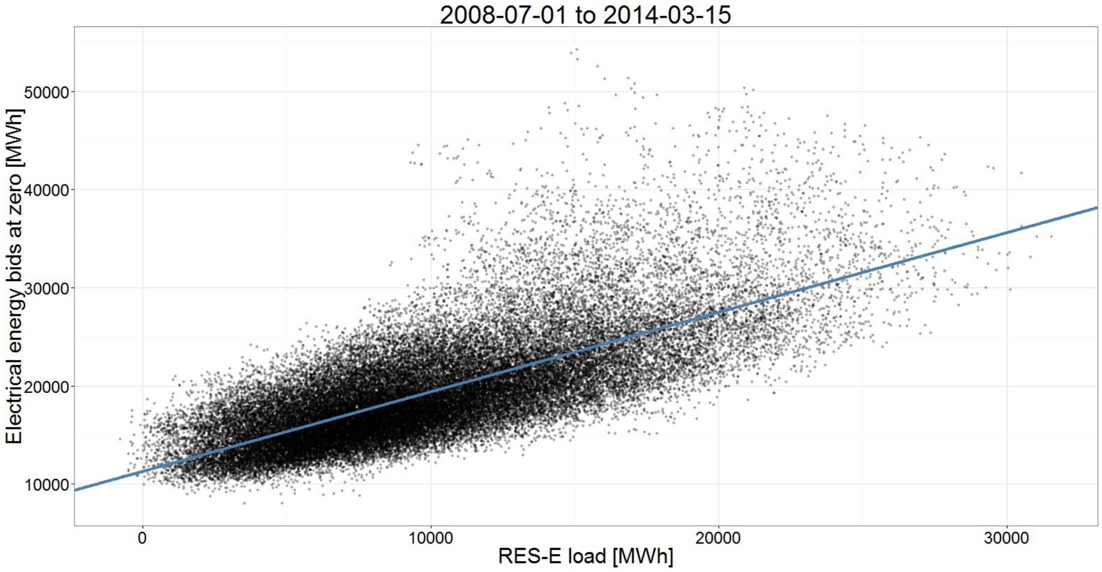

Figure 7.6: OMIE electrical energy bids at zero vs. renewable power generation

Additional concerns and challenges of high generation shares of RES-E are reported both in the technical sense and in the market design. On the technical sense, it is possible to list the following: generation variability and uncertainty, adequate transmission capacity, flexibility and standby of dispatchable generation, electrical system regulation and frequency control, demand-side response, RES-E curtailment, energy storage, adequate transmission grid and cross-border interconnections (Lynch et al., 2012; Mauritzen, 2010; Nicolosi, 2010; Ottmar Edenhofer et al., 2012). Concerning the market design, one can enumerate electricity market integration, cost allocation of transmission grid and cross-border interconnections, intraday and reserve power markets, RES-E financial support schemes and capacity support mechanisms (Benatia et al., 2013; Batlle et al., 2012; Nicolosi, 2010; MIT Energy Initiative, 2011).

Vis-à-vis market design, the reduced residual load and the depressed spot electricity prices, along with the technical challenges and costs of peaking conventional thermal power plants, are currently stressing utilities income. It is reported a revenue reduction of 60% for conventional power plants in regions with high RES-E

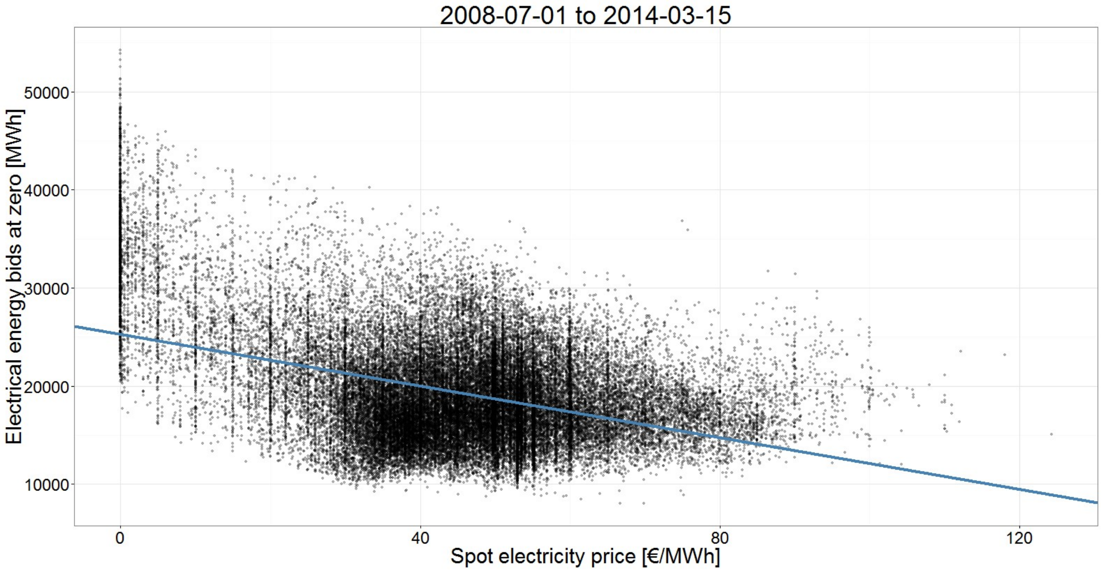

Figure 7.7: OMIE electrical energy bids at zero vs. spot electricity price

penetration, making capital cost recovery problematic (Schaber et al., 2012; Würzburg et al., 2013). Moreover, if in the presence of barriers to exit [2], conventional power producers remain available as market agents, further contributing for system electricity surplus, but thinning costs to a level where plant reliability may pose an issue (Nelson et al., 2015). Higher volatility can be expected with low plant reliability, which under an *"energy-only"* electricity market could provide adequate price signals to stakeholders. Nevertheless, high volatility and price caps conflict with these signals, rendering investment in new plant unattractive in the long run. The *"missing money problem"* of an energy-only electricity market arises when the market fails to provide incentives to sustain adequate generation capacity. Balancing markets and ancillary services, usually run by system operators, if suitable remunerated, might mitigate this issue by providing additional income to generators that are able to deliver these type of services to the grid [3] (Ottmar Edenhofer et al., 2013; Newbery, 2015; Cramton & Stoft, 2006).

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[2] Exit barriers, originating from policy or economic reasons, means retiring plants from the electricity market not mothballing (Nelson, Reid, & McNeill, 2015)

[3] Balancing services can consist of: primary reserve, secondary reserve, automatic generation control, voltage and frequency control and black start.

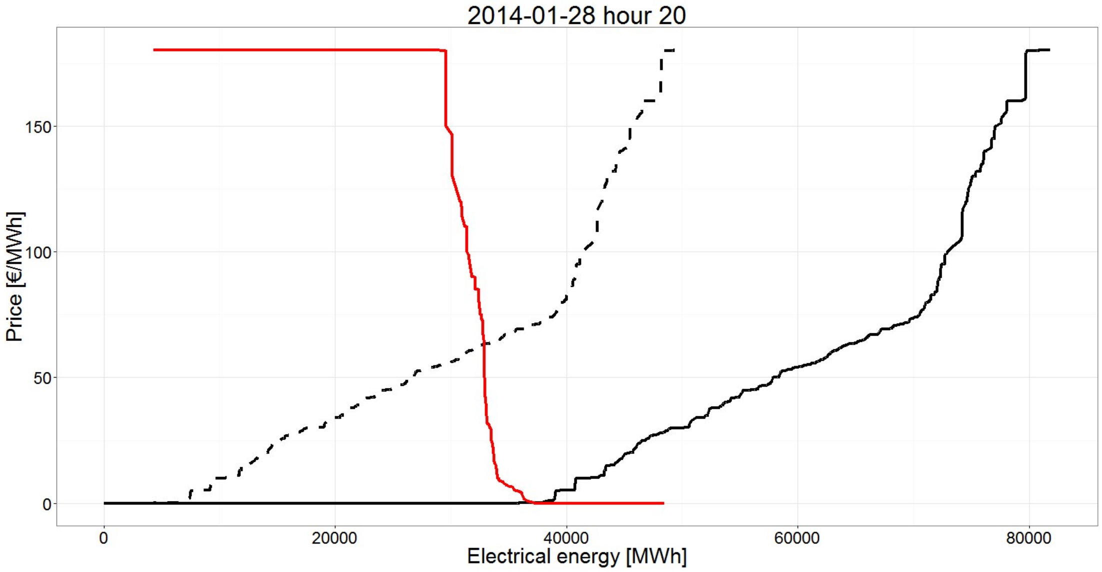

Figure 7.8: OMIE aggregated demand and supply curves (with RES-E bids – solid and without RES-E RES-E bids – dashed)

The *"missing money problem"* not only impacts conventional generation, but also affects RES-E market integration. If RES-E are exposed to market risks without the known financial support, given the depressed short-term marginal pricing from an *"energy-only"* electricity market, capital cost recovery would be problematic. Thus, investment in RES-E can also be at risk depending of future developments on financial incentives and electricity market integration of RES-E. Large amounts of RES-E might only be financially sustainable if incentives are kept and market integration and design is carefully considered. Given the EU targets of RES-E expansion to 45% generation share, further spot electricity price reductions will be seen, aggravating the missing money problem. Ottmar Edenhofer et al. (2013) summarises three possible causes for the *"missing money problem"*: capped spot prices during scarcity events; low spot electricity prices to sustain existing capacity, and investors discouraged by high price volatility and risks. A generation adequacy problem arises, given the absence of new capacity deployment (Cramton & Stoft, 2006). The challenges faced by the integration of high levels of RES-E require the introduction of additional strategies in the European electricity sector.

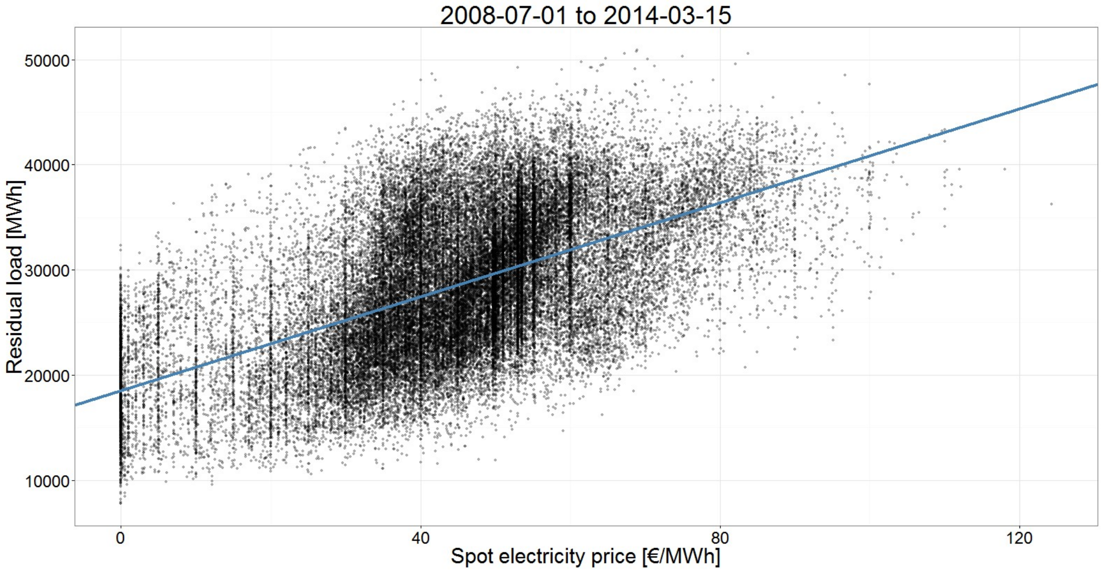

Figure 7.9: OMIE residual electrical energy vs. spot electricity price

These are discussed in the following section.

7.4 Market integration of high level RES-E

Market integration of RES-E is currently a hot topic and it is being addressed by an increasing number of researchers. The large penetration of RES-E in some of the European electricity markets created a set of challenges, both in a technical and a market perspective. As already unveiled in the previous section, the high level RES-E deployment caused market failures and distrust in the energy-only electricity markets implemented throughout the EU (Ottmar Edenhofer et al., 2013). The generation mix is not market driven, creating a non-sustainable financial situation for both utilities and consumers, the former with impaired revenues not being able to recover investments, and the latter having to support high value subsidy schemes for RES-E. The associated costs of the financial support mechanisms to RES-E raise some concerns. With RES-E technologies becoming mature, a gradual reduction of subsidies would be expected, due to the reduction investment costs, increasing competitiveness and the subsidy expiration of older units. Germany and its *"Energiewende"* is in the forefront, aiming to replace nuclear and coal power generation in one go, nevertheless with a demanding cost containment exercise (von Hirschhausen, 2014; Würzburg et al., 2013).

Two key expressions were introduced by Henriot and Glachant (2013) considering the integration of RES-E in the electricity markets and associated risks: *"melting-pot"* and *"salad-bowl"*. The former, exposes RES-E to the same rules as any other conventional generator capable of controlling dispatch (performing as any market agent bidding volumes of electricity at a price for each market period and subject to imbalance charges by non-compliance to deliver scheduled volumes of electrical energy); whilst the latter, could accommodate two different sets of rules, one for dispatchable units and another for non-dispatchable units. It is argued that RES-E particularities are inadequate for spot market bidding, since there is no control on the available renewable resource (therefore, no control on the electricity volumes fed into the system), prediction of future volumes of electricity generation is limited (high risk of exposure to imbalance charges), and, with low marginal cost pricing, investment costs might not be recovered (additionally, there are no incentives to invest in new RES-E and conventional power plant capacity). Moreover, (Batlle et al., 2012) endorse that the market power of incumbents would increase when owning RES-E and conventional power simultaneously, by adopting a strategic behaviour. However, without price signals, RES-E might not have incentives to optimise operational costs and the existing price signals, dependent on the residual load, are not adequate to sustain conventional power (Klessmann et al., 2008).

