Convergence of day-ahead and future prices in the context of European power market coupling:

Historical analysis of spot and futures electricity prices in Germany, Austria, France, Netherlands and Belgium.

Conclusions: What market hedging use for a Manager / consumer of electricity?

Ludovic AUTRAN – Master thesis in KTH – 2011
Electric Power Systems & INDAR Energy
Abstract

Since November 2010, the French, Belgian, German and Dutch electricity markets are sharing a common mechanism for Day Ahead price formation called “Market Coupling”. This implicit auctioning system for cross border flows management is part of a regional market integration policy which constitutes an intermediary step toward fully integrated European markets. Within a few years, power markets had evolved a lot, and faced many changes (completion of the deregulation process, renewable integration, …). They were also indirectly affected by the consequences of the Japanese nuclear catastrophe in 2011.

In this context, it is interesting to take a stock on the convergence process between these four countries, less than a year after the coupling was launched. Studying the convergence and its evolution for both spot and futures prices can give precious information in order to implement hedging strategies. In this thesis, we explore the dynamics of the convergence process through two main analyses: a Kalman filter and a more original approach based on Mean Reversion Jump Diffusion parameters estimation. We also describe and explore the convergence process under the light of market organisation, production portfolios and consumption profiles to highlight similarities but also divergences.

Despite a European framework suitable for convergence, we observe major differences in energy mixes, consumption profiles and renewable integration rates. However, prices are showing significant convergence patterns through the years. Indeed, we observed that the relation between prices was getting steadier and that the price spread was narrowing. Besides, we also noticed that such a convergence process was not constant but rather stepwise and could be affected by peculiar events.

France, Belgium, Netherlands and Germany’s electricity markets are already well integrated and seem to converge further but sudden changes can appear. This is why a hedging strategy between these countries is feasible but implies some risks.
Acknowledgments

I would like to express my gratitude to my supervisor, M. Mohammad Reza Hesamzadeh who helped me all along this work and provided me with useful advice. I would also like to thank my examiner L. Söder who accepted this master thesis and helped me define my topic. He was also the teacher who introduced me to the electricity market area.

A very special thanks goes to S. Lescoat, my supervisor at Indar Energy, without whom this thesis would not have been possible. He supported me during this hard work and shared a precious knowledge on energy markets and financial aspects that is hardly available in literature.

Last but not least, I would like to thank the other members of Indar Energy, Y. Kochanska, D. Pose, and D. Jessula who trusted me and gave me the opportunity to develop a concrete culture of energy markets. They offered me their support and their experience not only around my thesis’ topic but also on many other subjects.
Nomenclature

TLC: Trilateral Market Coupling
CWE: Central Western Europe
ACER: Agency for the Cooperation of Energy Regulators, European supra regulator
ENTSO-E: European Network Transmissions System Operators for Electricity
ATC: Available Transmission Capacity
MC: Market Coupling
TSO: Transmission System Operator
NEC: Net Export Curve
EuroPEX: Association of European Power Exchanges
PNX: PowerNext, the French power exchange (now EPEX Spot France for spot market and EEX French power derivatives for futures)
EEX: the German power exchange
APX(-ENDEX): the Dutch power exchange
BLX: Belpex, the Belgian power exchange
NBV: Net Block Volume
COSMOS: new market coupling algorithm
ERGEG: European Regulator Group for Electricity and Gas, dissolved when ACER was created.
RTE: Réseau de Transport de l'Electricité, the French TSO
EdF : Electricité de France, the french historical monopolistic company.
RWE , EnBW : german suppliers
Elia : Belgian TSO
TenneT: the Dutch TSO
OTC: Over The Counter, bilateral trading
CRE: the French regulator
CREG: the Belgian regulator
Bundesnetzagentur: the German regulator
CCGT: Combined Cycle Gas Turbine plant
OCGT: Open Cycle Gas Turbine plant
EPR: European Pressurized Reactor, third generation nuclear reactor.
Summary

Introduction .......................................................................................................................................................... 8

1. The CWE market: ........................................................................................................................................ 10
   1.1 What is the Market Coupling: General presentation ................................................................. 10
   1.1.1 Toward a European Unified Market .............................................................................. 10
   1.1.2 Market Coupling Mechanisms: .................................................................................. 12
   1.2 European regulation context: ............................................................................................... 16
      1.2.1 The three Energy packages, achieving the liberalization ....................................... 16
      1.2.2 EU 20-20-20: An ambitious environmental challenge ........................................ 20
   1.3 Markets overview: ....................................................................................................................... 24
      1.3.1 Market profiles ............................................................................................................... 24
      1.3.2 Production portfolios: ................................................................................................... 29
      1.3.3 Consumption profiles and seasonality ........................................................................... 39
      1.3.4 Cross-border transmission: general and seasonal trends in electric flows among MC countries ............................................................................................................................ 42
      1.3.5 Prices .............................................................................................................................. 44
   1.4 First results on the MC, general trends: ....................................................................................... 47
      1.4.1 Cross border capacity allocation and congestions: ................................................... 47
      1.4.2 Convergence statistics: .................................................................................................. 49
   1.5 Conclusion ......................................................................................................................................... 50

2. Three different analysis of electricity market integration ................................................................. 53
   2.1 Convergence of Electricity Wholesale Prices in Europe? A Kalman Filter approach, G. Zachmann, 2005 ........................................................................................................................................ 53
   2.2 The role of power exchanges for the creation of a single European electricity market: market design and market regulation, Boisseleau, 2005: ................................................................................................. 59
   2.3 Multiscale Analysis of European Electricity Markets, Carlos Pinho and Mara Madaleno, 2011 .................................................................................................................................................... 61
   2.4 Conclusion ........................................................................................................................................ 62

3. Econometric analysis of convergence ........................................................................................................ 63
   3.1 Preliminary analysis: ..................................................................................................................... 63
      3.1.1 Correlation analysis: ........................................................................................................... 67
      3.1.2 Time series: ......................................................................................................................... 68
3.1.3 Non stationarity ........................................................................................................... 69
3.1.4 Volatility: ..................................................................................................................... 71
3.2 Kalman filter analysis: .................................................................................................... 72
3.3 A second approach: estimation of Mean Reverting Jump Diffusion Parameters: ....... 80

4 What can we conclude for a manager who needs to hedge his electricity portfolio?
..................................................................................................................................................98

References: ..................................................................................................................................103

ANNEX: ........................................................................................................................................107

A- The Kalman Filter......................................................................................................................107
B- Itô’s Lemma: ............................................................................................................................109
Introduction

After the deregulation of electricity markets that was launched all over Europe in the past decade, the creation of regional market couplings integrating electricity markets from different areas, is the next step toward a single and unified European market. The biggest coupling created so far is the recently extended TLC (Tri Lateral Coupling) that includes the French, German-Austrian, Dutch, and Belgian power markets in the CWE area. Such a mechanism is supposed to ensure a higher level of supply security, to optimize the cross border transmissions supported by the implicit auctioning process for the allocations of transmission capacities, and also improve the markets liquidity (perhaps more for the French, Belgian and Dutch market where liquidity remains lower than in Germany). Market coupling should also tend to lower price differences between the involved countries and even, when there is no congestion on transmission lines, obtain identical day-ahead prices. Although day-ahead prices show signs of convergence, they are subject to major geo-political decisions and big differences in energy mix and consumption characteristics of the 4 countries.

Obviously electricity is not a common commodity, the storage impossibility implies a very unclear relationship between spot and futures prices by suppressing any arbitrage options. Moreover, estimating long term prices by considering current spot is a rather complicated, if not unrealistic task, especially when one observes the growing share of renewable and consequently unpredictable production portfolios. As a result, short and long term market must be considered as two separate markets, the first one being mostly influenced by momentary variations of numerous variables such as temperature, plants production availability, demand, while the second one reflects actors’ vision of tomorrow’s market considering possible evolutions of energy mix, geopolitical changes, network improvements, behaviour of related commodities. In that context, it seems interesting to study the evolution of the price convergence in order to assess the market integration.

This thesis is thus aimed at analysing the phenomenon of convergence through spot and futures historical data. The goal is to show that this process is evolving through the time, that structural relationships between prices are not constant and can be subject to external events. This question concerns market players in order to implement hedging strategies: steady relations and stable convergence process allows for international hedging approaches while unstable
situations can lead to local hedging strategies. It will highlight the big trends that were showed before and after the coupling for spot but also for futures in France, Germany, Belgium and Netherlands in a context of massive changes in energy policies and significant integration of renewable energy production units as well as pointing out the key points that could jeopardize further development in price convergence and markets integration.

My study will be divided into three parts. In the first part, I will explain the market coupling mechanisms. I will then present the regulatory context encompassing the topic and which will be the guiding thread for future market development. This part will also show an overview of the four markets. In this section, convergence is not considered in term of prices but in term of legislation, production portfolios, renewable integration and consumption which turn to be the major drivers for price convergence but could also be factors of divergence. Then, data collected between November the 22nd 2006 until September 1st 2011 will be analysed to highlight the general trends for transmission flows and prices. The second part is a literature review presenting three papers dealing with the analysis of price convergence, and electricity market integration through different approaches. The third part is constituted in a more detailed analysis of the convergence phenomenon on spot and future prices in order to show that such a phenomenon is highly related to external factors and important changes and to obtain a dynamic evolution of the convergence process through a Kalman filter and through a more original method of dynamic jump diffusion parameters estimations. The final part will be the conclusion. An electricity consumer has to decide whether he should hedge on a common basis (i.e. considering a single reference contract independent of the geographical location) or take into account the difference between contracts when choosing a hedging strategy.
1. The CWE market:

In this section, we will present the Central West European electricity market, its surrounding framework, and its characteristics. First of all, we will present the market coupling, and then explain the European framework behind this coupling. This general presentation may seem far from price convergence analysis but it is actually really important to understand the targets that have to be achieved for European energy policy because it directly or indirectly impacts the nations’ policies, production portfolio development, market organisation and therefore the price differences. Then the four countries will be presented in detail to show the common characteristics and differences.

Convergence is not only a matter of prices but also a question of legislation, market structure, consumption and production capacities. Creating a real single market needs coherent implementations of the European legislations, common market structures, consumption behaviours, and complementary production portfolios. This is why we investigate in this part the convergence under the light of these aforementioned factors.

1.1 What is the Market Coupling: General presentation

1.1.1 Toward a European Unified Market

Cooperation in energy management is one of the biggest EU challenges. The Third Energy Package strives toward energy security, efficiency, and competitiveness. The European Commission wants to achieve the liberalization of power markets while fighting against climate change which is one of the top priorities of the new European policy.

Such cooperation should eventually lead to the construction of a unique and efficient European Market for electricity. The second step of this common policy (after having launched the deregulation process) is the creation of regional markets (7 regions over the EU see figure 1.7) in order to work toward the unification. Cooperation is one of the requests of the EC’s Third Package along with more independency of transmission system operators, the enhancement of regulating bodies, and the creation of a European regulating entity: ACER, (Agency for the Cooperation of Energy Regulators). Thus, the newly created ENTSO-E (European of Network Transmissions System Operators for Electricity) illustrates the will to increase harmonization among members. Market Coupling is the mechanism developed by France, Belgium and The
Netherlands (that is to say by their respective Power Exchanges and TSO’s) to implement the regional market on the 21\textsuperscript{st} November 2006. This so called TLC was extended later on (November 9\textsuperscript{th} 2010) by integrating Germany and Austria and thus creating the regional CWE market coupling.

This is a congestion management method that allows a better allocation of cross border transmissions inspired from the Scandinavian model of market splitting used on Nordpool. The MC replaces the old day-ahead explicit auctioning mechanism used to allocate day-ahead transmission capacities by an implicit process. The former mechanism was completely dissociated from the bidding process on the Power exchange while with MC, transmission capacity and energy are bought simultaneously. In the Nordpool system, Denmark, Sweden, Finland and Norway share a common market place divided in interconnected price areas where transactions are independent from the location as long as there is no congestion on the cross border lines. If congestion appears, the system is divided into several price areas. In the MC process, each country establishes its own supply and demand curve while the TSO determinates the ATC (Available Transmission Capacity) for the next day and put it at the disposal of the markets. From the orders, Net Export Curves, stating the evolution of the equilibrium price in function of imports and exports, are established. NEC’s are then coupled to calculate new equilibrium prices optimizing the use of cross border transmission capacities.