Flexibility of the electricity system is paramount in obtaining an efficient electricity market incorporating high level of RES-E. A number of proposals are laid down in the literature to disentangle the above-mentioned RES-E market integration issues and introduce the required flexibility, as listed below:

- A premium system allows RES-E compensation above the spot electricity market, limiting market risk and allowing investment cost recovery. RES-E would be subject to the same market rules and risks of the other agents with conventional dispatchable power, including imbalance charges applicable to deviations from programmed electrical energy. Thus, forecasting RES-E generation is of the utmost importance, improving system predictability and minimising imbalance costs (Klessmann et al., 2008). A similar system, spot market price plus a premium with a cap and a floor, is already implemented in Spain as an option to agents with more than 1 MW, subject to all market rules, with the exception of mandatory secondary reserve market participation and the reactive regime remaining the same (Rivier Abbad, 2010). Furthermore, Nicolosi (2010) sates that this premium system for RES-E would limit negative pricing as it is the case in Germany;

- Improve demand-side response, including households and industry load management, and in a foreseeable future electrical vehicles smart charging. This would make the electrical system more flexible to cope with RES-E intermittency (Benatia et al., 2013);

- Development of storage technology in addition to hydro-pumped-storage, and growing storage installed capacity to allow the use of electricity surplus when there is abundant renewable resource, increasing RES-E utilisation (Benatia et al., 2013). The use of Compressed Air Energy Storage (CAES), as a new storage technology, is mentioned by Nicolosi (2010), given that most of the sites in Europe where hydro-pumped-storage is possible are already explored;

- Integration of electricity markets, including balancing and ancillary services markets, allowing generation optimisation and increasing RES-E utilization;

- Rising grid flexibility through the reinforcement of transmission and distribution lines and cross-border interconnections, increasing security of supply and regional imbalances. Additionally, by extending the transmission grid into zones of high availability of renewable resource, the RES-E potential can then be unleashed and used in other high demand zones (Schaber et al., 2012);

- Flexible and efficient generation mix sustained by high price spikes, recognising scarcity, and allowing investment cost recovery of conventional power. This is fundamental to guarantee security of supply in the absence of renewable resource and low RES-E generation;

- Capacity mechanisms might be required to support backup dispatchable generation, allowing for investment cost recovery and providing an incentive for new dispatchable, efficient and low emissions power plants (e.g. combined cycle gas turbines) (Henriot & Glachant, 2013).

Moreover, intermittency is a well-known characteristic of RES-E due to its non-dispatchability and the variable nature of renewable resources. F. Moreno and Martínez-Val (2011), for example, identify events in Spain when wind power decreases 10 GW within 24 hours coincident with increasing demand of 16 GW within 8 hours. Furthermore, the increasing deployment of photovoltaic power is changing the daily load profile and increases production prediction errors. The limited storability of electrical energy creates a difficulty in balancing these events. An electrical system with high shares of RES-E, as described above, needs to be flexible to guarantee a determined reliability level [4] of supply with or without renewable resources available. Therefore, a short notice electricity supply source is required when RES-E suddenly fail. These supply sources consist on the so-called *"backup power"* and have to be adequately compensated, guaranteeing not only their marginal costs but also fixed and investment costs, through adequate scarcity price signals or capacity mechanisms (Henriot & Glachant, 2013). This backup power can at first be provided by stand-by power plants, such as:

- power storage – hydro-pump-storage, CAES;
- dispatchable renewables – hydro-dams, biomass; or
- thermal power – combined cycle gas turbines (CCGT), coal and nuclear.

Given the GHG emission reduction targets and the flexibility required, it is fundamental to prioritise the development of power storage and dispatchable renewables. Hydro-pump-storage is beyond doubt the main storage technology available, which is capable of storing the large amounts of energy required nowadays. Nevertheless, given the limited sites available to further develop this type of power facilities, incentives should be provided for the research and development of

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[4] The reliability of a transmission system can be measured by a number of indicators: Loss of Load Expectation, Loss of Load Events, Loss of Expected Energy, Expected Energy Unserved and Value of Lost Load (Newbery, 2015)

new storage technologies, such as batteries or CAES (Benatia et al., 2013). In the thermal power category, Combined Cycle Gas Turbiness (CCGTs) are by far the most flexible and efficient (F. Moreno & Martínez-Val, 2011). However, due to the low amount of residual load, hence diminished load factors, their financial sustainability needs to be considered, either through adequate scarcity price signals or capacity mechanisms.

With the implementation of capacity mechanisms, power plants capable of dispatch control are remunerated for providing a power capacity guarantee. This capacity guarantee might be subject to regular testing if the plant is not operated for some time. Capacity mechanisms can be applied in various forms, of which, capacity payments, strategic reserves and capacity markets are the most common (Meulman & Méray, 2012). The idea of capacity mechanisms is not undisputed, as it is seen to introduce an additional subsidy and is subject to over-procurement (Hildmann, Ulbig, & Andersson, 2013; Newbery, 2015). In fact, some authors defend that energy-only markets are able to provide adequate price signals if combined with other measures, such as, adequate remuneration of security services, reinforcing transmission grids and cross-border interconnections, and demand response implementation, among others (Newbery, 2015; Henriot & Glachant, 2013).

Backup power can also be provided by a strong and flexible transmission grid and interconnections. This is a more suitable alternative, comparing to a massive supply infrastructure, built merely for backup and hard to be financially justified. Besides, reinforcing transmission grids also allows the optimisation of other existing production infrastructure, including baseload plants, such as nuclear and coal power plants (Schaber et al., 2012). With a strong transmission grid, surplus amounts of RES-E can be transported to other load centres without grid congestions and the need to proceed with curtailments, thus optimising RES-E production. This occurs when there is high availability of renewable resource and the RES-E installed capacity is able to produce more electrical energy than the amount demanded. In the absence of adequate transmission grid capacity, the surplus of electrical energy does not have where to flow and the lines become constrained, leading to selective curtailment of RES-E and inefficiencies. Cross-border interconnections can thenceforth facilitate the trade of these surplus amounts, whilst at the same time provide geographical dispersion and diversification of the generation mix available, improving security of supply and replacing the need for stand-by generation.

Flexibility of the electricity system can similarly be attained by adequate reactions on the demand side. Demand response or demand-side management is the concept involving consumers to respond to short-term price signals and adjust demand accordingly. Consumers would be able to decrease demand, if adequate incentives are provided, by transferring some loads to lower price periods of the day, including in the future the well-known electric vehicle charging (Benatia et al., 2013). These price signals would be part of smart grid information, to which each consumer would have access through the installed smart-meter. Rising demand elasticity would mitigate the missing money problem and help in balancing supply and demand (Newbery, 2015).

No unique answer can be found to the challenge of RES-E market integration, rather a mix of well-adjusted actions should be taken, from backup power with storage and thermal, to reinforced transmission grid and demand response - all can play a part in the future electricity system, desired to be reliable and sustainable.

7.5 RES-E optimisation through market integration

Market integration in wholesale electricity trading has been intensively pursued by the European policy pursuing the vision of a single energy market since the 1990s. Policy-makers have been encouraged by the pursuit of economic efficiency and greater competition, to reinforce interconnectors and harmonise trading rules, given the emergence of substantial amounts intermittent renewable generation.

High level of RES-E generation can create transmission grid congestion, thus reinforcing the transmission grid and cross-border interconnections is paramount in RES-E market integration and in regional electricity market integration. As stated in the previous section, this is one of the fundamental actions to be taken to achieve an efficient electricity market.

Cross-border interconnections present numerous advantages, such as production optimisation, increasing opportunities for operation with renewable energies, promotion of competition and improve supply security by providing backup supply. Yet, the existing limited capacity has to be managed efficiently, allowing for cross-border trading. The cross-border interconnection management made through implicit auctions, the market splitting/coupling mechanisms, allows the coordination of different price areas, increasing overall welfare in the electricity markets (Jacottet, 2012). Weber et al. (2010) clarifies the difference between market splitting and market coupling: while a single power exchange operates several electricity bidding areas through market splitting, under market coupling multiple power exchanges co-operate to manage different electricity bidding areas.

Extensive research on modelling electricity market integration can be found in the literature, expressed both in terms of price convergence and the dynamics of shock transmissions. Price convergence has been modelled by estimating the probability of market splitting between electricity bidding areas. In Figueiredo et al. (2015b), Figueiredo et al. (2015a) and Figueiredo, Silva, and Cerqueira (2016) non-parametric models were used to estimate market splitting probabilities unveiling its behaviour and determinants associated with RES-E. It was shown that different dimensions of electrical systems play a role in the behaviour of the electricity market splitting. For example, as shown in Figure 7.10, in Portugal, when we are in the presence of simultaneous high generation of wind and hydropower, market-splitting probability in Iberia increases. Low marginal cost generation is demonstrated to affect market splitting, therefore, cross-border congestion. This is true even considering the high level of cross-border interconnections between Iberian countries [5]. Furthermore, in Denmark with multi-interconnected bidding areas under the Nord Pool REM, it is once more shown that wind power generation has a significant influence on market splitting behaviour, however, dependent on the interconnections congestion configuration with adjacent bidding areas. With the existing large RES-E installed capacity, Denmark can only have a stable and reliable electricity system by having strong cross-border interconnections providing, not only an electricity export infrastructure, but also increased security of supply.

Coordination between the development of RES-E and reinforcements of transmission grid, including cross-border interconnections, should exist in the European

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[5] The current cross-border interconnection capacity is 3000 MW representing 32% of the smallest bidding area peak demand.

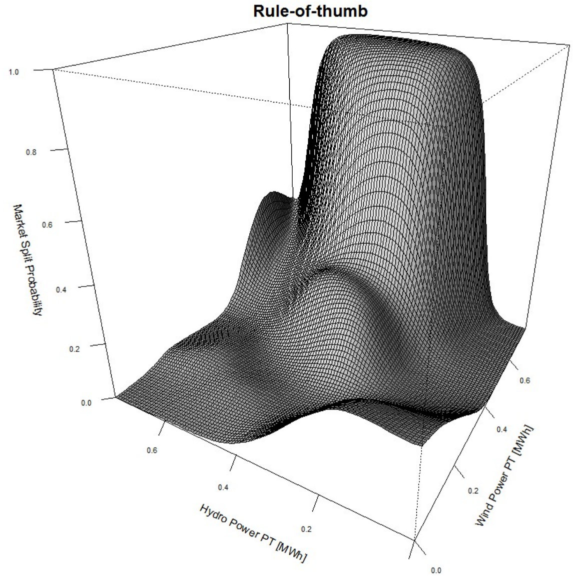

Figure 7.10: Predicted probability response to wind and hydro power generation shares in Portugal

energy policy. This would allow price convergence between bidding areas to be within reasonable levels, fostering market integration. This in turn provides the required RES-E integration and the appropriate security of supply.

Chapter 8

Conclusion

A future common competitive electricity market is aimed by European policy, giving guidance to Member-State policy and statutes. The Electricity Regional Initiative was later on launched along this long process to attain the common electricity market. Simultaneously, the promotion of electricity generation by renewable energy sources was similarly an objective in Europe, reducing the dependency on imported fossil fuels and allowing GHG emissions mitigation. Resulting from strong financial support mechanisms, a large deployment of RES-E generation in Europe has been successfully achieved.

The introduction of RES-E generation went through a global programme of incentives. This was seen mainly in Europe, but was also observed in Australia and the USA, with wind based generation having the highest growth from 48 GW in 2004 to 433 GW in 2015 of global installed capacity (REN21, 2015, 2016). Simultaneously, electricity markets and related liberalization is also observed in some regions of the world. Regional electricity markets are created and then integrated in order to achieve the desirable objectives of efficient competition, security of supply, respect for the environment and reduction of costs. Policy makers aim to regulate the above effectively; however difficulties come to light in face of the dynamics involved.

Electricity market integration is one the fundamental requirements for the introduction of RES-E into the electricity system, maintaining adequate levels of security of supply, whilst providing operational optimisation of generating infrastructure. Electricity markets integration benefits optimisation of RES-E generation and foster cross-border competition, benefiting end consumers.

The high penetration of RES-E, which is now being achieved in some world regions, associated with the integration of electricity markets, poses new problems needing detailed study. As seen, the literature is quite poor in addressing these issues simultaneously. Appropriate econometric modelling was inhere developed to allow the evaluation of the key determinants of electricity market integration and spot electricity price convergence, considering large-scale deployment of RES-E, by including exogenous variables which represent RES-E generation and climate data. The results extracted from the modelling executed provide information, which can be used by generators, TSOs, electricity retailers, consumers and policy makers, to guide investment priorities, establish risks, provide guidance in policy design and regulatory framework.

The current level of integration between electricity spot markets, under the influence of high penetration of RES-E was established for both the SWE and CWE REMs. Additionally, for the SWE REM this research obtained insights about the influence of weather conditions on the spot electricity market prices and for the CWE REM about the effects of renewable energy output variations across several integrated power markets. With the existing levels of RES-E, these weather conditions do not only influence electricity demand, but also influence generation, particularly wind power. Moreover, given that the EU electricity markets have been changing, it was interesting to determine the impact of the introduction of market coupling between the TLC and the German electricity market, finally completing the CWE REM.

Incentive policies for RES-E deployment have been quite successful. Spot electricity prices in the SWE REMs decrease when there is RES-E generation available, which is dependent on weather conditions. This of course does not mean decreasing electricity prices to the end consumer, as other studies demonstrate, given that financing these incentives might be transferred to consumer tariffs (Silva & Cerqueira, 2017). With the financial crisis, incentives for RES-E deployment were questioned, which might impact the deployment growth of RES-E generation capacity. Nevertheless, the maturity reached by some of the RES-E technologies (mainly wind and solar based generation) and the reducing investment costs might overcome these difficulties.

A good level of market integration was found in Iberia, part of SWE REM, and in CWE electricity markets. The MIBEL joint Iberian market was found to be fully integrated, in spite of the outstanding RES-E generation levels observed in both countries, achieving by 2014 60% in Portugal and 40% in Spain (British Petroleum, 2015). Little or no evidence of integration was found between the MIBEL and PWNX, as demonstrated by Granger-causality and IRF, however, it is to note the limited interconnection capacity, in relation to the peak demand of both electricity markets, and the absence of market coupling mechanism (Figueiredo & Silva, 2015, 2012).

Climate related exogenous variables were used in the VAR models produced for SWE REM. Relevant improvement in model specification is found by incorporating as exogenous variable the average wind speed, having significant negative contributions to spot electricity prices. Ambient temperature in the form of HDD and CDD, improves model specification only in some cases (Figueiredo & Silva, 2015). The average wind speed both in Portugal and Spain show a significant negative influence for the Portuguese and Spanish base, off-peak and peak log-daily spot electricity prices. Regarding the French average wind speed, there is a significant negative contribution in all PWNX base, off-peak and peak log-daily spot electricity prices. The lack of sufficient interconnection capacity between France and Spain is likely to explain the non-significance of Spanish average wind speed on the French electricity market price. Findings related with the impact of wind generation on interconnected markets are aligned with conclusions reached by several studies, albeit relying on a novel data and modelling approach. Once more, the significant negative contribution of wind speed on electricity spot market price does not mean that the consumer electricity price also decreases. As a matter of fact, Silva and Cerqueira (2017) established a significant positive impact of 1,8% increase in consumer price for each 1% of RES-E. The incentives for the deployment of RES-E should be reviewed as it has been established to be in some cases a high burden on consumer electricity prices (Amorim et al., 2010; Sáenz de Miera et al., 2008; Meyer, 2003), distorting the desired effect of the electricity spot market price reduction.

Market splitting behaviour was modelled through logit and, for the first time to our knowledge, with non-parametric models, estimating the probabilities of its occurrence. Our models expose the fact that different sizes of electrical systems play a role in the behaviour of electricity market splitting. Fundamentally, it is shown that in the SWE REM, when wind power generation is higher, or more generally, with higher low marginal cost electricity, such as nuclear power generation, market splitting probability increases, which is consistent with Salic and Rebours (2011) and Woo et al. (2011). Results also confirm that the available cross-border interconnection capacity has an influence on market splitting. To maintain the same market splitting probability level with increasing available low marginal cost electricity in the system, the requirements for interconnection capacity have to increase above the current EU recommended level of 10% of the peak demand of the smaller interconnected market. Actually Iberia has already surpassed this value reaching 25.6% in the data used and has currently 3150 MW, which represents 33.6% of the peak demand observed in the period considered. The large RES-E generation capacity deployment observed in Iberia is not seen to cause major issues on the integration level of the electricity markets. Nevertheless, it was demonstrated that with simultaneous increase of wind and hydro power generation shares, to a point where most of the demand can be supplied by these renewable sources, market splitting probability increases dramatically, causing electricity price divergence between both Iberian electricity markets. This fact can occur not only due to the congestion of interconnections with low marginal cost electricity, but also due to some degree of caution in the ATC calculation made by the TSOs, for grid security reasons (Figueiredo et al., 2015b). It was confirmed in Figueiredo et al. (2015a) that the ATC of the cross-border interconnections has an influence on market splitting, thus in electricity price convergence. Moreover, an adequate cross-border interconnection capacity will avoid the internal development of dispatchable reserve capacity for balancing and grid security purposes. In summary, the large RES-E generation capacity deployment observed in Iberia was demonstrated to have a major influence on electricity price divergence between spot electricity markets (Figueiredo et al., 2015b, 2015a).

In May 2014, market coupling between MIBEL and PWNX was implemented within the PCR initiative, however, the existing limited interconnection creates a physical barrier to electricity cross-border flows between Iberia and France. The interconnection capacity between France and Spain was increased through a new interconnector, which was declared project of European interest and financed by the EU within the framework of the EEPR - European Energy Program for Recovery. The new cross-border interconnection INELFE (2015) started commissioning in February 2015 and is in commercial operation since the 5th October 2015 (Red Eléctrica de España, 2015). In Figueiredo and Silva (2016a) it was established that some hour periods of equal price between Mibel and PWNX could already be found. Nevertheless, improvements in cross-border interconnection capacities are still required between Spain and France, as the market splitting level is high. The total interconnection capacity achieved between France and Spain is still far from the desired 10% target of the installed capacity. Having the current Internal Energy Market Directive aim as guideline, market coupling and interconnection capacity expansion should be continuously sought between the French and Spanish electricity markets in order to achieve a full functioning South West Electricity regional market.

Incentive policies for RES-E deployment have been successful, in particular in Germany with the *"Energiewende"* where the level of wind and solar power installed capacity reached together an outstanding 78.7 GW (British Petroleum, 2015). Spot electricity price in the CWE REMs tends to decrease mainly at off-peak periods, when RES-E generation available has a higher influence on power plant merit order. Yet again, this does not mean the decrease of electricity price to the end consumer as financing costs for the incentives are transferred to consumer tariffs and are not completely offset by the spot electricity price decrease. This is actually a big political debate within the German government coalition. Arguments about industrial competitiveness are exchanged, as the electricity costs and RES-E incentives burden can cause, in extreme, companies to leave Germany and Europe in general. Bearing in mind the costs derived from the RES-E incentives, further capacity deployment based on these technologies needs to be carefully assessed. Another issue to be assessed is the potential increase of GHG emissions due to the combination of high natural gas prices and low prices for coal and carbon emissions. The natural gas market contribution for the single energy European market and GHG emissions reduction requires detailed study.

The level of integration on the CWE regional electricity markets was evaluated in order to assess the accomplishment degree of the European Internal market development, as aimed by the European Directives. Previous studies addressed this subject with the evaluation of some of these markets, reporting in general existing market integration between the CWE regional electricity markets (Armstrong & Galli, 2005; Boisseleau, 2004; Bosco et al., 2010; Bower, 2002; Bunn & Gianfreda, 2010; Pellini, 2012b; Zachmann, 2008). Recent data was inhere incorporated with a new methodological approach for the evaluation of market coupling mechanism introduction between electricity markets, and thus contributing to robust conclusions. VAR models were specified for a data set which includes the start of the market coupling between the TLC and EEX. This was considered as a break point and two models were specified, before and after the assumed break point. Moreover, the influence of weather conditions on market integration was tested for CWE REM (wind speed, ambient temperature and cloud cover). Relevant improvement in model specification is found by incorporating in the specified models the exogenous variable related with the average wind speed, generally with a negative significant impact, higher in off-peak periods. The ambient temperature related variable expressing degree-days improves the specification for the base, peak and off-peak spot electricity price models, however without significance in the EEX equations. Surprisingly, cloud cover does not contribute to improve model specification, as one could expect with the large solar generation capacity installed in Germany (Figueiredo & Silva, 2013a).

In spite of the RES-E generation levels observed in the CWE countries in 2014, the highest reaching 26% in Germany, followed by Belgium with 19%, France with 16% and the Netherlands with 11% (British Petroleum, 2015), the CWE electricity spot markets were found to be integrated before and after the introduction of market coupling between the TLC and EEX. The TLC was well established leading to the conclusion that the price coupling mechanism contributes to the integration of spot electricity markets. Nonetheless, it was found that the introduction of the market coupling mechanism with EEX in November 2010 created an apparent smoothing of the responses to innovations, as observed in the IRF analysis, as if shocks were somehow absorbed by the large German electricity spot market (Figueiredo & Silva, 2013c). The new dynamics introduced by the market coupling mechanism with the largest central European electricity market, together with the small NTC between markets, in particular between Germany and France when compared with the installed electricity generation capacities, are likely to explain some of the results found. The high nuclear generation capacity existing in France, which is hard to displace due to its low cost and operational characteristics, can likewise explain the peak response in PWNX to innovations of the other CWE markets, agreeing with Boisseleau (2004) and Bunn and Gianfreda (2010). It is to note that the apparent smoothing of the responses to innovations observed after the introduction of the market coupling mechanism with EEX, reveals that the so called *"congestion revenue"* under implicit auctioning might decrease to a point where interconnection cost allocation needs reviewing. The absorption of price shocks seen after the complete CWE market coupling may reduce market splitting and therefore generation congestion revenues, creating additional difficulties in the interconnection financing and cost allocation. The transmission network expansion requirements and associated financing are critical, therefore cost allocation mechanisms are paramount. Together with transmission network expansion requirements, this can lead to the need to design and implement new policies addressing different cost allocation mechanisms.

In order to achieve a full functioning CWE REM, results found support that interconnection capacity expansion should be prioritised between Belgium and Germany, due to the inexistence of interconnections (line to be commissioned in 2017 and line in project for 2020 (ENTSO-E, 2012)), and between France and Germany, due to their large installed electricity generation capacities (line in project for 2020 (ENTSO-E, 2012)).

The observation that the effects of renewable energy output variations across several integrated power markets are likely to be complicated by price arbitrage and weather dynamics, motivated further research to the CWE REM behaviour. Wind in particular has supply side effects when associated with substantial generating facilities, but also demand side influences when associated with cold weather. This means that assessing the specific effects of weather conditions on various markets, e.g. for operational prediction or hedging, may require subtle analysis. Through detailed modelling of the CWE coupled market comprising Belgium, France, Germany and the Netherlands, it was found that despite efficient price arbitrage, it is not the case that daily wind power output shocks diffuse uniformly across all markets, or that the largest generator of wind energy creates the most significant spillovers or that high wind conditions necessarily lead to lower prices. Furthermore, whereas simple scatter diagrams appear to suggest very little relationship between cross-border energy flows and wind production in these countries (Figure 5.3), impulse response analysis from a large vector autoregression with endogenous and exogenous representations of price and weather variables indicated the potential for mutual spillovers across all countries. However, specific analyses of the coefficients of selected variables in the VAR revealed idiosyncratic characteristics. Whereas Germany was by far the largest energy market and the largest generator of wind energy, it also tended to import substantially from France (Figure 5.2) and had a flat supply function dominated in its mid-range by coal facilities (Figure 5.1). Thus, whilst neighbouring wind generation may be highly correlated (Roques et al. (2010), reported a correlation of 0.4 for France and Germany), on average, Germany did not appear to spillover wind-induced price effects to its neighbours. This more extensive modelling thereby reverses some of the conventional indications suggested elsewhere, e.g. Phan and Roques (2015). Alternatively France, being a low cost exporter, even with much less wind generation, had, on average, significant spillover effects in lowering prices for all neighbours when its wind output increased. Furthermore, France has substantially higher price response to demand, because of widespread electrical heating, and when wind conditions combine with cold weather to produce a wind chill effect, higher prices emerge and spillover to all neighbours. We also found that a smaller importing country such a Belgium created little spillover, but a similar smaller country like the Netherlands, being a transit between imports from Germany and exports to Belgium, proved to have a very sensitive effect on price spillovers if its wind production changed. Finally, the dynamics of the weather induced effects on demand and, as a consequence, on prices were longer lasting, as weather conditions moved across the countries, than the supply side effects. Overall, apart from market harmonisation and interconnector capacities, understanding the arbitrage dynamics of prices as more renewable energies enter the production mix requires rather specific unravelling of the supply-side and demand-side specificities of the countries involved. The relative slopes of the supply functions around demand levels are important, as well as the technology mix and possible market power effects determining the price spreads. The nature and regional dynamics of demand also requires careful analysis, as demand-side effects may significantly counteract the supply side. As a basis for analysis however, vector autoregression is useful and could well support weather risk models, although it appears to require large scale specification. An intraday hourly panel representation was not undertook, as model specification was already large in terms of lags, prices and weather variables, but it is likely that for operational precision, intraday granularity will be required in practice.

Two of the benefits of spot electricity markets integration are the optimization of RES-E generation and security of supply. In this context, the impact of increasing wind power generation on electricity spot market splitting in a multi-interconnected region was also studied. Being Denmark one of the best case studies due to the high level deployment of wind power and belonging to the oldest European integrated electricity market, the behaviour of market splitting between West and East Danish bidding areas was modelled through logit and non-parametric models, estimating the probabilities of its occurrence. It was shown that wind power generation has significant influence on market splitting behaviour. This behaviour, however, differs according to the congestion configuration of interconnections with adjacent bidding areas. Considering the existing level of market splitting and the modelled behaviour we conclude that for the existing wind power generation, and furthermore, if there are intentions to further expand it, the existing interconnection between West and East Denmark is adequate, as the EU recommendation of 10% of the peak demand of the smaller interconnected market (Amorim et al., 2014) is clearly surpassed, reaching a value of 16% in the considered data. Moreover, the occurrence of market splitting between West Denmark (DK1) and Germany (DE) should be avoided given the high probability of Danish market splitting found related with low share of wind power in West Denmark (DK1) (Figure 6.18 centre right). Therefore this cross-border interconnection should be reinforced in spite of the already 38,3% of the peak demand of the smaller interconnected market, which in this case is West Denmark's (DK1). Additionally, given that the cross-border interconnection between West Denmark (DK1) and Norway bidding area 2 (NO2) does not have a meaningful impact on the probability response profile of the Danish market splitting, it is believed to have enough capacity and does not require reinforcing.

As mentioned in the previous Chapters, the extensive deployment of RES-E in some European electricity markets creates demanding challenges to the electricity sector. RES-E development aims to improve energy security, decrease the dependency on fossil fuels and reduce greenhouse gas emissions. With targets set for 2030 by the EU, establishing a RES-E consumption share increase to 45%, RES-E is required to further grow in the electricity system. Given the *"merit order effect"*, where the low marginal cost RES-E displaces the aggregated supply bid curve to the right, the available residual load decreases dramatically for technologies with higher marginal costs. Additionally, spot electricity prices also decrease and the market fails to provide correct signals to sustain adequate generation capacity, the *"missing money problem"*. Moreover, RES-E integration into the electricity market requires market adjustments in order to overcome the identified failures. The *"melting-pot"* and *"salad-bowl"* express the two alternative routes for policy makers, however, one thing we can ascertain, flexibility of the electricity system is fundamental to obtain an efficient electricity market. This flexibility can be obtained through a number of strategies, of which, regional market integration and demand response seem to be unanimous throughout the literature.

Policy-makers pursue regional market integration because it is believed that it will lead to economic efficiency and greater competition, benefiting from cross-border interconnections and trade. It provides the desired electricity system flexibility for RES-E market integration and improves security of supply. Nevertheless, congestion of cross-border interconnections, thus electricity price divergence between bidding areas, is demonstrated to occur with high low marginal cost generation, consequently, reinforcing the transmission grid and cross-border interconnections is vital. Currently, as part of the climate and energy policy framework for the period 2020-2030, the cross-border interconnection target between Member States is set to be 15%. However, regulation should also be adjusted and coordinated to allow different mechanisms for optimisation, deployment of effective energy storage facilities, wind power production curtailment and transmission system expansion. Furthermore, in order to attain RES-E optimisation and the desired further growth (*"binding target"* of 27% of RES-E in EU) without endangering market integration, the EU should consider within this framework, the increase of cross-border interconnection capacity recommendation above the currently discussed target of

15%, depending on the existing and forecast RES-E installed capacities in the area, in order to optimise infrastructures and contribute to electricity price convergence. Moreover, an adequate cross-border interconnection capacity will avoid the internal development of dispatchable reserve capacity for balancing and grid security purposes.

Policies governing the coordination of both interconnection development and renewable incentives should be designed. ACER through its coordination role should have a more pro-active stance considering RES-E expansion, namely by adapting the Framework Guidelines on Electricity Grid Connection (ACER, 2014b). Policy makers and regulators aim to regulate the electricity sector successfully; however difficulties come to light in face of the dynamics involved. Moreover, utilities are facing new challenges in designing investment forecasts and require additional decision support tools. The results extracted from the modelling developed will be essential to provide information to generators, transmission system operators, electricity retailers, consumers and policy makers, in order to guide investment priorities, establish risks, provide guidance in policy design and regulatory framework. Albeit recognising some factors that influence the deployment of renewables, there is no defined formula to facilitate the integration of high levels of RES-E into the electricity system. Policy makers and stakeholders, in general, have to consider all available strategies and tailor the best possible path, bearing in mind that interactions between regions exist and that the objective is common: to obtain a competitive, reliable and sustainable electricity system.

In sum, there is a remarkable growth in demand for analytical tools at the European level in recent years. Policy emphasis in Europe, as represented by the Europe 2020 strategy, has shifted to encourage the development of green and sustainable measures, recognising that the environment and its diminishing resources represent a genuine threat to long-term prosperity. From both a policy and business perspective, the drive to make Europe the world leader in this area embodies both challenges and significant opportunities.