According to EuroPEX (the Association of European Power Exchanges), “market coupling can help to remove the unnecessary risks of trading short-term capacity and energy separately, encourage liquid, robust spot markets and allow all spot market participants to benefit from cross-border access” [1]. It is also supposed to reduce the price volatility and to make an optimal use of transmission capacities. Theoretically, when no congestions are observed, prices should be the same on both sides of the border. The difference between countries should be lowered, as more transmission equipments are built thanks to the so-called congestion rent perceived by TSO’s during times of fully used transmissions (and which is formed by the price difference observed among countries).
1.1.2 Market Coupling Mechanisms:

As explained earlier, the coupled power exchanges use a common algorithm that matches the different NECs in order to find an equilibrium price optimizing the cross border capacities. The Net export Curve is the net position of a market as a function of the equilibrium price. It is calculated for each hour by the difference between Divisible Hourly Bids and Divisible Hourly Offers for each price level. Accepted block orders are considered as price inelastic Divisible Hourly Orders. The following example illustrates the construction of a NEC for a given hour and a given offer-demand curve on the French power exchange PowerNext\(^2\) (where bids are defined by points representing a price/quantity couple):

![Figure 1.1: Linear NEC construction (PowerNext)](image)

see, for each price level the net position (import or export) is calculated by the difference between the demand and offer curves. Since bids are defined by a couple price/quantity, the NEC obtained is linear. The price level corresponding to the net position zero is the price formed for an isolated market.

For a power exchange where bids are defined by range of price/quantity as in APX (Netherlands) or Belpex (Belgium), the NEC is stepwise. Thus for a given price level on the NEC, a range of acceptable prices is possible. The traded volume on the market is then maximised up to the quantity \(Q^* = q2 - q1\).

---

1 This section provides explanations for the mechanism extracted from literature written prior to the extension with Germany ie the TLC algorithm.

2 The French and German Spot Exchange EPEX SPOT (joint venture of POWERNEXT and EEX) is also linearly interpolated.
The problem of block orders is solved by constructing a series of NEC considering each possible combination of accepted block orders (called Winning subsets) and rejected block orders. First a block-free NEC is built excluding block orders. Every set of NEC including each Winning subsets is then derived from this curve by translation called NBV (Net Block Volume which is the difference between accepted block bids and offers).

![Figure 1.2: Stepwise NEC construction (APX-Belpex)](image1.png)

The coupling algorithm takes as input:

- the Available Transfer Capacity given for each area, hours and direction by the different TSOs
- the block free NEC for each market, and time period
- the block orders for each market

Then, for each hour and each market, the price, the net position and the accepted block orders are determined by the algorithm following an iterative mechanism:

![Figure 1.3: A NEC obtained from the shifted block free NEC (for a given Winning Set resulting in a certain NBV)](image2.png)
Stage i:
- The coordination module, using for each market, the NEC shifted with a given NBV calculated by the block selector during stage (i-1), generates a price and a net position for each market (corresponding to a single point on the NEC).

- The block selectors then selects a Winning set of block orders for each market according to the price previously calculated and generates a NBV.

The mechanism stops when a stable solution is found, that is to say when the price at stage $P(i)=P(i-1)$. The coordination module gives the final prices and net positions for each market.

To generate a price from 3 NEC curves, the coordination module use the following mechanism:

The 3 markets are sorted by isolated prices (prices formed prior to the coupling): the low price market M1, the medium M2 and the third M3. M1 will export to M3 until one of these market is isolated (ATC is not sufficient) or reaches $P2$ (isolated price of M2). In this last case M1 (or M3) and M2 merge to create one market with a single aggregated NEC and the situation is then identical to a coupling between 2 markets.
NEC from the exporting market is reversed, equilibrium price and volume are given at the intersection if the exchanged quantity is not exceeding the ATC (non congested situation). In a congested situation, the exchanged volume is the ATC and the prices for each area can be read on the respective NECs.

Numerous situations are possible, from the creation of a single price area without any congestion between the 3 markets, to 3 isolated markets with different prices and congested transmissions. For instance, French and Belgian prices can converge while the Dutch market is isolated. As we can see, the NEC can be stepwise. As a result the system needs rules to select a volume and a price from a range of possible outcome. These rules will not be described here since this section is only aimed at understanding the main principles behind the market coupling.

Precisions on the new CWE algorithm:
Since the creation of the CWE market coupling (ie the extended TLC), the mechanisms rely on the algorithm COSMOS\(^3\) that outputs the net export positions, prices and executed orders for each market for each hour. It is a mixed integer quadratic program (MILP) in order to deal with the fill and kill constraints (ie: block orders are either totally accepted or totally rejected). It is a branch and bound algorithm taking as an objective function the total market value generated by executed orders that can deal with both ATC Based constraints and Flow Based constraints.

\(^3\) For more detail on COSMOS see: [3]
1.2 European regulation context:

1.2.1 The three Energy packages, achieving the liberalization

The European Energy packages have been conceived to achieve one main goal: creating a single European energy market for gas and power that would increase competition among European producers, economic efficiency and enhance supply security thanks to the extended network.

The Directive 96/92/EC [5] describes the electrical part of the first energy package. It “establishes common rules for the generation, transmission and distribution of electricity”. It is the first step in the reshaping and deregulation of electricity sector by laying down general organizational rules. Its main features are (cf [5],[6] and [7]):

- introducing competition in construction of new plants via two methods: A tendering procedure where a central planning body would define specifications and needed capacities that would have to be met by the winning bidder and an authorization procedure where any plant could be built provided it complies with the standards and criteria specified by law.

- independency of the Transmission System Operator (“at least in the management terms”)

- progressive opening of the electricity markets, for large users and distributors in a process divided into three steps where the national share of consumers equivalent to a community share should access to an open market.

<table>
<thead>
<tr>
<th>Year</th>
<th>1999</th>
<th>2000</th>
<th>2003</th>
</tr>
</thead>
<tbody>
<tr>
<td>EC share</td>
<td>26%</td>
<td>28%</td>
<td>33%</td>
</tr>
<tr>
<td>Equivalent Consumption threshold in the EC</td>
<td>40 GWh/year</td>
<td>20 GWh/year</td>
<td>9 GWh/year</td>
</tr>
</tbody>
</table>

Table 1.1: The progressive opening process under the first EC Directive
- unbundling of accounts in vertically integrated companies (ie separating transmission and distribution from generation and retail businesses in historical monopolistic companies) in order to avoid discriminatory procedures and unfair treatments among generators or retailers.

- ensuring a non-discriminatory access to the network

This Directive was followed by the second energy package [8] which accelerated the liberalisation process of energy markets by adding more specifications:

- authorisation procedures for the construction of new generating capacities was the rule (even if tendering was still available to promote new technologies or ensure sufficient capacities).

- Further market opening in a two step process:

<table>
<thead>
<tr>
<th>Year</th>
<th>2004</th>
<th>2007</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eligible consumers</td>
<td>All non residential consumers</td>
<td>All consumers</td>
</tr>
</tbody>
</table>

Table 1.2: The progressive opening process under the second EC Directive: toward a completely open market

- Enhancement of unbundling requirements with a full legal separation between transmission and distribution activities.

- State members had to create a national regulator and a cooperating body on the European level: the European Regulators Group for Electricity and Gas (ERGEG).

- Promoting international trade and development of interconnection capacities.

The first two Electricity Directives were aimed at introducing and completing liberalisation on a national level for state members. The third energy package marks the cornerstone for integration of electricity market on an international level and more cooperation. This package is constituted by:

- a directive on common rules for internal markets [9] which completes the previous ones

- a regulation on access conditions for cross border exchange
- a regulation establishing the cooperating agency for energy regulators ACER with an advisory role working on cross-border flow and laying the foundations for new network codes.

The main objectives of this last package are:

- improvements in the unbundling principle: implementing a more structural separation between transmission and production/supply activities by three possible options illustrated with the following drawings inspired from [10]:

<table>
<thead>
<tr>
<th>Ownership Unbundling</th>
<th>Independent System Operator</th>
<th>Independent Transmission Operator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production/Supply Companies</td>
<td>Production/Supply Companies</td>
<td>Production/Supply Companies</td>
</tr>
<tr>
<td>Minority shareholding and no control over</td>
<td>Transmission Network owned by vertically integrated companies</td>
<td>Transmission Network owned by vertically integrated companies</td>
</tr>
<tr>
<td>TSO owns and manages the network</td>
<td>Independent system operator (leasing the network)</td>
<td>Independent management and « monitored » operation</td>
</tr>
</tbody>
</table>

Table 1.3: Three possible options for unbundling

- strengthening national regulators’ power and independence
- the TSO should ensure long term ability of the system to meet demand/supply equilibrium considering environmental issues
- increasing cooperation among TSO: creation of ENTSO-E European Network Transmission System Operator for Electricity coordinating the european TSOs.
- Harmonization of technical standards and network codes
- More transparency and protection for final consumers

Figure 1.6: The ENTSO-E members (source ENTSO-E website)
This third package is thus oriented toward two main axes, increasing the level of competition in the internal markets while correcting some market failures, and improving cooperation and harmonization among regulators and transmission system operators, necessary step on the way to the single European market.

The European Commission also supports the regional initiatives that were born from the several fora that gathered national regulating bodies and that are supposed to deal with integration issues on a more direct basis by working on regional cooperation rather than using wide scope European legislation, efficient for harmonisation but unable to fix specific issues such as cross border exchange and congestion management. In 2004, seven electricity regional fora were established to focus on congestion management mechanisms. From these meetings and other discussions, the Regional Initiatives were launched by the ERGEG in spring 2006 as “a natural interim step toward a single European market” [11].

These Initiatives are based on the cooperation between the different stakeholders and are placed under the ruling of regulators. So far, several projects have been successfully carried out such as (cf [12]):

Figure 1.7: The 7 Regional Initiatives, source RTE
- Coordinated capacity calculation in the CWE and CEE areas.
- Regional transparency reports for six regions
- Implementation of cross border mechanisms to exchange balancing offers.
- Projects or implementation of congestion management mechanisms through market coupling for instance in the CWE region
- Creation of single regional auction offices in CWE and CEE regions for transmission capacity allocation.

Since its recent creation, these regional initiatives are placed under the supervision of the European supra-regulator ACER.

**1.2.2 EU 20-20-20 : An ambitious environmental challenge**

The creation of a single market in Europe is not the only goal the European Commission wants to achieve. Preserving the environment and cutting CO2 emissions in order to reduce greenhouse gas effect is also one of the main challenges energy actors will have to face in the next decades. With the European Union “20-20-20” plan, electricity markets will have to implement significant changes and evolve toward a more sustainable system by integrating new generation techniques in order to meet the commission’s objectives. Even if renewable energies are already being implemented on different levels in the different countries, especially within the CWE region, the coming years will see major reshaping of production portfolios. Differences in the strategies and energy policies on national levels could be a key point in the European and even regional market integration process. Therefore, prior studying national characteristics, it is important to introduce the main features of the EU 20-20-20 plan.

The 20-20-20 targets is the catch phrase summarizing the objectives set by the European Union in order to tackle climate change issues while increasing the energy security and keeping a high level of competitiveness.
The EU 20-20-20 targets:

- Reducing greenhouse gas emissions by 20% of its 1990 level.
- Reducing by 20% the consumption of primary energy with higher level of efficiency
- 20% of consumption should come from renewable energy sources.