A paradigm shift is faced in the electricity system. The increasing penetration of RES-E and the pressure on GHG emissions are in everyone minds. Stakeholders promote the discussion of this shift and try to prepare for the change that is already happening. The need to research the different impacts of RES-E on electricity markets, a vast field of study, was never so important. The research described throughout these Chapters is not closed and definitely not complete. Further research is required and it is suggested that multiple simultaneous cross-border interconnections are analysed, namely through novel non-parametric model application. These models have a high computational burden, however, with the current knowledge of parallel processing and computer clusters, the task might become feasible. Additionally, statistical inference might also be possible, for example by performing *"bootstrapping"*. Complex dynamics of integrated electricity markets justify a deeper analysis to clarify some of the observed behaviours.

One of the difficulties felt during these studies was, as always, the availability of data. In spite of the most welcomed help from different institutions, some of the data is simply not stored. For example, for solar generation, as most of the installed capacity is decentralised and connected to the low voltage grid, data is scarce. Maybe with the development of smart metering this type of data becomes available. One can hope that information will become more and more available, not only to academia, but also to consumers and stakeholders in general, supporting better decision making.

References

ACER. (2014a). ACER recommends the adoption of the Network Code on Forward Capacity Allocation. Retrieved June 3, 2014, from http://www.acer.europa.eu/Media/News/Pages/ACER-recommends-the-adoption-of-the-Network-Code-on-Forward-Capacity-Allocation.aspx

ACER. (2014b). Framework Guidelines and Network Codes. Retrieved November 5, 2014, from http://www.acer.europa.eu/Electricity/FG%7B%5C_%7Dand%7B%5C_%7Dnetwork%7B%5C_%7Dcodes/Pages/default.aspx

Agency, I. E. (2009). *France 2009 Review*. Retrieved June 18, 2013, from https://www.iea.org/publications/freepublications/publication/france2009.pdf

Agency, I. E. (2012). IEA Website. Retrieved May 15, 2012, from http://www.iea.org

Aggarwal, S. K., Saini, L. M., & Kumar, A. (2009). Electricity price forecasting in deregulated markets: A review and evaluation. *International Journal of Electrical Power & Energy Systems*, *31*(1), 13–22. doi:10.1016/j.ijepes.2008.09.003

Aitchison, J. & Aitken, C. G. G. (1976). Multivariate binary discrimination by the kernel method. *Biometrika*, *63*(3), 413–420. doi:10.1093/biomet/63.3.413

American Psychological Association. (2010). *Publication manual of the American Psychological Association* (6th edition). American Psychological Association. Retrieved from http://www.apa.org/pubs/books/4200066.aspx

Amjady, N. & Keynia, F. (2009). Short-term load forecasting of power systems by combination of wavelet transform and neuro-evolutionary algorithm. *Energy*, *34*(1), 46–57. doi:10.1016/j.energy.2008.09.020

Amorim, F., Martins, M. V. M., & Silva, P. P. d. (2010). A new perspective to account for renewables impacts in Portugal. In *2010 7th international con-*

ference on the european energy market (pp. 1–6). IEEE. doi:10.1109/EEM.2010.5558695

Amorim, F., Pina, A., Gerbelová, H., Silva, P. P. d., Vasconcelos, J., & Martins, V. (2014). Electricity decarbonisation pathways for 2050 in Portugal: A TIMES (The Integrated MARKAL-EFOM System) based approach in closed versus open systems modelling. *Energy*, *69*, 104–112. doi:10.1016/j.energy.2014.01.052

Amorim, F., Vasconcelos, J., Abreu, I., Silva, P. P. d., & Martins, V. (2013). How much room for a competitive electricity generation market in Portugal? *Renewable and Sustainable Energy Reviews*, *18*, 103–118. doi:10.1016/j.rser.2012.10.010

Amundsen, E. S. & Bergman, L. (2007). Integration of multiple national markets for electricity: The case of Norway and Sweden. *Energy Policy*, *35*(6), 3383–3394. doi:10.1016/j.enpol.2006.12.014

Ardian, F., Concettini, S., & Creti, A. (2015). Intermittent Renewable Generation and Network Congestion: An Empirical Analysis of Italian Power Market. *SSRN Electronic Journal*, 1–32. doi:10.2139/ssrn.2677118

Armstrong, M. & Galli, A. (2005). Are day-ahead prices for electricity converging in continental Europe? An exploratory data aproach. *CERNA, Working Paper*, *33*(February), 1–18.

Banovac, E., Glavic, M., & Tesnjak, S. (2009). Establishing an efficient regulatory mechanism-Prerequisite for successful energy activities regulation. *Energy*, *34*(2), 178–189. doi:10.1016/j.energy.2008.10.002

Baron, R. (2013). Renewable Energy : a Route to Decarbonisation in Peril? *OECD*, (June), 1–58.

Barth, R., Apfelbeck, J., Vogel, P., Meibom, P., & Weber, C. (2009). Load-flow based market coupling with large- scale wind power in Europe. *8th International Workshop on Large-scale Integration of Wind Power in Power Systems*, 1–8.

Batlle, C. (2011). A method for allocating renewable energy source subsidies among final energy consumers. *Energy Policy*, *39*(5), 2586–2595. doi:10.1016/j.enpol.2011.02.027

Batlle, C., Pérez-Arriaga, I. J., & Zambrano-Barragán, P. (2012). Regulatory design for RES-E support mechanisms: Learning curves, market structure, and burden-sharing. *Energy Policy*, *41*, 212–220. doi:10.1016/j.enpol.2011.10.039

Beaudin, M., Zareipour, H., Schellenberglabe, A., & Rosehart, W. (2010). Energy storage for mitigating the variability of renewable electricity sources: An updated review. *Energy for Sustainable Development*, *14*(4), 302–314. doi:10.1016/j.esd.2010.09.007

Benatia, D., Johnstone, N., & Haščič, I. (2013). Effectiveness of Policies and Strategies to Increase the Capacity Utilisation of Intermittent Renewable Power Plants. *OECD Environment Working Papers, OECD Publishing*, (57), 1–49. doi:10.1787/5k46j0trlrnn-en

Bessec, M. & Fouquau, J. (2008). The non-linear link between electricity consumption and temperature in Europe: A threshold panel approach. *Energy Economics*, *30*(5), 2705–2721. doi:10.1016/j.eneco.2008.02.003

Biskas, P. N., Chatzigiannis, D. I., & Bakirtzis, A. G. (2013). Market coupling feasibility between a power pool and a power exchange. *Electric Power Systems Research*, *104*, 116–128. doi:10.1016/j.epsr.2013.06.015

Boisseleau, F. (2004). The role of power exchanges for the creation of a single European electricity market: market design and market regulation. *Université Paris IX Dauphine*, 1–405.

Boletín Oficial del Estado - Spain. (1997). Ley del Sector Electrico. Retrieved May 4, 2012, from http://www.boe.es/boe/dias/1997/11/28/pdfs/A35097-35126.pdf

Bontemps, C., Racine, J. S., & Simioni, M. (2011). Nonparametric vs parametric binary choice models : An empirical investigation. In *Eaae 2011 congress change and uncertainty, challenges for agriculture, food and natural resources* (1, pp. 1–13).

Bordignon, S., Bunn, D. W., Lisi, F., & Nan, F. (2013). Combining day-ahead forecasts for British electricity prices. *Energy Economics*, *35*, 88–103. doi:10.1016/j.eneco.2011.12.001

Bosco, B., Parisio, L., Pelagatti, M., & Baldi, F. (2010). Long-run relations in European electricity prices. *Journal of Applied Econometrics*, *25*(5), 805–832. doi:10.1002/jae.1095

Bourbonnais, R. & Méritet, S. (2007). Electricity Spot Price Modelling: Univariate Time Series Approach. In J. H. Keppler, R. Bourbonnais, & J. Girod (Eds.), *The econometrics of energy systems* (Keppler, J, Chap. 3, pp. 51–74). Palgrave Macmillan.

Bower, J. (2002). Seeking the Single European Electricity Market - Evidence from an Emprirical Analysis of Wholesale Market Prices. *Report, Oxford Institute for Energy Studies*, (EL 01), 1–42. Retrieved December 8, 2011, from http://www.oxfordenergy.org/2002/07/seeking-the-single-european-electricity-market-evidence-from-an-empirical-analysis-of-wholesale-market-prices/

British Petroleum. (2015). *Statistical Review of World Energy 2015.* Retrieved March 31, 2016, from http://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html

Brown, A., Müller, S., & Dobrotková, Z. (2011). *Renewable Energy - Markets and Prospects by Technology.* IEA. Retrieved May 9, 2012, from http://www.iea.org/papers/2011/Renew%7B%5C_%7DTech.pdf

Brunekreeft, G. & Keller, K. (2000). The electricity supply industry in Germany: market power or power of the market? *Utilities Policy*, *9*(1), 15–29. doi:10.1016/S0957-1787(01)00002-9

Bunn, D. W. & Gianfreda, A. (2010). Integration and shock transmissions across European electricity forward markets. *Energy Economics*, *32*(2), 278–291. doi:10.1016/j.eneco.2009.09.005

Camacho, L. O. & Pérez-Arriaga, I. J. (2007). An assessment of inter-TSO compensation algorithms in the Internal Electricity Market of the European Union. *International Journal of Electrical Power & Energy Systems*, *29*(10), 699–712. doi:10.1016/j.ijepes.2007.05.004

Caramanis, M., Foster, J., & Goldis, E. (2010). Load Participation in Electricity Markets: Day-Ahead and Hour-Ahead Market Coupling with Wholesale/Transmission and Retail/Distribution Cost and Congestion Modeling. *Smart Grid Communications (SmartGridComm), 2010 First IEEE International Conference on*, 513–518. doi:10.1109/SMARTGRID.2010.5622096

Carvalho, M. G., Bonifacio, M., & Dechamps, P. (2011). Building a low carbon society. *Energy*, *36*(4), 1842–1847. doi:10.1016/j.energy.2010.09.030

Castagneto-Gissey, G., Chavez, M., & De Vico Fallani, F. (2014). Dynamic Granger-causal networks of electricity spot prices: A novel approach to market integration. *Energy Economics*, *44*, 422–432. doi:10.1016/j.eneco.2014.05.008

CEER. (2015). Electricity Regional Initiative. Retrieved May 4, 2015, from http://www.ceer.eu/portal/page/portal/EER%7B%5C_%7DHOME/EER%7B%5C_%7DACTIVITIES/EER%7B%5C_%7DINITIATIVES/ERI

Chen, H., Cong, T. N., Yang, W., Tan, C., Li, Y., & Ding, Y. (2009). Progress in electrical energy storage system: A critical review. *Progress in Natural Science*, *19*(3), 291–312. doi:10.1016/j.pnsc.2008.07.014

Christensen, T., a.S. Hurn, & Lindsay, K. (2012). Forecasting spikes in electricity prices. *International Journal of Forecasting*, *28*(2), 400–411. doi:10.1016/j.ijforecast.2011.02.019

Commission de Régulation de L'énergie. (2011). *Observatoire des marchés de l'électricité et du gaz - 4e trimestre 2011*. Retrieved March 17, 2012, from http://www.cre.fr/marches/observatoire-et-indicateurs-des-marches

Conselho de Reguladores do MIBEL. (2009). *Descrição do Funcionamento do MIBEL*. MIBEL. Retrieved March 17, 2012, from http://www.erse.pt/pt/mibel/conselhodereguladores/Documents/Estudo_MIBEL_PT.pdf

Coppens, F. & Vivet, D. (2006). The single European electricity market : A long road to convergence. Retrieved December 1, 2011, from www.nbb.be/doc/ts/publications/wp/wp84En.pdf

Crampes, C. & Fabra, N. (2005). The Spanish Electricity Industry: Plus ca change. *The Energy Journal*, *26*(01), 127–154. doi:10.5547/ISSN0195-6574-EJ-Vol26-NoSI-6

Cramton, P. & Stoft, S. (2006). *The Convergence of Market Designs for Adequate Generating Capacity* (tech. rep. No. April). Retrieved April 14, 2016, from https://works.bepress.com/cramton/34/

Creos. (2013). Creos Luxembourg S.A. Retrieved January 18, 2013, from http://www.creos-net.lu

Creti, A., Fumagalli, E., & Fumagalli, E. (2010). Integration of electricity markets in Europe: Relevant issues for Italy. *Energy Policy*, *38*(11), 6966–6976. doi:10.1016/j.enpol.2010.07.013

Cruz, A., Muñoz, A., Zamora, J. L., & Espínola, R. (2011). The effect of wind generation and weekday on Spanish electricity spot price forecasting. *Electric Power Systems Research*, *81*(10), 1924–1935. doi:10.1016/j.epsr.2011.06.002

Cutler, N. J., Boerema, N. D., MacGill, I. F., & Outhred, H. R. (2011). High penetration wind generation impacts on spot prices in the Australian national electricity market. *Energy Policy*, *39*(10), 5939–5949. doi:10.1016/j.enpol.2011.06.053

Danish Energy Agency. (2012). Energy Policy in Denmark. Retrieved February 24, 2015, from http://www.ens.dk/sites/ens.dk/files/dokumenter/publikationer/downloads/energy%7B%5C_%7Dpolicy%7B%5C_%7Din%7B%5C_%7Ddenmark%7B%5C_%7D-%7B%5C_%7Dweb.pdf

Danish Energy Authority. (2007). A visionary Danish energy policy. Retrieved February 27, 2015, from http://www.ens.dk/sites/ens.dk/files/dokumenter/publikationer/downloads/engelsk%7B%5C_%7Dendelig%7B%5C_%7Dudgave%7B%5C_%7Dvisionaer%7B%5C_%7Denergipolitika4.pdf

Danish Ministry of Climate Energy and Building. (2013). Energy Policy Report 2013. Retrieved February 27, 2015, from http://www.ens.dk/sites/ens.dk/files/policy/danish-climate-energy-policy/dkenergypolicyreport2013%7B%5C_%7Dfinal.pdf

Danish Ministry of Transport and Energy. (2007). *Energy Strategy 2025*. Retrieved March 1, 2015, from http://ens.netboghadel.dk

Danish Parliament. (2008). Promotion of Renewable Energy Act, retrieved March 1, 2015, from http://www.ens.dk/sites/ens.dk/files/supply/renewable-energy/wind-power/onshore-wind-power/Promotion%20of%20Renewable%20Energy%20Act%20-%20extract.pdf

Datastream. (2013). Thomson Reuters Datastream. Retrieved January 18, 2013, from Subscription

Davidson, R. & Mackinnon, J. G. (2004). *Econometric Theory and Methods* (illustrate). Oxford University Press.