Table 1.4: The EU 20-20-20 targets

The EU Climate and Energy package, the legislative framework implementing the EU 20-20-20 targets, was issued by the European Commission in January 2008, agreed in December 2008 and applied as a law in June 2009. It consists in:

- a revision of the European Trading Scheme with aiming at reducing by 21% its 2005 number of allowances by 2020, replacing free allocation of allowances by auctioning, expanding the sectors covered by the ETS and setting a single EU wide cap for the number of allowances emissions instead of 27 national allocation caps.
- Setting adapted targets (housing, agriculture, transports …) for the sectors non-covered by the ETS (the overall EU level will be reduced by 10% compare to 2005).
- Increasing the share of renewable energy sources by 20% on a EU average basis in order to cut gas emission and weaken EU’s energy dependency
- Promoting the development of carbon capture and storage technologies

Moreover, the target could also reach 30% of greenhouse gas emission reduction provided that other developed and advanced developing countries agree on comparable reduction plans.
Figure 1.8 shows the share of different energy sources in the primary energy consumption in the 27 member states in 2008. We can observe that oil, natural gas and coal account for the largest shares.

Figure 1.9: Renewable energy shares to the final consumption in 2008 and the Energy and Climate targets (source: EEA)
Figure 1.9 shows the share of renewable energy in the final consumption in 2008 and the EU-2020 targets. We can observe that France is a bit above the German level and has a higher target to reach. The gross final consumption of energy is defined “as energy commodities delivered for energy purposes to final consumers (industry, transport, households, services, agriculture, forestry and fisheries), including the consumption of electricity and heat by the energy branch for electricity and heat production and including losses of electricity and heat in distribution and transmission” [13]. The gross final consumption of energy from renewable sources is defined as the sum of gross final consumption of energy from renewable sources for heating and cooling, in transport and gross final consumption of electricity produced from renewable sources. Hydro and wind production have been normalized over respectively a 15 years and a 4 years weighted average. However, concerning the share of electricity from renewable sources in the gross electricity consumption (fig 1.10), France is behind its German neighbour in 2008. We observe the substantial progress made by Germany: the indicative 2010 target is already reached as for Belgium and The Netherlands. One must also notice that hydro-production accounts for the biggest share of electricity from renewable sources in France. This is relevant because the potential for new hydro plants is not really large. Therefore France will have to massively accelerate the rhythm of integration of other renewable sources to fulfill its objectives. We will discuss these aspects in the next parts.

To conclude with this section, the ambitious European program to reduce gas emissions sets the national objectives and the different levels each country has to reach. It fosters energy efficiency
and renewable integration which are two major factors in the market integration equation. However, different rhythm of progression toward energy efficiency and renewable targets could imply major differences in the demand and generation profiles of each state member.

1.3 Markets overview:

In this section, we will analyse the four electricity markets involved in the market coupling from three points of view: in the first sub-section we will describe the deregulation process in each country, the organization and features of the market, the main players, the second section will focus on production portfolio and renewable integration while the third will describe the consumption profiles. Finally, the last sub-section is dedicated to the transmission network, the cross border exchange and the link between the four countries.

1.3.1 Market profiles

Before the liberalisation of the energy market launched by the EU, the electricity sector in France was organized around a single monopolistic, partially state owned company, called EDF. It was vertically oriented and managed production, transmission and distribution businesses. The deregulation process started in France in 2000 following the first European Directive with 30% of the consumption opened to the market, corresponding to 107 TWh/year, 1300 industrial sites consuming more than 16 GWh/year. In a second step (2003), 37% were open (123 TWh/year) representing 3200 consumers above 7 GWh/year. In 2004, the market was totally open for professional consumers (310 TWh/year for 4.7 million of sites), in compliance with the second European Directive. And finally, in 2007 the liberalisation process was achieved and domestic consumers (27 million of clients) could also choose their supplier. In 2000, the historical producer EDF separates its production/retailing activities from the transmission system operations by founding RTE.

![Figure 1.11: Timeline for the French deregulation process](image-url)
The French power exchange, Powernext, originally owned by several transmission system operators in electricity and gas such as RTE, Elia, TenneT, by producers, banks and other stakeholders was created in June 2001. On November 26th 2001, Powernext Day-Ahead, the French spot market was launched and on June 18th 2004, futures contracts were available on Powernext futures while Powernext intraday market is introduced in July 2007.

On December 31st 2008, Powernext Day-Ahead and Intraday are transferred to the newly created power exchange EPEX Spot SE, a common trading platform based in Paris for France, Germany, Austria and Switzerland while Powernext Futures is transferred to EEX Power Derivatives GmbH based in Leipzig and covering the French and German futures markets. Finally, the clearing activities for spot and term contracts are also put in common through European Commodity Clearing AG.

As we said above, the development of the French organized market is rather recent and even if more and more volumes are traded on this market, it remains marginal compared to the volume traded OTC. Indeed, although the majority of day-ahead transactions are occurring on EPEX Spot as figure 1.13 shows, the main part of the traded volumes is based on term contracts especially monthly, quarterly and yearly contracts that are mostly traded through OTC markets (fig 1.14). Fig 1.13 shows the volumes and transactions on both organized (EPEX Spot) and OTC markets. The yellow curve stands for the volumes traded on EPEX Spot Auction (orders are accumulated in the order book and submit to the price algorithm before being executed) the
red one on EPEX Spot Continuous (orders can be executed as soon as placed in the order book), and the green one on OTC markets. The bars represent the number of transactions.

Figure 1.13: Day-ahead volumes and transactions on OTC markets and EPEX (source CRE)

Figure 1.14: Wholesale volumes of traded contracts (source CRE)

Figure 1.14 shows the traded volume of the different contracts on the wholesale market from 2008 to 2010 (first three bars) and for the first quarter of 2010 and 2011. As we can see, the market shares are relatively stable over the time. The biggest part is constituted by long term contracts. Most of these term contracts are exchanged on OTC markets, the organized market only stands for 6% of the volumes and number of transactions for the first quarter of year 2011 [14] and 14% of the total traded volumes in 2009 (see figure 1.14). However, exchanges on both day-ahead and futures organized markets are increasing from 2010 to 2011 as figure 1.15 shows.

Figure 1.15: Average traded volumes on organized markets (blue: spot and red: futures) (source CRE)
As mentioned earlier, the German power exchange for futures contracts is EEX, based in Leipzig which was born from the merger of the two former German power exchanges in Leipzig (Leipzig Power Exchange) and in Frankfurt (European Energy Exchange) in 2002.

Prior the deregulation process, German energy sector was organised around the coexistence of several public and private companies dividing the country into territorial monopolies, at different levels. For instance, big energy suppliers such as RWE, EnBW where vertical companies intervening on supra-regional areas, some smaller companies acted at regional scale while local energy suppliers and municipalities operated at smaller levels.

The deregulation process started in 1998 with the first Energy Act with an immediate and complete liberalisation for industry and domestic consumers [15] which resulted in many merger and acquisitions among supply companies. The second Energy Act in 2005 created the German Energy regulator Bundesnetzagentur and operated legal unbundling of transmission and production/retailing activities.

![Figure 1.16: Timeline for the German deregulation process](image)

![Figure 1.17: The German organisation for TSO (map: Wikipedia)](image)
As for France (but to a lower extent), most volumes are traded OTC as figure 1.18 shows.

![Figure 1.18: Traded volumes on OTC and organized market in Germany in 2009 (source: Bundesnetzagentur)](image)

On the federal level the Belgian energy regulator (CREG) was created in 2000. The EU directives were transposed into Belgian laws in 1999 and 2005. The market was progressively open following several steps and which were achieved in 2007 with the complete opening of the market. The only federal transmission system operator in Belgium is Elia since 2002. In 2005 the Belgian power exchange Belpex for Day-ahead and intraday electricity trading was created and the first electricity trading was launched on November 20th 2006 when the trilateral coupling started. The Belgian futures market for electricity is traded on APX-ENDEX which is the Dutch power exchange. The Belgian market is thus quite recent and the traded volumes on the power exchange Belpex remains rather low as figure 1.19 indicates.

Before the deregulation process, as in Germany, the Dutch electricity market was organised around centralized large scaled producers and decentralized local producers. In 1998 the Energy act transposed the EU Directive and consumers gradually gained a total freedom for electricity supply (from 2002 to 2004). The Dutch power exchange is APX ENDEX and the transmission system operator is TenneT.

As shown in the four market structures presentation, their creation, their evolution and main features, it is interesting to notice that the European Union’s Energy packages have not been implemented in the same way in each country. It is probably because the initial conditions were all different and also because electricity is a very peculiar commodity needed by anybody.
Its access is essential and may lead to diverging political decisions depending on the point of view adopted. This leads to different progressions along the full competition path with for instance divergence on the concentration levels of the market (France has still a single historical producer owning most of the market share while Germany’s market is divided into four main competitors), differences on the nature of TSO operation (natural monopoly for France, Belgium and Netherlands or 4 territorial monopolies for Germany). Finally, even the volume of transactions on the organized market is significantly different as figure 1.19 shows: France, Belgium and Netherlands’ volumes are rather low as highlighted earlier while the German organized market sees a significant share of its electricity trade operated on EPEX/EEX. On the one hand it is logical to think that market integration should have a positive effect on the liquidity of power exchanges by offering lower levels of concentration on the global CWE market. This should be even more significant for France, Belgium and Netherlands where volatility was low. On the other hand, such differences could also be a factor of failure in further market integration since in itself high concentration represents market failure for the deregulation process as it fails to introduce perfect competition.

![Figure 1.19](image.png)  
**Figure 1.19:** Average transactions on European Organized Markets, first quarter 2011 (source CRE)

### 1.3.2 Production portfolios:

In this section, we will focus on the different production portfolios available in each country. It is essential to understand which technology is the marginal unit and to identify the underlying drivers for the price formations.
France:
The French energy mix is largely dominated by nuclear power. The production portfolio was composed on January 1\textsuperscript{st} 2011 by: nuclear (63.1 GW), fossil fuel fired plants (27.1 GW) biothermal plants (1.2 GW), hydro (25.2 GW) wind turbines (5.8 GW) and photovoltaics (0.9 GW) for a total installed capacity of 123.3 GW.

![Figure 1.20: Installed capacity on January 1\textsuperscript{st} 2011 (data RTE)](image)

Such a big share of nuclear (58 reactors for a power between 900MW and 1500MW) in the portfolio induces that the main part of electricity produced comes from nuclear power plants according to the merit order principle.

![Figure 1.21: Net production in 2010 (data RTE)](image)

As a matter of fact, in 2010 approximately 74\% of the production came from this technology (figure 1.21). Nuclear is the base generating unit but hydropower and thermal plants cover the extra demand because they can be started quickly. Actually, nuclear is scarcely the marginal unit
(cf [17]) and the situation where run-of-the-river power plant, nuclear, wind power and solar power production are sufficient to cover demand and exports only happen at night and week ends. Therefore, thermal units are often the marginal ones. The thermal production park \(^4\) using fossil fuels is divided into two categories as said earlier:

- gas (CCGT) and coal fired power plants that supply electricity during both base and peak periods
- fuel oil and OCGT units that are reserved for peak end extreme peak periods.

![Figure 1.22: The thermal production park (data RTE)](image)

Due to the high seasonality of the French electric demand (as we will see in the next section), the country has to face period of peak and extreme peak that can be covered by:

- Hydropower (lakes and water pumps) for peak and extreme peak with a total power of \(\approx 13.5\) GW
- Gas (CCGT) and coal units during peak (\(\approx 10\) GW)
- Fuel oil and OCGT units for extreme peak periods (\(\approx 7\) GW)

Figure 1.23 illustrates the different sources of supply during winter 2009-2010. We notice that fuel oil (in red) is scarcely used apart from temporary extreme spikes of consumption. The increase in the demand is dealt with by a seasonal increase of nuclear production up to a certain level depending of course on the availability of the power plants. As said earlier, we also observe

\(^4\) Excluding decentralised thermal units: usually small units that are not managed according to the market. Their production is usually bought at a fixed price. It regroups many cogeneration plants or units using by-products as fuel or even small renewable units. They represent 8.3 GW.
that the equilibrium between demand and supply during peak periods is ensured by hydro and thermal (coal and gas) units (blue and yellow areas on the figure).

**Figure 1.23:** Power by production unit types during winter 2009-2010 (source UFE)

On the renewable sources aspect, France has a large share of hydropower plants constituted by run-off-the river units, locks, lakes and pumps. However, in comparison with other countries, wind power and photovoltaic remain marginal.

- Installed capacity for wind power is equal to 5 800 MW on January 1\(^{st}\) 2011. It has produced 9.7TWh in 2010 (1.77% of the total production) with an average capacity factor of 23% and an overall capacity credit value around 20%. Although the level of wind power integrated in the French production mix is far from the leading countries, installed capacity has considerably increased these last years as figure 1.24a shows.

- Electric generation through solar photovoltaic remains marginal in France with a total installed capacity of 900 MW (on December 31\(^{st}\) 2010) with a capacity factor around 14.5%. However the rate of growth since 2010 is high. As figure 1.24b shows, installed capacity jumped from 138 MW to 859MW during the year 2010.

**Figure 1.24a:** Evolution of wind power installed capacity (source RTE)

**Figure 1.24b:** Evolution of photovoltaic installed capacity (source RTE)
Finally, drawing a merit order curve for the French production unit is quite difficult. Indeed, if the low marginal cost units (wind and solar, nuclear, hydropower), and high marginal cost units used for peak (fuel and OCGT) have a rather well defined location on the curve, hierarchy among medium marginal cost units such as coal and CCGT power plants is not clear and varies according to the price of coal and gas. Even in the same technology, marginal cost can be very different from one unit to another because of the age and location. Therefore marginal cost intervals for coal and CCGT plants are largely overlapping.

To put it in a nutshell, the French production portfolio’s main features are:

- A large share of nuclear power. This could possibly evolve in the next decades since equipments are growing older and public opinion on the subject is less and less in favour of this technology (especially when people look at some neighbouring countries). However another nuclear power plant (EPR 1600MW) is in construction,

- A high percentage of hydropower units,

- A lack of real integration of renewable energy sources especially wind power and photovoltaic (but the trend could change in the coming years and some projects are already launched).

As we will see in the next part, the production park has to cope with significant seasonal variations of demand. This is done by using hydro and thermal unit (gas, coal and fuel oil) but also through imports as illustrated later on in this chapter.

**Germany:**

The German electricity production portfolio is characterized by a bigger share of fossil fuel units such as coal and natural gas while nuclear share is less important. The recent events in Fukushima considerably changed the German mix since 8 nuclear power plants out of 17 were disconnected from the grid. The years 2009 and 2010 also saw massive implementation of renewable energy (especially photovoltaic systems).
Figure 1.25 shows the installed generation capacity for 2011 and calculated from the data found on EEX transparency website by adding the generating units with a net nominal output above 100 MW and below 100 MW.

We observe that a major part of the generation capacity comes from fossil fuel units namely coal, lignite and gas which constitute approximately 42% of the total capacity and 65% of the production in 2010 (figure 1.26). One must also notice that the share of nuclear power is rather low (12%) with about 20 GW of capacity. However, since the decision to turn off nuclear plants by 2022, the energy mix has changed a bit: installed nuclear capacity dropped to 12 GW with 8 power plants disconnected.
The German government decided to progressively phase out nuclear power plants as figure 1.27 shows: the installed capacity will decrease in several steps (2011, 2015, 2017, 2019, 2021 and 2022) until it reaches zero. Therefore, the issue arising from this decision is security of supply and replacement of generating units.

![Figure 1.27: Nuclear generation capacity in 2011 in Germany (data: REUTERS)](image)

From figure 1.28 we can also notice the important share of renewable energy mainly wind and solar in the installed capacity. In 2010, they accounted for 8% of the electric production in Germany. And the amount of installed capacity is increasing rapidly thanks to feed-in tariffs as shown in figure 1.28:

![Figure 1.28: Development of installed capacity of installations receiving payment in accordance with the EEG (Renewable Energy Sources Act) (source: Bundesnetzagentur)](image)
To summarize, the German production portfolio is constituted by large shares of thermal units namely gas, coal and lignite which are likely to increase in order to cope with the recent decision concerning nuclear decommissioning. Thanks to an efficient renewable support program, massive integration of solar and wind power has been achieved and will probably continue. However, Germany will have to face the big challenge of replacing nuclear and ensuring a sufficient level of supply security which can partly be realised through new renewable installations but which will also imply a higher dependency on fossil fuels. Meeting the EU-20-20-20 target may also prove harder because of the shift from uranium to carbon emitting sources. Finally, as we will see later on, Germany was a major player in the CWE security of supply during peak periods (especially in winter),

**Belgium:**

The Belgian energy mix (figure 1.29), 18 250 MW in total at the end of 2010 [17] is constituted by approximately one third of nuclear generation, a large share of combined cycle gas turbines (ie gas and steam turbines), and cogeneration units (mainly gas fuelled). Wind and hydropower are the main renewable sources of production in the Belgian energy mix.

![Figure 1.29: Installed generation capacity in Belgium in 2011 (data CREG)](image-url)
And as figure 1.30 shows, nuclear produces around 50% of the total Belgian electricity while fossil fuels (gas and coal) also represent a considerable share of the production. Renewable sources stand for 6.9%. This share is composed by: wind turbines (on and off shore), hydropower, photovoltaics and biomass which remains the largest source of renewable energy with 4.2% of the total Belgian production.

To summarize, similarly to France (although to a lower extent), the Belgian production portfolio mainly relies on nuclear power. The rest of the electricity is supplied by a growing share of renewable and cogeneration while coal and gas (mainly CCGT and OCGT) ensure some flexibility. The Belgian electricity mix will also have to face aging nuclear power plants. According to [17], the progressive phase out should start in 2015 in the existing framework (law to close nuclear power plant after 40 years) and would lead to the end of nuclear electricity generation in 2026. [17] points out that Belgium needs to cope with insufficient generating capacities for the medium term (2012-2015) especially with a lack of flexible generating units (such as gas turbines or CCGT) to balance the expected share of fatal production units (cogeneration or renewable)).
The Netherlands:

The Dutch production mix is not very diversified. Nuclear represents a very small share of the total production because only one reactor is installed in the Netherlands with a generation capacity of 485 MW (another reactor of 1000-1600 MW is planned and construction should start in 2013). The main part of the production is composed by gas followed by coal. Renewable production sources composed in majority by biomass power plants and wind turbines.

![Figure 1.31: Net generating capacity in the Netherlands in 2010 (data ENTSOE-E)](image)

![Figure 1.32: Electricity produced in 2010 in the Netherlands (data IEA)](image)

We saw that the production portfolios in the four countries present some similarities: the general dynamics of introducing more renewable energy sources and the central part played by gas and
coal power plants (that are usually the marginal units). However the rates of integration (thus the shares of renewable and intermittent sources), the importance of nuclear production as well as the generating capacity of hydro power plants are varying from one country to another. These differences are at the origin of the price spreads between these four countries. Trading and market coupling helps obviously to reduce these gaps until transmission capacities are fully used. The coming years will be very important for the development of the CWE market. While the EU 20-20-20 deadline is approaching, massive integration of wind, solar, waste and other clean sources will be undertaken. In addition some countries (Germany and Belgium) will shut down nuclear plants while others (France and Netherlands) will maintain this technology. Therefore price disequilibrium could arise due to period of high or low supply from renewable sources and inadequacy of portfolios.

### 1.3.3 Consumption profiles and seasonality

The CWE market is characterized by two big and two smaller consumers, respectively France, Germany and Belgium, Netherlands. However, they all share common patterns (daily, weekly and seasonal variations). Figure 1.33 shows the annual consumption for Germany, France, Belgium and The Netherlands in 2008, 2009 and 2010 (calculations based on monthly data extracted from the ENTSO-E website).

![Figure 1.33: Annual consumption in the CWE countries from 2009 and 2011 (data ENTSO-E)](image)

First, the daily profiles present all in all the same patterns, a progressive increase in the morning as people wake up and industries start to produce until a maximum around noon. Then a decrease in the afternoon and a second peak between 18h00 and 20h00 with a massive use of electric...
devices when people come back home. At night the consumption decreases and reaches a minimum, when the main demand is due to continuously producing industries. On the French curve, one can notice a small spike between 22h00 and 00h00 that is produced by automatic devices starting at night to benefit from lower prices (boilers, …).

The demand side is also a factor of divergence among the four countries involved in the market coupling. As figure 1.35 shows, both German and French demands are subject to seasonal variations related to weather and temperatures. However, we observe larger variations for France.

Figure 1.34: Average daily consumption profile in 2010 (data ENTSO-E)

Figure 1.35: Monthly French and German consumption between 2000 and 2011 (data ENTSO-E)
than for Germany especially in the last years. One must also notice that the French consumption has increased faster (looking at the dashed trend lines) although climate conditions are highly related to the year to year variations.

The seasonal behaviour is more visible on Figure 1.36 which is a “zoom” on the last three years (2009-2010 and 2011). During the winter, demand is at its highest level because of the temperatures falling down, the need for heating and light. In summer, the demand is very low for the opposite reasons, however during spikes of temperature and heat waves, cooling devices may tend to increase the consumption.

![Figure 1.36: Monthly French and German consumption during 2009 and 2011 (data ENTSO-E)](image)

The French amplitude of consumption is significantly larger than the German variations as the orange and blue dashed lines show. Indeed, between 2009 and 2011, the French maximum of monthly consumptions was approximately 58 000 MWh and its minimum amounted to 33 000 MWh. In the meantime, the German consumption ranged between 40 000 and 52 000 MWh. Therefore France is about twice as more sensitive to seasonality as its neighbour. Such a dependency on the climate conditions can be explained by the important number of electric heating devices installed in France (in opposition with gas heaters).

Belgian and Dutch consumption as any country are also subject to seasonal variations. After having studied more precisely the German and French cases because they constitute the biggest consumers and producers of the CWE region, it is also interesting to draw a final comparison between the four countries by considering the monthly variations (in percentage) from the annual average, in figure 1.37.
France has clearly the most “season-dependent” demand whereas Germany, Belgium and Netherlands show similar level of variations from their respective annual average consumption. As explained in the previous section, part of the peak demand is supplied by the flexible generation units (hydro with reserves, gas turbine, and fuel unit), while the other part comes from cross border exchange. Imports/exports allow minimization of the generation costs, particularly high during peak periods and ensure security of supply in case of insufficient generation. France, for instance, imports an important share of electricity from Germany during peak periods in winter. However, with the recent phasing out of 8 nuclear plants (8 000 MW), the question is to know whether German exports will be sufficient to cover the French demand spikes and how much prices will rise.

1.3.4 Cross-border transmission: general and seasonal trends in electric flows among MC countries

Even before the creation of a market coupling area, the four countries were obviously not isolated and were highly relying on each other to ensure security of supply at the lowest costs.
possible considering the current allocation mechanisms. Indeed, imports/exports among the four countries (as well as with other neighbours) present seasonal pattern.

France, for instance, as we saw earlier on is well supplied during the summer thanks to its high nuclear capacity but experiences high demand and peaks during the winter season. Although France exports more power than it imports, these exchanges dependent on the countries involved (according to their production portfolios) and the season. As a result, for the countries involved in the market coupling and sharing a common border with France, namely Belgium and Germany, we notice that the yearly net contractual exchange is negative (i.e., France imports more power from Germany and Belgium than it solds) as figure 1.38 and figure 1.39 show.

![Figure 1.38: Contractual exchanges between France and its neighbors in 2010 (source RTE)](image)

![Figure 1.39: Contractual exchanges between France and its neighbours in 2010 (source RTE)](image)
However, it is interesting to observe a change in the global pattern of exchanges in March 2011. Indeed, as figure 1.40 shows, March 2011 (corresponding to the month of Fukushima’s event and the German decision to phase out 8 nuclear power plants) saw a significant decrease in the imports. For the next month, we notice a reverse in the usual net exchange: the French balance was positive while it is historically negative.