De Felice, M., Alessandri, A., & Ruti, P. M. (2013). Electricity demand forecasting over Italy: Potential benefits using numerical weather prediction models. *Electric Power Systems Research*, *104*, 71–79. doi:10.1016/j.epsr.2013.06.004

De Vany, A. S. & Walls, W. (1999). Cointegration analysis of spot electricity prices: insights on transmission efficiency in the western US. *Energy Economics*, *21*(5), 435–448. doi:10.1016/S0140-9883(99)00019-5

de Jager, D., Klessmann, C., Stricker, E., Winkel, T., de Visser, E., Koper, M., . . . Held, A. (2011). Financing Renewable Energy in the European Energy Market. Retrieved May 9, 2012, from http://ec.europa.eu/energy/renewables/studies/doc/renewables/2011%7B%5C_%7Dfinancing%7B%5C_%7Drenewable.pdf

de Jonghe, C., Meeus, L., & Belmans, R. (2008). Power exchange price volatility analysis after one year of Trilateral Market Coupling. In *2008 5th international conference on the european electricity market* (pp. 1–6). IEEE. doi:10.1109/EEM.2008.4579023

de Menezes, L. M. & Houllier, M. A. (2015). Germany's nuclear power plant closures and the integration of electricity markets in Europe. *Energy Policy*, *85*, 357–368. doi:10.1016/j.enpol.2015.05.023

de Menezes, L. M. & Houllier, M. a. (2014). Reassessing the integration of European electricity markets: A fractional cointegration analysis. *Energy Economics*. doi:10.1016/j.eneco.2014.10.021

de Menezes, L. M., Houllier, M. A., & Tamvakis, M. (2016). Time-varying convergence in European electricity spot markets and their association with carbon and fuel prices. *Energy Policy*, *88*, 613–627. doi:10.1016/j.enpol.2015.09.008

Diário da República Portuguesa. (1995). Decreto-lei 187/95 de 27 de Julho.

Diário da República Portuguesa. (2010). Portaria n.°765/2010.

Diekmann, J., Kemfert, C., & Neuhoff, K. (2012). The Proposed Adjustment of Germany's Renewable Energy Law: A Critical Assessment. *DIW Economic Bulletin*, *2*, 3–9. Retrieved March 31, 2016, from http://econpapers.repec.org/RePEc:diw:diwdeb:2012-6-1

Edenhofer, O. [O.], Pichs-Madruga, R., Sokona, Y., Seyboth, K., Kadner, S., Zwickel, T., . . . von Stechow, C., et al. (2011). *Renewable Energy Sources and Climate Change Mitigation: Special Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press. Retrieved March 5, 2015, from https://www.google.pt/books?id=AjP9sVg01zoC

Edenhofer, O. [Ottmar], Hirth, L., Knopf, B., Pahle, M., Schlömer, S., Schmid, E., & Ueckerdt, F. (2013). On the economics of renewable energy sources. *Energy Economics*, *40*, S12–S23. doi:10.1016/j.eneco.2013.09.015

Edenhofer, O. [Ottmar], Pichs Madruga, R., Sokona, Y., United Nations Environment Programme, World Meteorological Organization, Intergovernmental Panel on Climate Change, … Potsdam-Institut für Klimafolgenforschung. (2012). *Renewable energy sources and climate change mitigation: special report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, 2011. Retrieved March 1, 2015, from http://www.cambridge.org/us/academic/subjects/earth-and-environment

EDF Group. (2010). *Activity & Sustainable Development*. Retrieved December 1, 2011, from https://www.edf.fr/sites/default/files/contrib/finance/Annual%20Report%20VA/2010/Report/EDF2010_full_va.pdf

ELIA. (2013). ELIA website. Retrieved January 14, 2013, from www.elia.be

Energinet. (2015). Danish Transmission System Operator. Retrieved March 8, 2015, from http://www.energinet.dk/

Engle, R. (2002). Dynamic Conditional Correlation. *Journal of Business & Economic Statistics*, *20*(3), 339–350. doi:10.1198/073500102288618487

Engle, R. F. & Granger, C. W. J. (1987). Co-Integration and Error Correction: Representation, Estimation, and Testing. *Econometrica*, *55*(2), 251. doi:10.2307/1913236

ENTSO-E. (2011). Indicative values for Net Transfer Capacities (NTC) in Continental Europe. Retrieved January 18, 2013, from https://www.entsoe.eu/publications/market-and-rd-reports/ntc-values/ntc-matrix/

ENTSO-E. (2012). *10-Year Network Development Plan 2012*. Retrieved January 18, 2013, from https://www.entsoe.eu/publications/general-reports/

ENTSO-E. (2015a). ENTSO-E Transparency Platform. Retrieved April 22, 2015, from https://transparency.entsoe.eu/

ENTSO-E. (2015b). *Scenario Outlook & Adequacy Forecast*. Retrieved October 5, 2015, from https://www.entsoe.eu/publications/system-development-reports/adequacy-forecasts/Pages/default.aspx

EPEX. (2016). EPEX Website. Retrieved January 19, 2016, from www.epexspot.com

EPEX, Apx-endex, & BelPEX. (2010). *CWE MARKET COUPLING ALGORITHM* (tech. rep. No. June). Retrieved November 27, 2012, from http://static.epexspot.com/document/20015/COSMOS%7B%5C_%7Dpublic%7B%5C_%7Ddescription.pdf

ERGEG. (2006). *The Electricity Regional Initiative: Making Progress Towards a Single European Market* (tech. rep. No. E05-ERF-03-06b). Retrieved March 8, 2012, from http://www.energy-regulators.eu/portal/page/portal/EER%7B%5C_%7DHOME/EER%7B%5C_%7DPUBLICATIONS/FACTSHEETS/Tab5/E05-ERF-03-06B%7B%5C_%7DERI%7B%5C_%7DFS-05-02-22.PDF

European Commission. (2012). *EU energy in figures - Statistical Pocketbook 2012*. Luxembourg: Publications Office of the European Union, 2012. doi:10.2833/11169

European Commission. (2014). European Energy Security Strategy. *Communication from the Commission to the European Parliament and the Council*, 1–24. Retrieved August 9, 2015, from http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52014DC0330%7B%5C&%7Dfrom=EN

European Commission. (2015a). Energy Union Package: A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy. *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee, the Committee of the Regions and the European Investment Bank*, 1–21. Retrieved August 9, 2015, from http://ec.europa.eu/priorities/energy-union/docs/energyunion%7B%5C_%7Den.pdf

European Commission. (2015b). Lauching the public consultation process on a new energy market design. *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions*, 1–17. Retrieved August 9, 2015, from http://ec.europa.eu/energy/sites/ener/files/documents/1%7B%5C_%7DEN%7B%5C_%7DACT%7B%5C_%7Dpart1%7B%5C_%7Dv11.pdf

European Union. (1990a). Directive 90/377/EEC of 29 June 1990 concerning a Community procedure to improve the transparency of gas and electricity prices charged to industrial end-users. *Official Journal of the European Communities*, *L 185*(29/06/1990), 16–24.

European Union. (1990b). Directive 90/547/EEC of 29 October 1990 on the transit of electricity through transmission grids. *Official Journal of the European Communities*, *L 313*(29/10/1990), 30–33.

European Union. (1997). Directive 96/92/EC of the European Parliament and of the Council of 19 December 1996 concerning common rules for the internal market in electricity. *Official Journal of the European Union*, *L 027*(30/01/1997), 0020–0029.

European Union. (2001). Directive 2001/77/EC of the European Parliament and of the Council of 27 September 2001 on the promotion of electricity produced from renewable energy sources in the internal electricity market. *Official Journal of the European Communities*, *L283*, 33–40.

European Union. (2003a). Directive 2003/54/EC of the European Parliament and of the Council of 26 June 2003 concerning common rules for the internal market in electricity and repealing Directive 96/92/EC. *Official Journal of the European Union*, *L 176*(15/07/2003), 37–56.

European Union. (2003b). European Community Regulation 1228/2003/EC of the European Parliament and of the Council of 26 June 2003 on conditions for access to the network for cross-border exchanges in electricity. *Official Journal of the European Union*, *L 176*(15/07/2003), 1–10.

European Union. (2003c). Regulation (EC) No 1228/2003 of the European Parliament and of the Council of 26 June 2003 on conditions for access to the network for cross-border exchanges in electricity. *Official Journal of the European Union*, *L176*, 1–10.

European Union. (2009a). Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. *Official Journal of the European Union*, *L140*(5-6-2009), 16–62. Retrieved from http://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=URISERV:l27002&from=EN

European Union. (2009b). Directive 2009/72/EC of the European Parliament and of the Council of 13 July 2009 concerning common rules for the internal market in electricity and repealing Directive 2003/54/EC. *Official Journal of the European Union*, *L 211*(14/08/2009), 55–93.

European Union. (2009c). Regulation (EC) No 713/2009 of the European Parliament and of the Council of 13 July 2009 establishing an Agency for the Cooperation of Energy Regulators. *Official Journal of the European Union, L 211*(14/08/2009), 1–14.

European Union. (2009d). Regulation (EC) No 714/2009 of the European Parliament and of the Council of 13 July 2009 on conditions for access to the network for cross-border exchanges in electricity and repealing Regulation (EC) No 1228/2003. *Official Journal of the European Union, L 211*(14/08/2009), 15–35.

European Union. (2010). Commission Regulation (EU) No 838/2010 of 23 September 2010 on laying down guidelines relating to the inter-transmission system operator compensation mechanism and a common regulatory approach to transmission charging. *Official Journal of the European Union, L 250*(24/09/2010), 5–11.

European Union. (2014). Roadmap for moving to a low-carbon economy in 2050. Retrieved December 5, 2014, from http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52011DC0112%7B%5C&%7Dfrom=EN

Europex. (2009). Multi Regional Day-Ahead Price Coupling - Towards Implementation of the PCG Target Model. *Conference Proceedings, Florence Regulatory Forum*, 1–5. Retrieved April 2, 2012, from http://www.europex.org/index/pages/id%7B%5C_%7Dpage-49/lang-en/

Europex. (2011). Status of Implementation of PCR for Day-Ahead Price Coupling. *Conference Proceedings, Florence Regulatory Forum*, 1–7. Retrieved April 2, 2012, from http://www.europex.org/index/pages/id%7B%5C_%7Dpage-49/lang-en/

Eurostat. (2015). Eurostat - database. Retrieved March 6, 2015, from http://ec.europa.eu/eurostat/data/database

Everis & Mercados EMI. (2010). *From Regional Markets to a Single European Market*. Retrieved March 8, 2012, from http://ec.europa.eu/energy/gas%7B%5C_%7Delectricity/studies/doc/2010%7B%5C_%7Dgas%7B%5C_%7Delectricity%7B%5C_%7Dmarkets.pdf

Eydeland, A. & Wolyniec, K. (2003). *Energy and Power Risk Management*. John Wiley & Sons, Inc.

Felder, F. A. (2011). Examining Electricity Price Suppression Due to Renewable Resources and Other Grid Investments. *The Electricity Journal*, *24*(4), 34–46. doi:10.1016/j.tej.2011.04.001

Figueiredo, N. C. & Silva, P. P. d. (2012). Integration of South-West Spot Electricity Markets: An Update. In *12th IAEE - European Energy Conference* (pp. 1–14).

Figueiredo, N. C. & Silva, P. P. d. (2013a). Explanatory Variables on Central-West Spot Electricity Markets Integration. In *Energy for Sustainability 2013, Sustainable Cities: Designing for People and the Planet* (September, pp. 1–15).

Figueiredo, N. C. & Silva, P. P. d. (2013b). Explanatory Variables on South-West Spot Electricity Markets Integration. In *Icee - energy & environment: Bringing together economics and engineering* (pp. 1–13).

Figueiredo, N. C. & Silva, P. P. d. (2013c). Integration of Central West Europe spot electricity markets: An update. In *10th International Conference on the European Energy Market (EEM)* (pp. 1–7). IEEE. doi:10.1109/EEM.2013.6607299

Figueiredo, N. C. & Silva, P. P. d. (2015). Explanatory variables on south-west spot electricity markets integration. In P. Godinho & J. Dias (Eds.), *Assessment methodologies: Energy, mobility and other real world application* (pp. 65–88). Imprensa da Universidade de Coimbra. doi:10.14195/978-989-26-1039-9_3

Figueiredo, N. C. & Silva, P. P. d. (2016a). Price Coupling of Regions: What changed in Western Europe? In *Eeic 2016 energy economics iberia conference* (pp. 1–6).

Figueiredo, N. C. & Silva, P. P. d. (2016b). Renewables Optimization in Energy-Only Markets. In V. Blanco (Ed.), *Analysis of energy systems. management, planning and policy* (Chap. 6). Taylor & Francis.

Figueiredo, N. C., Silva, P. P. d., & Bunn, D. (2016). Weather and market specificities in the regional transmission of renewable energy price effects. *Energy*, *114*, 188–200. doi:10.1016/j.energy.2016.07.157

Figueiredo, N. C., Silva, P. P. d., & Cerqueira, P. A. (2014). The Renewables Influence on Market Splitting : the Iberian Spot Electricity Market. In *14th IAEE - European Energy Conference.*

Figueiredo, N. C., Silva, P. P. d., & Cerqueira, P. A. (2015a). Evaluating the market splitting determinants: evidence from the Iberian spot electricity prices. *Energy Policy*, *85*, 218–234. doi:10.1016/j.enpol.2015.06.013

Figueiredo, N. C., Silva, P. P. d., & Cerqueira, P. A. (2015b). Wind generation influence on market splitting: The Iberian spot electricity market. In *12th International Conference on the European Energy Market (EEM)* (pp. 1–5). IEEE. doi:10.1109/EEM.2015.7216649

Figueiredo, N. C., Silva, P. P. d., & Cerqueira, P. A. (2016). It is windy in Denmark: Does market integration suffer? *Energy*. doi:10.1016/j.energy.2016.05.038

Franco, A. & Salza, P. (2011). Strategies for optimal penetration of intermittent renewables in complex energy systems based on techno-operational objectives. *Renewable Energy*, *36*(2), 743–753. doi:10.1016/j.renene.2010.07.022

Freitas, C. & Silva, P. P. d. (2013). Evaluation of dynamic pass-through of carbon prices into electricity prices - a cointegrated VECM analysis. *International Journal of Public Policy*, *9*(1/2), 65–85. doi:10.1504/IJPP.2013.053440

Freitas, C. & Silva, P. P. d. (2015). European Union emissions trading scheme impact on the Spanish electricity price during phase II and phase III implementation. *Utilities Policy*, *33*, 54–62. doi:10.1016/j.jup.2015.01.004

Frondel, M., Ritter, N., Schmidt, C. M., & Vance, C. (2010). Economic impacts from the promotion of renewable energy technologies: The German experience. *Energy Policy*, *38*(8), 4048–4056. doi:10.1016/j.enpol.2010.03.029

Furió, D. & Lucia, J. J. (2009). Congestion management rules and trading strategies in the Spanish electricity market. *Energy Economics*, *31*(1), 48–60. doi:10.1016/j.eneco.2008.07.004

Galiana, F., Conejo, A., & Gil, H. (2003). Transmission network cost allocation based on equivalent bilateral exchanges. *IEEE Transactions on Power Systems*, *18*(4), 1425–1431. doi:10.1109/TPWRS.2003.818689