![Figure 1.40: Net Contractual exchanges between France and Germany in 2010 (source RTE)](image)

1.3.5 Prices

The different production portfolios and the characteristics of consumption profiles are the main reason for the differences observed in electricity prices. France for example produces cheaper electricity in summer thanks to its nuclear production and low demand; however, in winter when demand is higher and there is a need for peak production units, the French prices are higher than the German ones. As a result, price curves also show seasonality:
This is also logically observed in long term contracts, with French summer quarter cheaper and winter quarter more expensive than in Germany. Even if no general conclusion can be drawn, the German calendar contract was more often cheaper than the French one which is logical given the net balance exchange between France and Germany (see figures 1.42). As we notice in figure 1.43, since September 2009, the French contract calendar 2012 (for delivery in 2012) is clearly above the German calendar.

However we also observe a recent change since June 2011 with yearly contracts for electricity delivery in 2012 and 2013 in Germany at higher prices than their French equivalents (see figure 1.44). This has to be put in parallel with sudden cuts in the German nuclear production that could...
lead to higher prices and less exports to France in winter since the country will have to ensure first its own demand with reduced capacity production (and usually lower production from solar panels during this season).

Figure 1.43: The contracts calendar 2012 for the four markets (source EEX ENDEX)

Figure 1.44: price difference between the French and German cal-12 (source EEX)
1.4 First results on the MC, general trends:

1.4.1 Cross border capacity allocation and congestions:

The cross border transmission capacities are allocated through explicit and implicit auctioning process and for different time scales:

- annual (explicit process)
- monthly (explicit process)
- daily (implicit process via market coupling mechanisms)
- intraday (explicit pro-rata and implicit process)

After calculations, a certain amount of yearly/monthly/daily transmission capacity is allocated for auction. Yearly and monthly bought capacities can be resold, and in addition, a use-it or sell-it mechanism is employed that pays for bought capacity that were not nominated (ie used) and which guarantees a better efficiency in the use of transmission lines and more adequacy between flows and price difference.

Figure 1.45: Transmission capacity allocation mechanisms (source RTE)
Although a big part of the cross border transmissions are realised through long term contract, one first basic way of assessing the efficiency of the market coupling is to compare the main direction of power flows with the price differences. Indeed, an optimal use of the capacities and production units would lead to power flowing from the low price area to the high price area. Therefore, we should observe some changes in the flows/price differences graph before and after market coupling was implemented.

*Figure 1.46:* flows and price difference between France and Germany before and after Market coupling (source RTE)
Figure 1.46 shows the flows of energy between France and Germany plotted versus the price difference among the two countries for the 1st hour of the day and the 12th. In the X axis, we can read the net exchange for France (ie Exports-Imports with Germany). The Y axis is the difference French hourly price – German hourly price. The blue series corresponds to the period between January 4th 2010 and November 8th 2010, prior to the market coupling. The red series corresponds to the time period between November 11th 2010 and August 31st 2011 (ie after the implementation of the market coupling). First, we notice that prices tend to be closer, as the majority of the red points are centred around 0€/MWh, which indicates that the coupling is efficient. Secondly, the points corresponding to a price difference non equal to zero are more logically located: there are fewer, if any, incoherent flows. The points are either on (X>0;Y<0) or (X<0;Y>0) areas which indicates that power flows from the low price area to the high price area, and therefore, that market coupling results to a more efficient allocation of transmission capacities.

1.4.2 Convergence statistics:

As we saw, on the level of flow and price coherency, the market coupling has been very efficient. In addition, the gap between prices has narrowed and hourly prices has been more often equal. Indeed between November 2010 and April 2011, the coupling resulted into a single price area (for hourly prices) during 68% of the time in average (ie the percentage of hours of total price convergence averaged 68% on the considered time period) [19]. The percentage of hours of convergence between two countries varies. We observe on figure 1.46 that France and Belgium reached the highest level of convergence during the first six months of the coupling. Germany and the Netherlands also converged during 85%. Therefore we can distinguish 2 blocks: France and Belgium on the one hand, Germany and the Netherlands on the other hand. This can be easily interpreted regarding the geographical position and the nature of the energy mixes. Finally we observe that the average percentage of hourly price convergence between France and Germany is the lowest (68%) despite their direct connection. This seems logical since they constitute the two biggest producing and consuming countries involved in the market coupling.
1.5 Conclusion

The European regulatory framework sets the basis for a real integration and convergence among power markets, on a regional level first and perhaps on a wider scale later. The EU legislation helped to improve homogeneity and competition through common rules concerning deregulation, unbundling, access to the network, cooperation between TSO (with ENTSO-E) and among regulators (with ACER). The Regional Initiatives illustrate this will to increase integration. This resulted into the implementation of the market coupling mechanism in the Central West Europe region. The European Union also helps harmonizing energy policies and production technologies through environmental regulations such as the European Trading Scheme for carbon emission reduction, which influences the choices in the power plant investments and valorises renewable energies.

However, there are still major differences among the four CWE countries as we saw in the market profiles overview. Indeed the political decisions taken to implement the European legislation for market deregulation on national levels were different and led to heterogeneity in
market organization. This is well illustrated by the various timeline for deregulations processes. Therefore divergence points remain strong: the markets liquidity and the traded volumes in France, Belgium and The Netherlands are still low compared to Germany. The market share of historical monopolistic companies is rather different with for instance one major player in France (EdF) against four in Germany. Even natural monopolies organizations (ie: the transmission system operations) are inhomogeneous: EdF is still very close to the French national TSO RTE while Germany is divided into four different area, each of them managed by a TSO independent from the producers.

The differences in national production portfolios are one of the main sources for price inequity. Indeed, France and Belgium are mainly supplied with nuclear power while Germany and The Netherlands produce their electricity with thermal units. This is also why we observe close relationship between France and Belgium on the one hand, Germany and The Netherlands on the other hand. The rhythm of renewable integration in each nation is not similar and therefore we could observe situations with intermittent production confronted to steady nuclear power potentially causing irregularities and price disequilibrium. Consumption profiles are another root of divergence: the French profile shows high seasonality (which is not particularly adapted to a massive share of nuclear production, ), while the other countries are flatter. Therefore imports/exports and usual cross border flows among the CWE are also seasonal (France importing during winter and exporting during summer) that were recently questioned with the German decision to phase out nuclear

All these factors support the idea that convergence is not achieved yet. Diverging elements can even be observed (seasonal variations are increasing in France, production portfolios are getting more and more different with nuclear plant being shut down on one side on the border). However, there are clear evidences for common evolution and close relation of prices. Market Coupling and improvement of auction system for cross border transmission capacities improved economic efficiency by removing incoherent flows directions, which is obviously a big step toward market integration. In addition, the percentage of common hourly prices is rather high which show that the markets are already partially integrated.

Although preliminary observations on prices provided information on the state of the integration process in the CWE markets, it is necessary to study in details the historical prices obtained in order to qualify this evolution: Is there really a convergence process? Is it steady or
step-wise? Can we obtain a dynamic view on this convergence? These questions are obviously important for anyone wishing to act in the CWE markets especially hedger who would like to develop multinational strategies.

To answer them, the next part will present three different techniques used to analyse electricity market integrations and their conclusions.
2. Three different analysis of electricity market integration

In this literature review, we chose to present three different approaches to price convergence in electricity, the first one is based on a Kalman filtering method to estimate unobservable parameters and gives a good view on the dynamics of price convergence. The second paper is a study of the market using correlation and regression analyses. Finally, the last paper, the most recent, uses a wavelet transformation to highlight the temporal co-movements of prices among several European markets.

2.1 Convergence of Electricity Wholesale Prices in Europe ? A Kalman Filter approach, G. Zachmann, 2005

In his paper, Zachmann tests the hypothesis of convergence toward arbitrage freeness and the law of one price using hourly spot prices and cross-border capacity auction results from the Dutch-German and the Danish-German border from 2002 to 2004. He applies a time varying coefficient model based on the law of one price in order to take into account the evolution over the time.

First of all, Zachmann studies interaction between 8 areas (France, Germany, Netherlands, Poland, Czech Republic, East Denmark, West Denmark and Sweden) using Principal Component Analysis to show regional similarities.

Finally, he applies a time varying coefficient model on two borders (Danish-German and Dutch-German) where auctioning results of transmission capacity were available (from 2002 until 2004) in order to test for the convergence of prices according to the law of one price.

Zachmann chooses to focus on hourly prices in order to deal with daily seasonality and to compare, for each hour of the day, the aforementioned countries. He also gets rid of the week end days to remove weekly seasonality. He obtains for each of the 24 hours, a matrix of 8 series of data (for the 8 markets) on 784 weekdays. The data sets are tested under the unit root
hypothesis\(^5\) in order to be able to carry out other statistical techniques requiring stationary signals. He observes through the ADF (Augmented Dickey Fuller) test, that electricity prices in the 8 power exchanges did not show unit root behaviour.

Then a Principal Component Analysis is performed to analyse interactions between the different countries. The goal is to find a “linear combination of the original data matrix explaining the most of the variance”. In other words it consists in finding the vectors \((U_i)\) so that the projection of the data on these directions has a maximal variance. These vectors are actually the eigenvectors of the covariance matrix and the eigenv values associated are empirical variance of the projection on this direction. The first and second directions are thus the eigenv vectors corresponding to the two highest eigenv values.

The PCA performed by Zachmann is quite interesting since it shows 3 distinct groups of markets and thus provides an evidence for the early creation of regional markets as we can observe on the plot:

---

\(^5\) Absence of unit root means that the series of data are stationary which is, according to some authors, a typical statistical feature of electricity. Indeed, its non storability as explained in the introduction induces a certain independency between today and tomorrow’s prices.
data. It provides support for an intermediary step in the creation the European market constituted by geographically close and strongly interconnected countries converging toward each other. When this study was performed (data from 2002 to 2004), auction mechanisms throughout Europe were very different from one country to another. Belgium and France used a first-come first-serve system, while Germany and Netherlands had an explicit auction mechanism and Nordpool the famous implicit auction process that constitutes the main feature of the market splitting. As we know now, the market coupling also relies on an implicit auction mechanism for day-ahead transmission. Since the study of Zachmann focuses on arbitrage freeness and needs to consider the daily auction results (or cost for transmission) in his analyses, it only considers borders where auction results or transmission prices are available, namely the Dutch-German and the Danish-German borders. Zachmann’s hypothesis is that electricity market should also follow the Law of One Price and that electricity prices are converging under the studied period (2002-2004) and that inefficiencies resulting in price differences have been lowered as reforms in the sector were applied. He applies the following model translating arbitrage freeness condition:

\[ P_1(t) + \text{trans}_{1-2}(t) = P_2(t) + \text{trans}_{2-1}(t) \]  

(2.1)

Where:

- \( P_1(t) \) and \( P_2(t) \) are the spot prices in markets 1 and 2 at time t.
- \( \text{trans}_{1-2}(t) \) and \( \text{trans}_{2-1}(t) \) are the transmission cost (resulting from auctions) between countries 1 and 2 of which one of them is set to zero (even if there are positive prices for transmissions in both directions). To model the deviation from this mathematical expression he introduces in the following model:
  - A long term time varying component: \( \alpha(t) \)
  - White noises reflecting short run uncertainties: \( \epsilon(t) \sim N(0, \sigma_\epsilon^2) \) and \( \nu(t) \sim N(0, \sigma_\nu^2) \)

\[ x(t) = \alpha(t) y(t) + \epsilon(t) \]  

(2.2)

\[ \alpha(t) = \alpha(t-1) + \nu(t) \]  

(2.3)

Where \( x(t) = P_1(t) \) and \( y(t) = \text{trans}_{2-1}(t) - \text{trans}_{1-2}(t) \) to suppress the negative correlation between price differences and transmission costs.
The time dependency of $\alpha(t)$ is represented by (2.3). This coefficient is an unobservable variable that is a measure of the evolution of prices toward equality and it will be estimated by using a Kalman filter method, well suited for such situations. As Zachman describes, the general process behind the Kalman filter is to calculate, for each step a prediction, to calculate the difference between the prediction and the realization and to include it in the next step.

Estimating the initial values for the variance of $\alpha_0$, $\epsilon$ and $v$ is also an important issue. Zachmann sets the variance of $\alpha_0$ to $E[\frac{x(t)}{y(t)}]$, the variance of $\epsilon(t)$ to 1 and the variance of $v(t)$ equal to $0.0001$ times the variance of $y(t)-x(t)$. The idea is to differentiate the statistic shocks represented by $\epsilon(t)$ from the convergence process that leads to modify the value of $\alpha(t)$ through $v(t)$. That is why he ensures that $\sigma^2_\epsilon$ is $10\,000$ times bigger than $\sigma^2_v$.

The time dependent parameter $\alpha(t)$ is estimated for each hour of the day using the Kalman Filter algorithm for the Dutch-German and the Danish-German borders. The results for the third and the thirteenth hours are shown in the following graphs:

![Graphs](image)

**Figure 2.2:** Time varying coefficient for the German-Dutch and German Danish borders, hours 3 and 13

The method used by Zachmann is interesting because it clearly shows the evolution of the parameter $\alpha(t)$ through the time. For instance he explains the big deviation found in the graph DKE vs EEX in 2003 (the red circle) by the closure of the Kontek direct current cable.
Zachmann also introduces the notion of proximity and of convergence rate. To do so, he creates an indicator:

\[
\gamma(t) = \begin{cases} 
\alpha(t) & \text{if } \alpha(t) < 1 \\
1 / \alpha(t) & \text{if } \alpha(t) > 1 
\end{cases}
\]  
(2.4)

The underlying idea is to estimate whether the two prices are close (\(\gamma \) near 1) or not (\(\gamma \) near 0).

The slope of the trend line of the \(\gamma(t)\) defines a new indicator \(\theta\) that can be seen as the global convergence rate. If this parameter is significantly positive then it shows that the markets are converging according to the Law of One Price and that arbitrage opportunities are reduced.

The results of this analysis show that there was a convergence (at a 10% level of significance) during 12 hours out of 24 between APX and EEX, during 19 hours between West Denmark and Germany and null between East Denmark and Germany. In addition the highest rate of convergence is found for the West Danish-German border. High spikes for the Dutch market during peak periods can explain absence of significant convergence for 12 remaining hours. Zachmann also finds three explanations for lack of significant convergence between East Denmark and Germany: the fact that the two networks are linked asynchronously, that there was only one cable (Kontek) linking the two area which was subject to unplanned maintenances and finally the differences in the design of transmission auction mechanisms. The following diagrams represent the proximity indices and convergence rate for the studied borders:
Zachmann finally observes that (for the Dutch-German and West Danish-German borders), arbitrage opportunities have decreased over the studied period and that it indicates the adaptation of market players to the new framework defined by reforms and market based congestion management methods. He explains that gradual convergence process has been mainly driven by this adaptation. However he finds evidences that the convergence process is not always a reality (peak periods in Netherlands and the East Danish/German border). Therefore he concludes that despite clear improvements in the cross border trade, a single European electricity market is still far from being implemented. He also points out the requirements to accelerate the convergence process: a higher liquidity, more market players and improved congestion management methods as well as physical reduction of bottlenecks.

Zachmann’s analysis is really interesting because he manages to create a simple model with time dependant coefficient reflecting variability of convergence. This Kalman filter approach, used in many other econometric studies dealing with convergence seems well suited to observe the dynamics of price differentials. He also introduces the notion of proximity and convergence rate as indicators to assess the convergence process over the time. His conclusion clearly shows that creation of regional markets is the following step preceding a single European market. However Zachmann’s study was carried out a long time ago, focused on data from 2002 to 2004 and mainly on the Dutch, German and Danish borders. Many reforms have been engaged, new congestion management methods have been launched (namely implicit auctioning in the CWE Market coupling mechanism) and the recent years (2006-2011) have seen a lot of changes in the European electricity markets. That is why it is interesting to focus on the CWE region in order to
study the second step of the European market implementation: regional couplings. In addition it also seems interesting to consider spot prices on a daily basis (distinguishing peak and base load periods) rather the hourly fixing. Moreover it is important to carry out such an analysis on futures contract that also reflects market players’ adaptation to the coupling mechanisms without all the temporary variations that characterises spot prices.

2.2 The role of power exchanges for the creation of a single European electricity market: market design and market regulation, Boisseleau, 2005:

In the chapter of his thesis relevant with the issues of European markets integration, Boisseleau analyses the weekdays base and peak prices from APX (Netherlands), LPX (Germany), PowerNext (France), UKPX (United Kingdom) Nordpool (the system prices, and three other area prices: West Denmark, Norway-Kristiansand and Sweden), and finally OMEL (Spain) from the year 2002. He uses correlation and regression analysis in order to assess the level of integration among each market. First of all he carries out calculations of the correlation coefficient between two series of prices x and y corresponding to different countries according to the formula:

\[ \rho_{xy} = \frac{Cov(x,y)}{\sigma_x \sigma_y} \]  

Where:
- \(Cov(x,y)\) is the covariance between x and y
- \(\sigma_x\) and \(\sigma_y\) are the standard deviation of respectively x and y.

Such a calculation has to be dealt carefully because the two series can be linked with each other through a lag (one series can move in response to another with a delay) that would not be reflected in the correlation coefficient. On the other hand, a high correlation can appear when both series are influenced by the same external factor, in the case of electricity two different series can present the same seasonality because demands in both countries are also strongly depend on the seasonality. Boisseleau gets partially rid of this issue by suppressing week ends in the series of prices and using base and peak prices.

Despite these flaws, a correlation analysis can give a first idea on the integration level between two markets. The results show that there is a lack of integration on a European level. However, there are evidences for already well integrated regional markets. Obviously, Norway, Sweden
and Denmark are highly correlated. Boisseleau interprets this degree of correlation by the fact that demand and supply shocks have a direct impact on the whole Nordpool system. Another regional market identified by Boisseleau, to a lower extent, is the French and German area where the correlation is good.

The second approach used is more precise and consists in a classical linear regression based on the Ordinary Least Squares between two price series, to estimate the model of locational prices, where the price in one country is equal to the price in the other one plus the transmission fees (as in 2.1). But first, as explained in the previous part, in order to avoid spurious regressions showing false economic relationships among prices, one have to test for the stationary properties of the series with the unit root test. If it appears that the series are stationary, a regression analysis is possible. Otherwise, one needs to perform a cointegration analysis to study the relationship between prices, in order to look for “an equilibrium relationship toward which prices gravitate”.

The series studied by Boisseleau are tested for stationarity with an ADF Test. They appear to be stationary except for Norway and Sweden which showed a unit root at a 5% level. Therefore Boisseleau performs a regression analysis to show the link between prices in the different European countries. From the results he distinguishes three levels of relationships, ordered by R-squared value:

- very high level of integration for Sweden and Norway and a slope of regression close to 1
- significant but imperfect integration between Germany and France and Denmark with Sweden or Norway
- unsignificant R-squared values for other pairs of countries.

Here again his analysis supports the idea that there is no single European Market but some regional integration.

Boisseleau’s analysis gives a good overview on the state of the power markets when the study was carried out. We can notice that, back in 2002, regional integration was already in process. Since then, many improvements have been made to enhanced regional integration such as the
market coupling, the gathering of Powernext and EEX, in the joint venture spot power exchange EPEX. Although this study showed that the regional market (especially France and Germany) were relatively integrated when comparing with a European basis, it is important to “zoom in” and to study more in details the integration in the entire CWE regional market some years after, for a longer period. In addition, convergence or integration process has to be considered as a dynamic process instead of a static phenomenon in order to highlight the underlying issues.

2.3 Multiscale Analysis of European Electricity Markets, Carlos Pinho and Mara Madaleno, 2011

In their paper, C.Pinho and M.Madaleno analyse the comovements between prices obtained in 6 different European markets (the Nordpool countries, France, Germany, Spain, Netherlands, and Austria) using daily power prices from 2000 until 2009 through coherence and phase analysis of wavelet transformations. They performed a study on the time/frequency evolution of prices. They conclude by rejecting the assumption of full market integration but show evidences for regional convergences especially in the CWE area with a high integration for France, Germany, Netherlands and Austria. They also notice changes in the behaviour of price series through time showing that markets are evolving with the implementation of EU measures. They explain the price divergence observed by the limited cross border transmission capacities, the different level of concentration among markets, and the difference in generation mix. In other words, structural differences are still too strong to create a single European market and there is a need for an intermediary step constituted by the development of regional markets (geographically close countries) where co-movements and cointegration were already observable. Another interesting part of their paper brings to light the impact of generation mix differences on the coherences between markets. Indeed they observed that in 2005 data show a lack of coherence among countries and explained that by (among other reasons) the high level of gas prices that year impacting more gas depending countries than countries with high shares of nuclear or hydropower units.

This last paper is interesting because it provides a new approach to dynamic analysis of market integration and convergence: using a wavelet transformation allows visually highlighting the evolution. They also pinpoint several events on the time-scale that supports the idea of external drivers for convergence. It is however a very abstract analysis. A concrete approach seems to us more appropriate to give practical conclusions.
2.4 Conclusion

Although not exhaustive, this overview gives 3 different approaches to deal with market integration and convergence:

- A classical “static” correlation/regression analysis
- A dynamic estimation through Kalman filter
- A more original approach with wavelet transforms.

These papers do not deal with the same period nor the same countries but the generally show that a single European Electricity Market is far from being established and that regional integration is a necessary intermediary step. To a certain extent, such regional integration can already be observed.

However, they do not focus on the CWE markets, especially not in the recent years (2006-2011). Inspired from these studies that are rather representative of what we read on the subject and present good tools for convergence analysis, we investigate the convergence process in this special area from 2006 to 2011 for both spot and future prices. We already saw in the first part evidences of strong market integration and factors weighing against convergence. We will now perform a more detail analysis on prices to highlight the state(s) of this convergence process. We will first study the different series and show the strong link existing between the countries. Then we will use two different methods to catch the dynamics of this convergence:

- A Kalman filter approach
- A more original method, using a Mean Reversion Jump Diffusion model for spot electricity prices.
3. Econometric analysis of convergence:

3.1 Preliminary analysis:

We saw in the first part that the four countries share some common characteristics and are evolving in the same direction after the deregulation process that took place some years ago. Moreover, the implementation of market coupling first between Belgium, France and the Netherlands and later on extended to Germany supports the convergence of prices. However, there are still major differences among the four members of this coupling as we explained in the first part, and all the decisions taken, or development undertaken are not always necessarily strengthening this movement. That is why it is interesting to consider the temporal evolution of prices (spot as well as futures since they provide different information). However, distinguishing clear pattern in the spot price difference is not easy as figure 3.1 shows:

![Figure 3.1: Difference between maximum and minimum day ahead base price](image)

Figure 3.2 represent the moving average of the difference between maximum and minimum day-ahead base prices of the four countries. It shows the evolution of the maximum spread (on a 365 day moving average) from 2008 to the beginning of September 2011. The 365 day moving average tends to smooth the curve and to reduce the effect of the momentary price spikes. However in order to get a clearer vision of the process, one spike was removed (on the
19/10/2009, the day-ahead base price on the French power exchange PNX reached 612.77€/MWh).

Different movements seem to appear on the graph: periods of fast convergence when the spread is decreasing, equilibrium or slow convergence when the spread seems to reach a certain level, and even period of “gap widening” when the difference is increasing. Two important dates are placed on the figure:

-9/11/10: the launching of the CWE market coupling
-11/03/2011: the Fukushima event.