Galli, A. & Armstrong, M. (2007). *Comparing the Spot Prices from Powernext and EEX*, CERNA. Retrieved from http://www.erasmusenergy.com/articles/29/1/Comparing-the-spot-prices-from-Powernext-and-EEX/Page1.html

Garrué-Irurzun, J. & López-García, S. (2009). Red Eléctrica de España S.A.: Instrument of regulation and liberalization of the Spanish electricity market (1944-2004). *Renewable and Sustainable Energy Reviews*, *13*, 2061–2069. doi:10.1016/j.rser.2009.01.028

Gelabert, L., Labandeira, X., & Linares, P. (2011). An ex-post analysis of the effect of renewables and cogeneration on Spanish electricity prices. *Energy Economics*, *33*, S59–S65. doi:10.1016/j.eneco.2011.07.027

Genesi, C., Marannino, P., Montagna, M., Siviero, I., & Zanellini, F. (2008). A multilateral market coupling approach for the allocation of cross border transmission capacity. *Proceedings of the Universities Power Engineering Conference*, (1100). doi:10.1109/UPEC.2008.4651501

Genesi, C., Rossi, S., Siviero, I., Marannino, P., Zanellini, F., & Montagna, M. (2008). Cross border transmission capacity allocation by multilateral market coupling. *Proceedings of the Mediterranean Electrotechnical Conference - MELECON*, 744–749. doi:10.1109/MELCON.2008.4618524

Gianfreda, A. & Grossi, L. (2009). Zonal price analysis of the Italian wholesale electricity market. *6th International Conference on the European Energy Market*, (37129), 1–6. doi:10.1109/EEM.2009.5207198

Gianfreda, A. & Grossi, L. (2012). Forecasting Italian electricity zonal prices with exogenous variables. *Energy Economics*, *34*(6), 2228–2239. doi:10.1016/j.eneco.2012.06.024

Glachant, J. M. & Ruester, S. (2014). The EU internal electricity market: Done forever? *Utilities Policy*, *30*, 1–7. doi:10.1016/j.jup.2014.05.003

Glachant, J.-M. (2010). The Achievement of the EU Electricity Internal Market through Market Coupling. Retrieved March 28, 2015, from http://cadmus.eui.eu/bitstream/handle/1814/15189/RSCAS%7B%5C_%7D2010%7B%5C_%7D87.pdf?sequence=1

Glachant, J.-M. & Finon, D. (2005). A Competitive Fringe in the Shadow of a State Owned Incumbent: The Case of France. *The Energy Journal*, *26*(01), 181–204. doi:10.5547/ISSN0195-6574-EJ-Vol26-NoSI-8

Glachant, J.-m. & Lévêque, F. (2005). Electricity Internal Market in the European Union: What to do next? MIT Center for Energy and Environmental Policy Research. Retrieved December 1, 2011, from http://hdl.handle.net/1721.1/45045

Goto, M. & Karolyi, G. A. (2004). Understanding Electricity Price Volatility Within and Across Markets. *SSRN Electronic Journal*, *2004-12*(614), 1–41. doi:10.2139/ssrn.576982

Granger, C. W. J. (1969). Investigating Causal Relations by Econometric Models and Cross-spectral Methods. *Econometrica*, *37*(3), 424. doi:10.2307/1912791

Green, R., Lorenzoni, A., Perez, Y., & Pollitt, M. (2005). Benchmarking Electricity Liberalisation in Europe. Retrieved April 15, 2012, from http://www.dspace.cam.ac.uk/handle/1810/131686

Grewal, R., Mills, J. A., Mehta, R., & Mujumdar, S. (2001). Using cointegration analysis for modeling marketing interactions in dynamic environments: Methodological issues and an empirical illustration. *Journal of Business Research*, *51*(2), 127–144. doi:10.1016/S0148-2963(99)00054-5

Grossi, L., Heim, S., Hüschelrath, K., & Waterson, M. (2015). Electricity Market Integration and the Impact of Unilateral Policy Reforms. Retrieved December 31, 2015, from http://ftp.zew.de/pub/zew-docs/dp/dp15072.pdf

Hadsell, L., Marathe, A., & Shawky, H. a. (2004). Estimating the Volatility of Wholesale Electricity Spot Prices in the US. *The Energy Journal*, *25*(4), 23–40. doi:10.5547/ISSN0195-6574-EJ-Vol25-No4-2

Haldrup, N. & Nielsen, M. Ø. (2006). A regime switching long memory model for electricity prices. *Journal of Econometrics*, *135*(1-2), 349–376. doi:10.1016/j.jeconom.2005.07.021

Hayfield, T. & Racine, J. S. (2008). Nonparametric Econometrics: The np Package. *Journal of Statistical Software*, *27*(5), 1–32. doi:10.18637/jss.v027.i05

Henriot, A. & Glachant, J. M. (2013). Melting-pots and salad bowls: The current debate on electricity market design for integration of intermittent RES. *Utilities Policy*, *27*, 57–64. doi:10.1016/j.jup.2013.09.001

Henriot, A., Lavoine, O., Regairaz, F., Hiroux-Marcy, C., Gilmore, J., Riesz, J., & Yuen, C. (2013). *Market Design for Large Scale Integration of Intermittent Renewable Energy Sources*. Retrieved December 2, 2014, from http://c5.cigre.org/Members-Area/WG-C5-11-Market-Design-for-Large-Scale-Integration-of-Renewable-Energy-Sources-and-Demand-side-Management

Higgs, H. (2008). Modelling spot prices in deregulated wholesale electricity markets : A selected empirical review. Retrieved May 8, 2012, from http://ssrn.com/abstract=1290909

Higgs, H. (2009). Modelling price and volatility inter-relationships in the Australian wholesale spot electricity markets. *Energy Economics*, *31*(5), 748–756. doi:10.1016/j.eneco.2009.05.003

Higgs, H. & Worthington, A. (2008). Stochastic price modeling of high volatility, mean-reverting, spike-prone commodities: The Australian wholesale spot electricity market. *Energy Economics*, *30*(6), 3172–3185. doi:10.1016/j.eneco.2008.04.006

Hildmann, M., Ulbig, A., & Andersson, G. (2013). Revisiting the Merit-Order Effect of Renewable Energy Sources. arXiv: 1307.0444. Retrieved March 30, 2016, from http://arxiv.org/abs/1307.0444

Hobbs, B. F., Rijkers, F. A. M., & Boots, M. G. (2005). The more cooperation, the more competition? A Cournot analysis of the benefits of electric market coupling. *Energy Journal*, *26*(4), 69–97. doi:10.5547/ISSN0195-6574-EJ-Vol26-No4-5

Holttinen, H., Vogstad, K.-O., Botterud, A., & Hirvonen, R. (2001). Effects of Large Scale Wind Production on the Nordic Electricity Market. (pp. 1–4). Retrieved January 6, 2016, from https://www.researchgate.net/publication/229000443_Effects_of_large_scale_wind_production_on_the_Nordic_electricity_market

Hooper, E. & Medvedev, A. (2009). Electrifying integration: Electricity production and the South East Europe regional energy market. *Utilities Policy*, *17*(1), 24–33. doi:10.1016/j.jup.2008.02.009

Huisman, R. & Kiliç, M. (2013). A history of European electricity day-ahead prices. *Applied Economics*, *45*(18), 2683–2693. doi:10.1080/00036846.2012.665601

INELFE. (2015). INELFE Website. Retrieved November 29, 2015, from http://www.inelfe.eu/?-rubrique25-%7B%5C&%7Dlang=en

International Energy Agency. (2007). *Germany 2007 Review*. Retrieved January 14, 2013, from https://www.iea.org/publications/freepublications/publication/germany2007.pdf

International Energy Agency. (2009a). *Luxembourg 2008 Review.* Retrieved January 18, 2013, from https://www.iea.org/publications/freepublications/publication/Luxembourg2008.pdf

International Energy Agency. (2009b). *The Netherlands 2008 Review.* Retrieved January 14, 2013, from http://www.iea.org/publications/freepublications/publication/Netherlands2008.pdf

International Energy Agency. (2010). *Belgium 2009 Review.* Retrieved January 14, 2013, from https://www.iea.org/publications/freepublications/publication/belgium2009.pdf

International Energy Agency. (2011). *Denmark 2011 Review.* Retrieved January 13, 2015, from http://www.ens.dk/sites/ens.dk/files/politik/dansk-klima-energipolitik/denmark2011_unsecured-3.pdf

International Energy Agency. (2013). *Wind Annual Report for 2013.* Retrieved March 1, 2015, from http://www.ieawind.org/annual_reports_PDF/2013/2013%20AR_small_090114.pdf

Islam, S. M., Al-Alawi, S. M., & Ellithy, K. a. (1995). Forecasting monthly electric load and energy for a fast growing utility using an artificial neural network. *Electric Power Systems Research*, *34*(1), 1–9. doi:10.1016/0378-7796(95)00950-M

Jacottet, A. (2012). *Cross-border electricity interconnections for a well-functioning EU Internal Electricity Market* (tech. rep. No. June). The Oxford Institute for Energy Studies. Retrieved July 3, 2012, from https://www.oxfordenergy.org/publications/cross-border-electricity-interconnections-for-a-well-functioning-eu-internal-electricity-market-2/

Jäger-waldau, A., Szabó, M., Monforti-ferrario, F., Bloem, H., Huld, T., & Arantegui, R. L. (2011). *Renewable Energy Snapshots 2011.* JRC-IET. doi:10.2788/79722

Jamasb, T. & Pollitt, M. (2005). Electricity Market Reform in the European Union : Review of Progress toward Liberalization & Integration. *The Energy Journal*, *26*, 11–41. Retrieved from http://www.jstor.org/stable/23297005

Jensen, S. & Skytte, K. (2002). Interactions between the power and green certificate markets. *Energy Policy*, *30*(5), 425–435. doi:10.1016/S0301-4215(01)00111-2

Jónsson, T., Pinson, P., & Madsen, H. (2010). On the market impact of wind energy forecasts. *Energy Economics*, *32*(2), 313–320. doi:10.1016/j.eneco.2009.10.018

Jónsson, T., Pinson, P., Nielsen, H. A., Madsen, H., & Nielsen, T. S. (2013). Forecasting Electricity Spot Prices Accounting for Wind Power Predictions. *IEEE Transactions on Sustainable Energy*, *4*(1), 210–218. doi:10.1109/TSTE.2012.2212731

Joskow, P. L. (2008). Lessons Learned from Electricity Market Liberalization. *The Energy Journal*, *29*(01), 9–42. doi:10.5547/ISSN0195-6574-EJ-Vol29-NoSI2-3

Journal Officiel de la République Française. (2000). LOI n° 2000-108 10 février relative à la modernisation et au développement du service public de l'électricité. Retrieved December 1, 2011, from https://www.legifrance.gouv.fr/affichTexte.do?cidTexte=JORFTEXT000000750321

Journal Officiel de la République Française. (2010). LOI n. 2010-1488 du 7 décembre portant nouvelle organisation du marché de l'électricité. Retrieved December 1, 2011, from https://www.legifrance.gouv.fr/affichTexte.do?cidTexte=JORFTEXT000023174854

Jullien, C., Pignon, V., Robin, S., & Staropoli, C. (2012). Coordinating cross-border congestion management through auctions: An experimental approach to European solutions. *Energy Economics*, *34*(1), 1–13. doi:10.1016/j.eneco.2011.08.017

Karakatsani, N. V. & Bunn, D. W. (2008a). Forecasting electricity prices: The impact of fundamentals and time-varying coefficients. *International Journal of Forecasting*, *24*(4), 764–785. doi:10.1016/j.ijforecast.2008.09.008

Karakatsani, N. V. & Bunn, D. W. (2008b). Intra-day and regime-switching dynamics in electricity price formation. *Energy Economics*, *30*(4), 1776–1797. doi:10.1016/j.eneco.2008.02.004

Karova, R. (2011). Regional electricity markets in Europe: Focus on the Energy Community. *Utilities Policy*, *19*(2), 80–86. doi:10.1016/j.jup.2010.10.001

Keles, D., Genoese, M., Möst, D., Ortlieb, S., & Fichtner, W. (2013). A combined modeling approach for wind power feed-in and electricity spot prices. *Energy Policy*, *59*, 213–225. doi:10.1016/j.enpol.2013.03.028

Klessmann, C., Nabe, C., & Burges, K. (2008). Pros and cons of exposing renewables to electricity market risks—A comparison of the market integration approaches in Germany, Spain, and the UK. *Energy Policy*, *36*(10), 3646–3661. doi:10.1016/j.enpol.2008.06.022

Kristiansen, T. (2007). A preliminary assessment of the market coupling arrangement on the Kontek cable. *Energy Policy*, *35*(6), 3247–3255. doi:10.1016/j.enpol.2006.11.025

Kurzidem, M. J. (2010). *Analysis of Flow-based Market Coupling in Oligopolistic Power Markets* (Doctoral dissertation, ETH Zurich). Retrieved April 15, 2012, from https://www.eeh.ee.ethz.ch/uploads/tx%7B%5C_%7Dethpublications/Kurzidem%7B%5C_%7Ddiss.pdf

Kwiatkowski, D., Phillips, P. C., Schmidt, P., & Shin, Y. (1992). Testing the null hypothesis of stationarity against the alternative of a unit root. *Journal of Econometrics*, *54*(1-3), 159–178. doi:10.1016/0304-4076(92)90104-Y

Lei Wu & Shahidehpour, M. (2010). A Hybrid Model for Day-Ahead Price Forecasting. *IEEE Transactions on Power Systems*, *25*(3), 1519–1530. doi:10.1109/TPWRS.2009.2039948

Lévêque, F. (2010). *La nouvelle loi française de l' électricité : un barrage contre le marché et l' Europe*, CERNA, Centre d'économie industrille - MINES ParisTech. Retrieved March 20, 2012, from http://www.cerna.ensmp.fr/images/DocumentsWP/nomewpfl.pdf

Li, Q. & Racine, J. S. (2007). *Nonparametric econometrics : theory and practice.* Princeton University Press.