We must be very cautious concerning the interpretation of the consequences such events had on the convergence. However they are close to what appears to be changes in the graph and are obviously impacting the CWE countries. This is why it seems appropriate to formulate the hypothesis of a stepwise convergence process and to try to draw its evolution through the time.

Figure 3.2: Moving average of the spread between the maximum and minimum prices

Figure 3.3 also provides support for this hypothesis. It represents the 365 Day moving average of the Day-Ahead prices of France (PNX), Germany (EEX), the Netherlands (APX) and Belgium (BLX). Ignoring the general movement of the four curves, we only consider the distance between
each other. First, we must notice that the three TLC countries: France, Belgium and the Netherlands are moving together while EEX remains below them. But as the maximum spread between the four curves seems to reduce, the trend is changing and France is moving away whereas the Belgian and Dutch curves are getting closer to the German prices. Then the maximum spread still caused by France and Germany undergoes a widening period to diminish again at the end of 2010. The very last months show a widening of the spread as Germany is moving up to higher prices.

The evolution of convergence can also be seen through futures contracts. Since the link between spot and long term contract is not direct, futures contracts can be perceived as the vision of market players for the coming years. As such, the difference between prices for future delivery in the four countries should be really impacted by major events that could jeopardize the convergence (like Fukushima) or help closing the price gap (market coupling …). As we can see on figure 3.4, the maximum difference between the four countries evolved a lot through the time. The year 2009 was a rather steady period, followed by strong variations for the year 2010. The first half of the 2011 was marked by the nuclear catastrophe and all its consequences on the

Figure 3.3: 365 day moving average of day-ahead prices

The evolution of convergence can also be seen through futures contracts. Since the link between spot and long term contract is not direct, futures contracts can be perceived as the vision of market players for the coming years. As such, the difference between prices for future delivery in the four countries should be really impacted by major events that could jeopardize the convergence (like Fukushima) or help closing the price gap (market coupling …). As we can see on figure 3.4, the maximum difference between the four countries evolved a lot through the time. The year 2009 was a rather steady period, followed by strong variations for the year 2010. The first half of the 2011 was marked by the nuclear catastrophe and all its consequences on the
German nuclear portfolio which triggered a change in the sign of the difference France-Germany as said earlier. Futures with other maturity show some variations similar to the calendar 2012. See for instance figure 3.5 for the calendar 2013.

The different figures presented so far seem to indicate that the gap between the four prices, on both day-ahead and future markets is evolving through the time. Some peculiar events have been
pinpointed and although their consequences on the curve are not clearly defined, they provide support for a time-depending convergence process. That is the reason why a Kalman filter approach and a dynamic estimation of a Mean Reversion Jump Diffusion model have been chosen to perform the analysis of the convergence phenomenon: it will give a time varying perspective on the studied phenomenon.

3.1.1 Correlation analysis:

As explained on the first part, it seems that two groups can be distinguished within the CWE coupling: France-Belgium on the one hand, Germany-Netherlands on the other hand, according to the percentage of common hourly prices. In order to check these first observations, the correlation coefficients have been calculated as the Pearson’s product-moment:

\[ r = \frac{\sigma_{xy}}{\sigma_x \sigma_y} \]  

(3.1)

\[ r = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^{n} (y_i - \bar{y})^2}} \]  

(3.2)

Table 3.1 show the values of the correlation coefficients calculated with Matlab for the period January 1\textsuperscript{st} 2010 to the September 7\textsuperscript{Th} 2011, and the p-values for testing the hypothesis of no correlation. If the p-value is less than 0.05 the correlation is significant (at a 5% level).

The coefficients confirm the strong link between the German and Dutch prices as well as between France and Belgium (with respective correlation coefficients 0.936 and 0.8312). On the long term markets, the correlations seem to be (logically) stronger since all the coefficients are above 0.9.

<table>
<thead>
<tr>
<th></th>
<th>APX</th>
<th>EEX</th>
<th>PNX</th>
<th>BLX</th>
</tr>
</thead>
<tbody>
<tr>
<td>APX</td>
<td>0.9360</td>
<td>0.7676</td>
<td>0.7733</td>
<td>0.8312</td>
</tr>
<tr>
<td>EEX</td>
<td>0.7373</td>
<td>0.7027</td>
<td>0.8312</td>
<td></td>
</tr>
<tr>
<td>PNX</td>
<td>0.7733</td>
<td>0.7027</td>
<td>0.8312</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.1: correlation coefficient for day-ahead time series (January 2010-September 2011)
3.1.2 Time series:

The data studied on the next parts of this analysis are:

- The week days Day-Ahead base prices from November 21\textsuperscript{th} 2006 to September 7\textsuperscript{th} 2011 for Germany, France, the Netherlands and Belgium from EPEX France and Germany, APX NL and Belpex, the week end have been put aside in order to avoid a problem of weekly seasonality as Zachman and Boisseleau did in their thesis.

- The data from the contract calendar 2012 from EEX, EPD and APX-ENDEX from January 4\textsuperscript{th} 2010 until September 09\textsuperscript{th} 2011.

Figure 3.6 presents the time series distribution for the spot data:

We can notice that the German price distribution presents one negative bar which corresponds to negative prices obtained in peculiar situation with high renewable subsidized energy production. These four charts also highlight the singularity of electricity: as we can see on the graphs (even
without test), the distributions are non Gaussian, with a high standard deviation. They also show positive skewness\(^6\) which is a measure of the asymmetry of the distributed data and reflects the fact that (very) high prices and spikes can occur (longer tail on the right of the distribution). Electricity is also usually characterized by high values of kurtosis (fat tails) implying the frequent abnormal values (more than for instance for a normally distributed series)

### 3.1.3 Non stationarity

The data are then tested for stationarity through an ADF test (Augmented Dickey Fuller). Although some of the studies quoted earlier found stationary time series (Boisseleau, Zachmann), it seems rather logical to obtain non stationary data for both spot and futures for a convergence process evolving through the time. First of all a reminder of stationary and non-stationary series:

A discrete process \((Z_t)\) is said to be weakly stationary (Wide Sense Stationarity) if its first and second moments are time independent. More precisely, its mean and variance are constant, and its covariance function only depends on the lag \(k\) between \(Z(i)\) and \(Z(i-k)\), not on the time position \(i\).

\[
\begin{align*}
\cdot & E[Z_i] = \mu \quad \forall i = 1..t \\
\cdot & Var[Z_i] = \sigma^2 \neq \infty \quad \forall i = 1..t \\
\cdot & Cov[Z_i,Z_{i-k}] = f(k) = \rho(k) \quad \forall i = 1..t, \forall k = 1..t
\end{align*}
\] (3.3)

Two different types of non-stationary process can be distinguished:

- trend stationarity (deterministic): \(x_t = a_0 + a_1 \cdot t + \varepsilon_t\) (with \(\varepsilon_t\) stationary) \(\quad (3.4)\)
- differency stationarity (stochastic): \((1-D)x_t = \beta + \varepsilon_t \iff x_t = x_{t-1} + \beta + \varepsilon_t\) (with \(\varepsilon_t\) stationary) \(\quad (3.5)\)

These two types present different characteristics, in a TS process stochastic shocks are temporary and their effect disappear while shocks in a DS process will impact the future values of the

\(^6\) \(\mu_k = \frac{1}{n} \sum_{i=1}^{n} (x_i - \mu)^k\) the \(k\)-th standardized moment, Skewness is: \(\beta_1 = \frac{\mu_3}{\mu_2^{3/2}}\) and Kurtosis is: \(\beta_2 = \frac{\mu_4}{\mu_2^2}\) for a normal distribution, skewness is equal to zero and kurtosis to 3.

69
series. Moreover, many statistical tests and analysis require stationary time series. Non-stationary series can however be studied after stationarisation: a TS process is stationarized through Ordinary Least Square regression while a DS series must be submitted to a difference filter.

A Dickey Fuller Test allows us to determine the non-stationarity characteristics of a time series by testing whether there is a unit root in one of these auto-regressive models:

- AR \( x_t = \Phi x_{t-1} + \epsilon_t \)  
  \( (3.6) \)
- AR with drift: \( x_t = \Phi x_{t-1} + \beta + \epsilon \)  
  \( (3.7) \)
- AR with trend and drift: \( x_t = \Phi x_{t-1} + \beta t + c + \epsilon \)  
  \( (3.8) \)

The null hypothesis for each model: \( H_0: \Phi = 1 \) meaning the non-stationarity. The critical values are not the classical student values but values tabulated by Dickey and Fuller because of the non-stationary properties assumed in \((H0)\). Finally the Augmented Dickey Fuller test is an improved version that takes into account the possible autocorrelation of the error \( \epsilon \).

The stationarity tests were conducted for all spot and future time series using Eviews. Figure 3.7 shows an example of outcome from Eviews ADF test for APX Day-Ahead series while and table 3.3 recaps the results obtained for all the series.

| Variable | Coefficient | Std. Error | t-Statistic | Prob. *
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>APX -1</td>
<td>-2.9833333</td>
<td>0.0113333</td>
<td>-266.3333</td>
<td>0.0000</td>
</tr>
<tr>
<td>EEX -3</td>
<td>-3.5666666</td>
<td>0.0111111</td>
<td>-322.2222</td>
<td>0.0000</td>
</tr>
<tr>
<td>PNX -5</td>
<td>-3.5666666</td>
<td>0.0111111</td>
<td>-322.2222</td>
<td>0.0000</td>
</tr>
<tr>
<td>BLPX -7</td>
<td>-3.5666666</td>
<td>0.0111111</td>
<td>-322.2222</td>
<td>0.0000</td>
</tr>
<tr>
<td>APX</td>
<td>-2.9833333</td>
<td>0.0113333</td>
<td>-266.3333</td>
<td>0.0000</td>
</tr>
<tr>
<td>EEX</td>
<td>-2.9833333</td>
<td>0.0113333</td>
<td>-266.3333</td>
<td>0.0000</td>
</tr>
<tr>
<td>PNX</td>
<td>-2.9833333</td>
<td>0.0113333</td>
<td>-266.3333</td>
<td>0.0000</td>
</tr>
<tr>
<td>BLPX</td>
<td>-2.9833333</td>
<td>0.0113333</td>
<td>-266.3333</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

The results show that Day-Ahead price series are stationary at a 5% confidence level which is coherent with previous studies on the subject but that contradicts our first guess on the subject.

Figure 3.7: Eviews ADF test outcome
Futures time series, unlike their underlying asset, are non stationary which is also coherent with many observations on financial time series. Therefore, we can notice that Day-ahead electricity prices do not show classical financial behaviour and must be cautiously considered because of their physical features (non storability and occurrence of spikes during tight supply or high demand periods) that imply mathematical particularities (as said earlier skewness, high kurtosis and stationarity).

3.1.4 Volatility:

It is also interesting to observe the evolution of the maximum difference volatility between prices (day-ahead for week days). It is calculated for the week days Day-Ahead prices:

\[
X(i) = \text{Max}(EEX, PNX, APX, BLX) - \text{Min}(EEX, PNX, APX, BLX)
\]

\[
\sigma(X_j, \ldots, X_{j+15}) = \text{std}(X_j, \ldots, X_{j+15})
\]

\[\text{(3.9)}\]

![Figure 3.8: 15-days volatility of the max difference between Day-Ahead prices (week days)](image-url)
Although we do not observe striking significant change in the volatility, it seems that the spikes of volatility are becoming smaller. The big peak of volatility observed in October 2009 is due to the price spike on PowerNext already mentioned.

3.2 Kalman filter analysis:

As we saw in the literature review, the Kalman Filter approach is a method often employed when analysing convergence because it provides estimation of time varying unobservable coefficients modelling the convergence relationship.