Lucia, J. J. & Schwartz, E. S. (2002). Electricity Prices and Power Derivatives: Evidence from the Nordic Power Exchange. *Review of Derivatives Research*, *5*, 5–50. doi:10.1023/A:1013846631785

Luna, L. & Martínez, J. (2011). Impact of Wind Power Generation on the ATC value. In *17th power systems computation conference* (pp. 1–7). Retrieved March 27, 2014, from http://pscc.ee.ethz.ch/uploads/tx_ethpublications/fp394.pdf

Lund, H. (1999). A green energy plan for Denmark: Job creation as a strategy to implement both economic growth and a CO2 reduction. *Environmental and Resource Economics*, *14*, 431–439. doi:10.1023/A:1008344032223

Lund, H. (2007). Renewable energy strategies for sustainable development. *Energy*, *32*, 912–919. doi:10.1016/j.energy.2006.10.017

Lund, H. (2010). The implementation of renewable energy systems. Lessons learned from the Danish case. *Energy*, *35*(10), 4003–4009. doi:10.1016/j.energy.2010.01.036

Lund, H. & Clark, W. W. (2002). Management of fluctuations in wind power and CHP comparing two possible Danish strategies. *Energy*, *27*, 471–483. doi:10.1016/S0360-5442(01)00098-6

Lund, H., Hvelplund, F., Østergaard, P. A., Möller, B., Mathiesen, B. V., Karnøe, P., . . . Wenzel, H. (2013). System and market integration of wind power in Denmark. *Energy Strategy Reviews*, *1*, 143–156. doi:10.1016/j.esr.2012.12.003

Lund, H. & Mathiesen, B. (2009). Energy system analysis of 100% renewable energy systems—The case of Denmark in years 2030 and 2050. *Energy*, *34*(5), 524–531. doi:10.1016/j.energy.2008.04.003

Lund, H. & Münster, E. (2006). Integrated energy systems and local energy markets. *Energy Policy*, *34*, 1152–1160. doi:10.1016/j.enpol.2004.10.004

Lütkepohl, H. (2005). *New Introduction to Multiple Time Series Analysis*. Springer.

Lütkepohl, H. & Krätzig, M. (2004). *Applied Time Series Econometrics*. Cambridge University Press.

Lynch, M. Á., Tol, R. S., & O'Malley, M. J. (2012). Optimal interconnection and renewable targets for north-west Europe. *Energy Policy*, *51*, 605–617. doi:10.1016/j.enpol.2012.09.002

Mauritzen, J. (2010). What Happens When It's Windy in Denmark? An Empirical Analysis of Wind Power on Price Volatility in the Nordic Electricity Market. doi:10.2139/ssrn.1754931

Meeus, L. (2011). Why (and how) to regulate power exchanges in the EU market integration context? *Energy Policy*, *39*(3), 1470–1475. doi:10.1016/j.enpol.2010.12.019

Meeus, L. & Belmans, R. (2008). Electricity Market Integration in Europe. Retrieved March 8, 2012, from https://www.researchgate.net/profile/Leonardo_Meeus/publication/228642113_Electricity_market_integration_in_Europe/links/00b7d52fe7e8d33df9000000.pdf

Meeus, L., Belmans, R., & Glachant, J.-M. (2006). Regional Electricity Market Integration France-Belgium-Netherlands. *Response to the public consultation on regional integration of the electricity market by the French, Belgian and Dutch regulator, respectively CRE, CREG and DTE*, 1–7. Retrieved November 30, 2015, from https://www.acm.nl/en/download/attachment/?id=10431

Meeus, L., Purchala, K., Van Hertem, D., & Belmans, R. (2006). Regulated cross-border transmission investment in Europe. *European Transactions on Electrical Power*, *16*(6), 591–601. doi:10.1002/etep.106

Meeus, L., Vandezande, L., Cole, S., & Belmans, R. (2009). Market coupling and the importance of price coordination between power exchanges. *Energy*, *34*(3), 228–234. doi:10.1016/j.energy.2008.04.013

Meulman, L. & Méray, N. (2012). *Capacity Mechanisms in Northwest Europe*. Retrieved April 17, 2016, from http://clingendael.info/publications/2012/20121200%7B%5C_%7Dcapacity%7B%5C_%7Dmechanisms%7B%5C_%7Din%7B%5C_%7Dnorthwest%7B%5C_%7Deurope%7B%5C_%7Ddecember.pdf

Meyer, N. I. (2003). European schemes for promoting renewables in liberalised markets. *Energy Policy*, *31*(7), 665–676. doi:10.1016/S0301-4215(02)00151-9

Milligan, M., Lew, D., Corbus, D., Piwko, R., Miller, N., Clark, K., ... Freeman, L. (2009). *Large-Scale Wind Integration Studies in the United States : Preliminary Results*. Retrieved January 8, 2016, from http://www.nrel.gov/docs/fy09osti/46505.pdf

Ministerio de Industria y Energía - Spain. (1996). Protocolo para el Establecimiento de una Nueva Regulación del Sistema Eléctrico Nacional. Retrieved November 28, 2011, from http://www.unesa.es/sector-electrico/la-regulacion-electrica-en-espana-y-europa/1941-protocolo-electrico

Mirasgedis, S., Sarafidis, Y., Georgopoulou, E., Lalas, D. P., Moschovits, M., Karagiannis, F., & Papakonstantinou, D. (2006). Models for mid-term electricity demand forecasting incorporating weather influences. *Energy*, *31*(2-3), 208–227. doi:10.1016/j.energy.2005.02.016

MIT Energy Initiative. (2011). *Managing large-scale penetration of intermittent renewables.* Retrieved March 2, 2015, from http://energy.mit.edu/publication/managing-large-scale-penetration-of-intermittent-renewables/

Mood, C. (2009). Logistic Regression: Why We Cannot Do What We Think We Can Do, and What We Can Do About It. *European Sociological Review*, *26*(1), 67–82. doi:10.1093/esr/jcp006

Moreno, B., López, A. J., & García-Álvarez, M. T. (2012). The electricity prices in the European Union. The role of renewable energies and regulatory electric market reforms. *Energy*, *48*(1), 307–313. doi:10.1016/j.energy.2012.06.059

Moreno, B. & Silva, P. P. d. (2016). How do Spanish polluting sectors' stock market returns react to European Union allowances prices? A panel data approach. *Energy*, *103*, 240–250. doi:10.1016/j.energy.2016.02.094

Moreno, F. & Martínez-Val, J. M. (2011). Collateral effects of renewable energies deployment in Spain: Impact on thermal power plants performance and management. *Energy Policy*, *39*(10), 6561–6574. doi:10.1016/j.enpol.2011.07.061

Morris, C. & Pehnt, M. (2015). Energy Transition - The German Energiewende. Retrieved July 30, 2015, from http://energytransition.de/

Mourshed, M. (2012). Relationship between annual mean temperature and degree-days. *Energy and Buildings*, *54*, 418–425. doi:10.1016/j.enbuild.2012.07.024

Mulder, M. & Scholtens, B. (2013). The impact of renewable energy on electricity prices in the Netherlands. *Renewable Energy*, *57*, 94–100. doi:10.1016/j.renene.2013.01.025

Munksgaard, J. & Morthorst, P. E. (2008). Wind power in the Danish liberalised power market—Policy measures, price impact and investor incentives. *Energy Policy*, *36*(10), 3940–3947. doi:10.1016/j.enpol.2008.07.024

Murray, B. (2009). *Power Markets and Economics.* John Wiley & Sons, Ltd.

Murray, M. P. (1994). A Drunk and Her Dog: An Illustration of Cointegration and Error Correction. *The American Statistician*, *48*(1), 37. doi:10.2307/2685084

Nelson, T., Reid, C., & McNeill, J. (2015). Energy-only markets and renewable energy targets: Complementary policy or policy collision? *Economic Analysis and Policy*, *46*, 25–42. doi:10.1016/j.eap.2015.04.001

Nepal, R. & Jamasb, T. (2012). Reforming the power sector in transition: Do institutions matter? *Energy Economics*. doi:10.1016/j.eneco.2012.02.002

Neuhoff, K., Barquin, J., Bialek, J. W., Boyd, R., Dent, C. J., Echavarren, F., . . . Weigt, H. (2013). Renewable electric energy integration: Quantifying the value of design of markets for international transmission capacity. *Energy Economics*, *40*, 760–772. doi:10.1016/j.eneco.2013.09.004

Newbery, D. (2005). Refining Market Design. In *Proc. implementing the internal market of electricity: Proposals and time-tables* (September). SESSA - Sustainable Energy Specific Support Assessment. Retrieved December 1, 2011, from http://www.eprg.group.cam.ac.uk/wp-content/uploads/2008/11/eprg0515.pdf

Newbery, D. (2015). Missing money and missing markets: Reliability, capacity auctions and interconnectors. *Energy Policy*, (February 2015). doi:10.1016/j.enpol.2015.10.028

Newbery, D., Strbac, G., & Ivan, V. (2015). The benefits of integrating European electricity markets. *Faculty of Economics, University of Cambridge*, (February 2015), 1–22. Retrieved December 31, 2015, from https://www.repository.cam.ac.uk/handle/1810/255360

Nicolosi, M. (2010). Wind power integration and power system flexibility-An empirical analysis of extreme events in Germany under the new negative price regime. *Energy Policy*, *38*(11), 7257–7268. doi:10.1016/j.enpol.2010.08.002

Nord Pool. (2015a). Explicit and implicit capacity auction. Retrieved March 17, 2015, from https://nordpoolspot.com/globalassets/download-center/pcr/how-does-it-work%7B%5C_%7Dexplicit-and-implicit-capacity-auction.pdf

Nord Pool. (2015b). Nord Pool ftp server. Retrieved January 14, 2015, from http://www.nordpoolspot.com/

Ochoa, C. & van Ackere, A. (2014). Does size matter? Simulating electricity market coupling between Colombia and Ecuador. *Renewable and Sustainable Energy Reviews*, *50*, 1108–1124. doi:10.1016/j.rser.2015.05.054

Ochoa, C. & van Ackere, A. (2015). Winners and losers of market coupling. *Energy*, *80*, 522–534. doi:10.1016/j.energy.2014.11.088

OECD. (1998). *Netherlands - Regulatory Reform in the Electricity Industry.* Retrieved January 14, 2013, from http://www.oecd.org/regreform/liberalisationandcompetitionint 2497395.pdf

Oggioni, G. & Smeers, Y. (2010). Market coupling and the organization of countertrading: separating energy and transmission again? *Center for Operations Research and Econometrics.*

Oggioni, G. & Smeers, Y. (2013). Market failures of Market Coupling and countertrading in Europe: An illustrative model based discussion. *Energy Economics*, *35*, 74–87. doi:10.1016/j.eneco.2011.11.018

Oggioni, G., Smeers, Y., Allevi, E., & Schaible, S. (2012). A Generalized Nash Equilibrium Model of Market Coupling in the European Power System. *Networks and Spatial Economics*, *12*(4), 503–560. doi:10.1007/s11067-011-9166-7

Okumura, H. & Naito, K. (2004). Weighted kernel estimators in nonparametric binomial regression. *Journal of Nonparametric Statistics*, *16*(1-2), 39–62. doi:10.1080/10485250310001624828

OMIE. (2013). Market Results. Retrieved March 13, 2014, from http://www.omie.es/files/flash/ResultadosMercado.swf

OMIE. (2014). Our electricity markets. Retrieved July 28, 2014, from http://www.omel.es/en/home/markets-and-products/electricity-market/our-electricity-markets

OMIE. (2015). OMIE Operating Rules. Retrieved March 17, 2015, from http://www.omie.es/inicio/normativa-de-mercado/reglas-omie

Oseni, M. O. & Pollitt, M. G. (2016). The promotion of regional integration of electricity markets: Lessons for developing countries. *Energy Policy*, *88*, 628–638. doi:10.1016/j.enpol.2015.09.007

Pagan, A. R. & Ullah, A. (1999). *Nonparametric Econometrics.* Cambridge University Press.

Pardo, A., Meneu, V., & Valor, E. (2002). Temperature and seasonality influences on Spanish electricity load. *Energy Economics*, *24*(1), 55–70. doi:10.1016/S0140-9883(01)00082-2

Park, H., Mjelde, J. W., & Bessler, D. a. (2006). Price dynamics among U.S. electricity spot markets. *Energy Economics*, *28*(1), 81–101. doi:10.1016/j.eneco.2005.09.009

Parsons, B., Ela, E., Holttinen, H., Meibom, P., Orths, A., O'Malley, M., … Smith, J. C. (2008). *Impacts of Large Amounts of Wind Power on Design and Operation of Power Systems; Results of IEA Collaboration* (tech. rep. No. 2). EERE Publication and Product Library. doi:10.2172/1218407

Pellini, E. (2012a). Measuring the impact of market coupling on the Italian electricity market. *Energy Policy*, *48*, 322–333. doi:10.1016/j.enpol.2012.05.029

Pellini, E. (2012b). Wholesale Spot Markets: Still a Way To Go. Retrieved January 31, 2013, from http://www.iaeeconf2012.altervista.org/index.html

Pereira, A. J. C. & Saraiva, J. T. (2013). Long term impact of wind power generation in the Iberian day-ahead electricity market price. *Energy*, *55*, 1159–1171. doi:10.1016/j.energy.2013.04.018

Perez-Arriaga, I. J. & Olmos, L. (2005). A plausible congestion management scheme for the internal electricity market of the European Union. *Utilities Policy*, *13*(2), 117–134. doi:http://dx.doi.org/10.1016/j.jup.2004.12.003

Pesaran, H. & Shin, Y. (1998). Generalized impulse response analysis in linear multivariate models. *Economics Letters*, *58*(1), 17–29. doi:10.1016/S0165-1765(97)00214-0

Phan, S. & Roques, F. (2015). Is the depressive effect of renewables on power prices contagious? A cross border econometric analysis. *CEEM Working Paper 2015-16*, 1–20. Retrieved October 5, 2015, from http://www.econ.cam.ac.uk/research/repec/cam/pdf/cwpe1527.pdf

PHILLIPS, P. C. B. & PERRON, P. (1988). Testing for a unit root in time series regression. *Biometrika*, *75*(2), 335–346. doi:10.1093/biomet/75.2.335

Polgari, B., Raisz, D., & Sores, P. (2014). The Effects of the Day-ahead Czech-Slovak- Hungarian Electricity Market Coupling. *Conference Proceedings, 9th International Conference on Deregulated Electricity Market Issues in South Eastern Europe*, 1–8. doi:10.13140/RG.2.1.1588.4966

Powernext. (2013). Powernext History. Retrieved January 14, 2013, from http://www.powernext.com/%7B%5C#%7Dsk;tp=app;n=page;f=getPage;t=page;fp=system%7B%5C_%7Dname:History;lang=en%7B%5C_%7DUS;m=Powernext%7B%5C_%7DGroup

Racine, J. S. (2007). Nonparametric Econometrics: A Primer. *Foundations and Trends® in Econometrics*, *3*(1), 1–88. doi:10.1561/0800000009

Ragwitz, M., Steinhilber, S., Breitschopf, B., Isi, F., Resch, G., Panzer, C., … Diw, I. (2012). *RE-Shaping: Shaping an effective and efficient European renewable energy market* (tech. rep. No. February). Retrieved October 4, 2013, from http://s3.amazonaws.com/academia.edu.documents/41199493/545667d50cf2bccc490f28c2.pdf20160115-19908-1gfffs.pdf?AWSAccessKeyId=AKIAJ56TQJRTWSMTNPEA&Expires=1469920445&Signature=VYRMELtlJ1VolRg6Ax
3D&response-content-disposition=inline%3B%20filename%3DRE-Shaping_Shaping_an_effective_and_effi.pdf

Red Eléctrica de España. (2012). *El sistema eléctrico español*. Retrieved July 27, 2014, from http://www.ree.es/sites/default/files/informe%7B%5C_%7Danual%7B%5C_%7Dsobre%7B%5C_%7Dla%7B%5C_%7Doperacion%7B%5C_%7Ddel%7B%5C_%7Dsistema%7B%5C_%7Delectrico.pdf

Red Eléctrica de España. (2014). REE web site. Retrieved May 1, 2014, from www.ree.es

Red Eléctrica de España. (2015). Spain-France underground interconnection. Retrieved December 27, 2015, from http://www.ree.es/es/actividades/proyectos-singulares/nueva-interconexion-electrica-con-francia

Redes Energéticas Nacionais. (2012a). Estrutura Accionista. Retrieved March 21, 2012, from http://www.ren.pt/vPT/Investidor/InformacaoaoAccionista/EstruturaAccionista/Pages/InvestidorGrupoRENEstrutura.aspx

Redes Energéticas Nacionais. (2012b). Monthly Statistics SEN. Retrieved May 9, 2012, from http://www.centrodeinformacao.ren.pt/EN/InformacaoExploracao/Pages/EstatisticaMensal.aspx

Redes Energéticas Nacionais. (2012c). REN-2012-grupo-ren_historia.pdf. Retrieved March 21, 2012, from http://www.ren.pt/vPT/Investidor/GrupoREN/Historia/Pages/investidor%7B%5C_%7Dgrupo%7B%5C_%7Dren-historia.aspx

Redes Energéticas Nacionais. (2013). *Caracterização das interligações em 31 de Dezembro de 2012*. Retrieved March 13, 2014, from http://www.centrodeinformacao.ren.pt/PT/publicacoes/CaracterizacaoInterligacoes/Caracteriza%C3%A7%C3%A3o%20das%20Interliga%C3%A7%C3%B5es%20em%2031%20de%20dezembro%20de%202012.pdf

Redes Energéticas Nacionais. (2014). REN web site. Retrieved September 27, 2014, from www.ren.pt

Redes Energéticas Nacionais. (2015). *Capacidades indicativas de interligação para fins comerciais para o ano de 2015.* Retrieved May 8, 2015, from http://www.mercado.ren.pt/PT/Electr/InfoMercado/Interlig/Previsao/BibRelAno/Cap2015.pdf

REN21. (2015). *Renewables 2015.* Retrieved May 25, 2016, from http://www.ren21.net/wp-content/uploads/2015/07/GSR2015%7B%5C_%7DKeyFindings%7B%5C_%7Dlowres.pdf

REN21. (2016). *Renewables 2016.* REN21. Retrieved July 3, 2016, from http://www.ren21.net/wp-content/uploads/2016/06/GSR%7B%5C_%7D2016%7B%5C_%7DFull%7B%5C_%7DReport%7B%5C_%7DREN21.pdf

Rious, V., Usaola, J., Saguan, M., Glachant, J.-M., & Dessante, P. (2008). Assessing available transfer capacity on a realistic European Network: Impact of assumptions on wind power generation. In *2008 first international conference on infrastructure systems and services: Building networks for a brighter future (infra)* (pp. 1–6). IEEE. doi:10.1109/INFRA.2008.5439613

Rivier Abbad, J. (2010). Electricity market participation of wind farms: the success story of the Spanish pragmatism. *Energy Policy*, *38*(7), 3174–3179. doi:10.1016/j.enpol.2009.07.032

Robinson, P. J. (1997). Modeling Utility Load and Temperature Relationships for Use with Long-Lead Forecasts. *Journal of Applied Meteorology*, *36*(5), 591–598. doi:10.1175/1520-0450(1997)036⟨0591:MULATR⟩2.0.CO;2

Roques, F., Hiroux, C., & Saguan, M. (2010). Optimal wind power deployment in Europe—A portfolio approach. *Energy Policy*, *38*(7), 3245–3256. doi:10.1016/j.enpol.2009.07.048

Ruiz Romero, S., Colmenar Santos, A., & Castro Gil, M. A. (2012). EU plans for renewable energy. An application to the Spanish case. *Renewable Energy*, *43*, 322–330. doi:10.1016/j.renene.2011.11.033

Sáenz de Miera, G., del Río González, P., & Vizcaíno, I. (2008). Analysing the impact of renewable electricity support schemes on power prices: The case of wind electricity in Spain. *Energy Policy*, *36*(9), 3345–3359. doi:10.1016/j.enpol.2008.04.022

Sailor, D. J. & Muñoz, J. R. (1997). Sensitivity of electricity and natural gas consumption to climate in the U.S.A. - Methodology and results for eight states. *Energy*, *22*(10), 987–998. doi:10.1016/S0360-5442(97)00034-0

Salic, G. & Rebours, Y. (2011). Impact of German wind generation forecasts on net transfer capacities. In *2011 8th international conference on the european energy market (eem)* (May, pp. 635–640). IEEE. doi:10.1109/EEM.2011.5953089

Santos, P. J., Martins, a. G., & Pires, a. J. (2007). Designing the input vector to ANN-based models for short-term load forecast in electricity distribution systems. *International Journal of Electrical Power and Energy Systems*, *29*(4), 338–347. doi:10.1016/j.ijepes.2006.09.002

Sapio, A. (2015). The Impact of Renewables on Electricity Prices and Congestion in a Regime Switching Model: Evidence from the Italian Grid. (pp. 441–451). doi:10.1007/978-3-319-13881-7_49

Schaber, K., Steinke, F., & Hamacher, T. (2012). Transmission grid extensions for the integration of variable renewable energies in Europe: Who benefits where? *Energy Policy*, *43*, 123–135. doi:10.1016/j.enpol.2011.12.040

Sensfuß, F., Ragwitz, M., & Genoese, M. (2008). The merit-order effect: A detailed analysis of the price effect of renewable electricity generation on spot market prices in Germany. *Energy Policy*, *36*(8), 3076–3084. doi:10.1016/j.enpol.2008.03.035

Sforna, M. (1995). Searching for the electric load-weather temperature function by using the group method of data handling. *Electric Power Systems Research*, *32*(1), 1–9. doi:10.1016/0378-7796(94)00891-7

Silva, P. P. d. (2007). *O sector da energia eléctrica na União Europeia: Evolução e Perspectivas*. Imprensa da Universidade de Coimbra.

Silva, P. P. d. & Cerqueira, P. A. (2017). Assessing the determinants of household electricity prices in the EU: a system-GMM panel data approach. *Renewable and Sustainable Energy Reviews*, *73*, 1131–1137. doi:10.1016/j.rser.2017.02.016

Silva, P. P. d., Moreno, B., & Figueiredo, N. C. (2016). Firm-specific impacts of CO2 prices on the stock market value of the Spanish power industry. *Energy Policy*, *94*, 492–501. doi:10.1016/j.enpol.2016.01.005

Silva, P. P. d., Moreno, B., & Fonseca, A. R. (2015). Towards an auction system in the allocation of EU Emission Rights: its effect on firms' stock market returns. In *Assessment methodologies: Energy, mobility and other real world application* (pp. 33–63). Imprensa da Universidade de Coimbra. doi:10.14195/978-989-26-1039-9_2

Silva, P. P. d. & Soares, I. (2008). EU spot prices and industry structure: assessing electricity market integration. *International Journal of Energy Sector Management*, *2*(3), 340–350. doi:10.1108/17506220810892919

Sims, C. A. (1980). Macroeconomics and reality. *Econometrica*, *48*(1), 1–48. Retrieved from http://www.jstor.org/stable/1912017

Sioshansi, F. P. (2008). *Competitive Electricity Markets*. Elsevier Ltd.

Sisodia, G. S., Soares, I., Ferreira, P., Banerji, S., Van den Poel, D., & Kumar, M. (2015). Does the Use of Solar and Wind Energy Increase Retail Prices in Europe? Evidence from EU-27. *Energy Procedia*, *79*, 506–512. doi:10.1016/j.egypro.2015.11.526

Söder, L., Hofmann, L., Orths, A., Holttinen, H., Wan, Y.-h., & Tuohy, A. (2007). Experience From Wind Integration in Some High Penetration Areas. *IEEE Transactions on Energy Conversion*, *22*(1), 4–12. doi:10.1109/TEC.2006.889604

Suganthi, L. & Samuel, A. a. (2012). Energy models for demand forecasting - A review. *Renewable and Sustainable Energy Reviews*, *16*(2), 1223–1240. doi:10.1016/j.rser.2011.08.014

Taylor, J. W. (2003). Using Weather Ensemble Predictions in Electricity Demand Forecasting Using Weather Ensemble Predictions in Electricity Demand Forecasting. *International Journal of Forecasting*, *19*(0), 57–70.

Tersteegen, B., Schröders, C., Stein, S., & Haubrich, H.-J. (2009). Algorithmic challenges and current problems in market coupling regimes. *European Transactions on Electrical Power*, *19*(4), 532–543. doi:10.1002/etep.354

The R Foundation for Statistical Computing. (2014). R. Retrieved June 30, 2014, from http://www.r-project.org/index.html

Traber, T. & Kemfert, C. (2011). Gone with the wind? — Electricity market prices and incentives to invest in thermal power plants under increasing wind energy supply. *Energy Economics*, *33*(2), 249–256. doi:10.1016/j.eneco.2010.07.002

Tse, Y. K. & Tsui, A. K. C. (2002). A Multivariate Generalized Autoregressive Conditional Heteroscedasticity Model With Time-Varying Correlations. *Journal of Business & Economic Statistics*, *20*(3), 351–362. doi:10.1198/073500102288618496

Turvey, R. (2006). Interconnector economics. *Energy Policy*, *34*(13), 1457–1472. doi:10.1016/j.enpol.2004.11.009

Tusk, D. (2014). Roadmap towards an Energy Union for Europe: Non-paper addressing the EU's energy dependency challenges. Retrieved August 9, 2015, from https://www.msz.gov.pl/resource/34efc44a-3b67-4f5e-b360-ad7c71082604:JCR

UK Climate Projections. (2013). How have Cooling Degree Days (CDD) and Heating Degree Days (HDD) been calculated in UKCP09? - Crown copyright. Retrieved June 10, 2013, from http://ukclimateprojections.defra.gov.uk/22715

van Damme, E. E. C. (2005). Liberalizing the Dutch Electricity Market: 1998-2004. *Energy Journal*, *26*(special), 155–179.

Vasconcelos, J. (2005). Towards the Internal Energy Market: how to bridge a regulatory gap and build a regulatory framework. In *European review of energy markets* (Vol. 1, *1*, pp. 81–103). European Energy Institute. Retrieved from http://www.eeinstitute.org/european-review-of-energy-market/EREM1Vasconcelos.pdf

Verbruggen, A. & Vanderstappen, E. (1999). Electricity sector restructuring in Belgium during the 90's. *Utilities Policy*, *8*(3), 159–171. doi:10.1016/S0957-1787(99)00017-X

von Hirschhausen, C. (2014). The German " Energiewende "— An Introduction. *Economics of Energy & Environmental Policy*, *3*(2), 1–12. doi:10.5547/2160-5890.3.2.chir

Waniek, D., Rehtanz, C., & Handschin, E. (2009). Analysis of market coupling based on a combined network and market model. In *2009 ieee bucharest powertech* (pp. 1–6). IEEE. doi:10.1109/PTC.2009.5282231

Weather Wunderground. (2015). Weather Underground. Retrieved 2015, from www.wunderground.com

Weber, A., Graeber, D., & Semmig, A. (2010). Market Coupling and the CWE Project. *Zeitschrift für Energiewirtschaft*, *34*(4), 303–309. doi:10.1007/s12398-010-0033-x

Weigt, H. (2009). Germany's wind energy: The potential for fossil capacity replacement and cost saving. *Applied Energy*, *86*(10), 1857–1863. doi:10.1016/j.apenergy.2008.11.031

Weron, R. & Misiorek, A. (2008). Forecasting spot electricity prices: A comparison of parametric and semiparametric time series models. *International Journal of Forecasting*, *24*(4), 744–763. doi:10.1016/j.ijforecast.2008.08.004

Wiseman, J., Edwards, T., & Luckins, K. (2013). Post carbon pathways: A meta-analysis of 18 large-scale post carbon economy transition strategies. *Environmental Innovation and Societal Transitions*, *8*, 76–93. doi:10.1016/j.eist.2013.04.001

Woo, C., Zarnikau, J., Moore, J., & Horowitz, I. (2011). Wind generation and zonal-market price divergence: Evidence from Texas. *Energy Policy*, *39*(7), 3928–3938. doi:10.1016/j.enpol.2010.11.046

Wooldridge, J. M. [Jeffrey M.]. (2003). *Introductory Econometrics - A modern approach* (2nd ed.). Thomson South-Western.

Wooldridge, J. (2010). *Econometric analysis of cross section and panel data* (2nd ed.). MIT Press. Retrieved from https://mitpress.mit.edu/books/econometric-analysis-cross-section-and-panel-data

World Commission on Environment and Development. (1987). *Our common future*. Oxford University Press.

World Nuclear Association. (2015a). Nuclear Energy in Denmark. Retrieved March 6, 2015, from http://www.world-nuclear.org/info/Country-Profiles/Countries-A-F/Denmark/

World Nuclear Association. (2015b). Nuclear Energy in Germany. Retrieved April 6, 2015, from http://www.world-nuclear.org/info/Country-Profiles/Countries-G-N/Germany/

World Nuclear Association. (2015c). Nuclear Power in Spain. Retrieved March 23, 2015, from http://www.world-nuclear.org/info/Country-Profiles/Countries-O-S/Spain/

Worthington, A., Kay-Spratley, A., & Higgs, H. (2005). Transmission of prices and price volatility in Australian electricity spot markets: a multivariate GARCH analysis. *Energy Economics*, *27*(2), 337–350. doi:10.1016/j.eneco.2003.11.002

Würzburg, K., Labandeira, X., & Linares, P. (2013). Renewable generation and electricity prices: Taking stock and new evidence for Germany and Austria. *Energy Economics*, *40*(0), S159–S171. doi:10.1016/j.eneco.2013.09.011

Zachmann, G. (2008). Electricity wholesale market prices in Europe: Convergence? *Energy Economics*, *30*(4), 1659–1671. doi:10.1016/j.eneco.2007.07.002

Zachmann, G. (2013). A stochastic fuel switching model for electricity prices. *Energy Economics*, *35*, 5–13. doi:10.1016/j.eneco.2012.06.019

Zeileis, A., Koenker, R., & Doebler, P. (2013). Generalized Linear Models Extended. The Comprehensive R Archive Network. Retrieved from https://cran.r-project.org/web/packages/glmx/index.html

Ziel, F., Steinert, R., & Husmann, S. (2015). Efficient modeling and forecasting of electricity spot prices. *Energy Economics*, *47*, 98–111. doi:10.1016/j.eneco.2014.10.012