Let \( p_1(t) \) and \( p_2(t) \) be the prices in the country 1 and the country 2. We construct a simple convergence model:

\[
p_1(t) = \alpha(t) p_2(t) + \beta(t) + \epsilon(t) \tag{3.10}
\]

The idea behind this formula is to characterise the strength of the convergence process: if during a certain period, the time varying unobservable coefficient \( \alpha(t) \) is getting closer to 1 and \( \beta(t) \) is reaching a steady level, then we could say that there actually is a convergence process. In order to support our hypothesis of a stepwise convergence, we should observe various level for \( \beta(t) \) as well as disruptions in the evolution of \( \alpha(t) \). Since these parameters are unobservable, they will have to be estimated. This is the goal of the Kalman filtration. Equation (3.10) can be seen as a measurement or observation equation where \( \epsilon(t) \) is a white noise which can be interpreted as the measurement error or the error between the convergence relationship and the prices observed. The state equation is the one that defines the evolution of the time varying coefficient. Here simple autoregressive equations are used, as in [27] with white noises.

\[
\alpha(t) = \alpha(t-1) + u(t) \\
\beta(t) = \beta(t-1) + v(t) \tag{3.11}
\]

Equation (3.11) is said to define a state space model because \( \alpha(t) \) and \( \beta(t) \) can be seen as the system state, only observable through the measurement equation, in other words, the state of convergence at time \( t \) is defined by the state vector \((\alpha, \beta)\). This state is allowed to evolve smoothly over the time through (3.11) and with \( u(t) \) and \( v(t) \) being white noises. For more details on the Kalman filter process see the annex.
First of all, a simple simulation test can be performed in order to illustrate the interest of the Kalman filter approach of convergence. Using the series of day-ahead prices for France (PowerNext), we create another price series imposing three steps of convergence: a first step where prices are getting closer and closer until they reach a constant difference level (the second step of the convergence). Prices will then move together and the difference between them will be fixed. Then, in the final step, this level will change to a new fixed difference. Figure 3.9 illustrates the three state of convergence:

![Figure 3.9: Difference between the newly created series and the powernext series](image)

This series is created with Matlab:

\[
\begin{align*}
    s(1 \leq k \leq \text{Length}(\text{px})/3) &= \text{px}(k) + 4 + \left(\text{Length}(\text{px})/3 - k\right)/20 \\
    s(\text{Length}(\text{px})/3 + 1 \leq k \leq 2\text{Length}(\text{px})/3) &= \text{px}(k) + 4 \\
    s(2\text{Length}(\text{px})/3 \leq k \leq \text{Length}(\text{px})) &= \text{px}(k) + 1
\end{align*}
\]  

(3.12)

Then a white noise is added to represent the temporary shocks of electricity prices. The variance chosen is 6.5 in order to be relatively high compare to the difference between prices. Thus for a while price difference can be larger than imposed by the convergence equation because of a temporary error. Figure 3.10 shows the price difference when the white noise is added.
Now the convergence evolution is less clear, and the difference between the prices looks a bit like a possible real situation. Figure 3.11 shows the two price series: the real French spot prices and the prices created with Matlab to simulate a stepwise convergence situation.

\[ p(t) = \alpha(t) \cdot p(t) + \beta(t) + \epsilon(t) \]  

(3.13)

The mathematical model chosen to represent the convergence process is the same as described previously:

Using this model on Eviews and applying the Kalman Filter first by letting Eviews estimating the three variances for \( \epsilon(t) \), \( u(t) \) and \( v(t) \), we obtain the following results in figure 3.12.
We observe that results give a rather good estimate for the convergence process. We clearly distinguish three steps on the Beta graph, and two phases on the alpha graph. The calibrations of the parameters can also be performed manually although it is rather difficult for real time series to estimate variances of errors. Figure 3.13 is thus the kalman filtering with manual calibration for error variances: $\sigma_v = 6.5; \sigma_u = 0.00001$ and $\sigma_v = 0.01$.
convergence between the four countries at the same date, we consider two new series derived from the four Day-Ahead price series: the minimum and the maximum prices:

\[
\begin{align*}
\min(t) &= \min(apx(t), eex(t), blx(t), pnx(t)) \\
\max(t) &= \max(apx(t), eex(t), blx(t), pnx(t))
\end{align*}
\] (3.14)

We use the same mathematical model as previously, and we let E-Views estimate the different variances:

\[
p_t = \alpha(t) p_{t-1} + \beta(t) + \epsilon(t)
\]

\[
\alpha(t) = \alpha(t-1) + u(t) \\
\beta(t) = \beta(t-1) + v(t)
\] (3.15)

Figure 3.14 shows the estimated parameters $\alpha$ (on the left diagram) and $\beta$ (on the right diagram) obtained after Kalman filtering. We observe large “disruptions” that tend to disturb the system and the interpretation of the outcome. Thus we chose to suppress some of the temporary price spikes that results from exceptional conditions in order to get better estimates of the time varying coefficients. This method may seem arbitrary but the goal of this analysis is to observe the convergence process during “normal conditions”, it is therefore necessary to get rid of some peculiar shocks.

![Figure 3.14: Kalman filter results for min and max Day-Ahead series (week days)](image)

---

7 Only two spikes were removed (the biggest ones): on May 21st 2007 APX: 277.41€/MWh and October 18th 2009: PNX 612.77€/MWh
Figure 3.15: Kalman filter results for min and max Day-Ahead corrected series (week days)

Figure 3.15 shows the results after this correction. Estimation of the parameters is not perfect due to the difficulty to give values for the three variances: a change in the weight of the different variances might affect more one coefficient than another. Ideally $\varepsilon$ might absorb all the temporary deviations from the convergence state while $u$ and $v$ allow the time varying coefficient to move slowly in order to adapt to the changes in the convergence state. If these variances are not well calibrated, the values and the shape of the diagrams might differ from the “real convergence state”. Another important flaw is the fact that the series do not present Gaussian characteristics. Despite these difficulties, the previous results provide some useful information. Considering both curves at the same time and ignoring the values of the estimates but focusing on the global shape of the diagrams, we observe that convergence is increasing as the coefficients seem to stabilize. We distinguish 3 phases: in the first one, both coefficients are changing a lot and no real convergence is achieved. The second part corresponds to the year 2009. The $\beta$ coefficient seems to stabilize indicating improvement in the convergence state,
although the $\alpha$ parameter is decreasing. This period also corresponds to a decrease in the consumption due to the economic crisis. The last part shows the steadier state and could thus represent another improvement in the convergence process. We also observe that winter season implies (green dotted circles) higher variations and a tougher time for convergence. The black arrow shows the approximate date of the market coupling launching: no real changes can be noticed afterward except perhaps a quicker dampening of the winter variations. Finally, the end of this last period (number 4) seems to be disturbed as the $\beta$ is changing after the end of May 2011 and seems to indicate a new change of state.

Trying to gives values for the variances of $\epsilon$, $u$ and $v$ gives a different curve, but we still observe the same behaviour of the different parameters as can be seen on figure 3.16. Here the chosen value is 100 for the variance of $\epsilon$ because it corresponds to the variance of the difference between the min and max series. The variance of $u$ was set to 0.0001 and for $v$ 0.01 so that the maximum of variations is absorbed by the measurement error $\epsilon$, then by $\beta$ and finally by $\alpha$.

![Figure 3.16: Kalman filter results for min and max Day-Ahead series (week days) and with manual values for the variances](image-url)
Studying convergence for Day-Ahead prices is difficult since these prices are highly volatile, and as a consequence, the difference between them is itself volatile. In order to try to distinguish temporary variations from structural changes, we suggested using the Kalman filter approach. We clearly saw that the four markets are “converging” as the maximum and minimum Day-Ahead prices are reaching equilibrium relations that could be defined as convergence states (both parameters are stabilizing). In addition this convergence process seems to show several steps in the diagrams that cannot only be attributed to temporary spikes. This approach has several flaws as explained earlier but it constitutes an attractive way to observe connections between series and a good alternative to the classical correlation/cointegration analysis.

Performing the same filter with calendar 2012 minimum and maximum series gives the following results:

![Figure 3.17: Kalman filter results for min and max Cal-12 series](image-url)
Here the problem of spikes disappears since futures are not subject to temporary tensions of demand and supply conditions or exceptional temperatures. The dynamic of long term prices is dependent on the vision market players have concerning the average price of electricity for delivery in 2012. Therefore it implies a strong link with energy portfolio evolution: we can notice that both $\alpha$ and $\beta$ parameters change abruptly in the middle of March which corresponds to the Fukushima event. We observed that the sign of the difference between France and Germany for the calendar 2012 contract changed in the end of May 2011, this can be observed on the graph. However, the “state of convergence” seems stable since March 2011. The close relation between prices is clear as the two parameters are rather stable.

### 3.3 A second approach: estimation of Mean Reverting Jump Diffusion Parameters:

In order to obtain a second vision on the dynamic evolution of prices and convergence, another approach is suggested. It also relies on the estimation of parameters as in the Kalman filter, but the idea is to model each price series separately and to estimate the corresponding parameters for different time interval in order to obtain evolution profiles of each parameter. Comparing the profiles of the different series will then hopefully give evidences for convergence and stability of convergence state.

Modelling electricity spot prices is not an easy task. Price formation in electricity is driven by supply and demand equilibrium. Demand being mostly non-elastic toward price levels implies the occurrence of spikes in period of tight supply or extreme temperatures. In addition, as most of the commodities, electricity prices tend to return to a long term mean level due to the demand and supply characteristics. Therefore, the chosen model must be able to catch these stylized features (mean reversion and jumps) in order to describe as accurately as possible the price dynamics. From the many models created on the subject, a jump diffusion model constituted by a geometric Brownian motion with mean reversion and a Poisson process for the jump part seems well adapted, simple and provides an explicit formulation of the likelihood function necessary to easily estimate the different parameters. In the existing literature, many models have been implemented to represent spot prices as accurately as possible. There is however no consensus on the best model to use. Since this thesis is not aimed at improving a model, the Mean Reverting Jump Diffusion process used will be composed by a single jump with normally
distributed amplitude. For a detailed review on the spot price models see [20]. The following explanations are based among others on [21], [22] and [23].

**Geometric Brownian Motion:**

Diffusion models for stochastic price formations are defined in a general form by the following stochastic differential equation based on the work of Bachelier in 1900, called Itô process see [23] or [24].

\[ dS_t = \mu(S,t)dt + \sigma(S,t)dW_t \]  \hspace{1cm} (3.16)

Where \( \mu \) and \( \sigma \) are respectively the drift and the volatility and \( W_t \) is a standard Brownian motion (or a Wiener process), that is to say:

- \( W_0 = 0 \)
- \( W(t) \) is almost surely continuous
- any increments of \( W(t) \) are independent: for all \( t \geq s \geq 0 \), \( W(t) - W(s) \) is an independent variable.
- any increments of follow a normal distribution with zero mean and variance \( (t-s) \): for all \( t \geq s \geq 0 \), \( W(t) - W(s) \overset{\text{iid}}{\sim} N(0, t-s) \)

A special case derived from this formula is called the Arithmetic Brownian Motion when the drift and volatility are constants.

The most famous process derived from this formula is the Geometric Brownian Motion used in the first evaluation of options premium in the Black and Scholes formula to model underlying asset prices and which is widely used in stock and other markets. It corresponds to a special case of (3.16) when \( \mu(S,t) = \mu S \) and \( \sigma(S,t) = \sigma S \) with \( \mu \) and \( \sigma \) constant.

\[ dS(t) = \mu S(t)dt + \sigma S(t)dW(t) \] \hspace{1cm} (3.17)

Or:
While $W(t)$ is a Wiener process.

The Geometric Brownian motion is a process where the natural logarithm of prices is following an Arithmetic Brownian Motion. Indeed with Ito’s lemma, for $X = \ln(S)$, we obtain the formula:

$$dX = (\mu - \frac{\sigma^2}{2})dt + \sigma dW$$

(3.19)

The solution of the stochastic differential equation, given the initial value $S_0$, is thus:

$$S(t) = S_0 e^{((\mu - \frac{\sigma^2}{2})t + \sigma W(t))}$$

(3.20)

**Mean Reverting BM (Ornstein Uhlenbeck):**

Geometric Brownian Motion is not adapted to the mean reversion features of energy commodities. Such a feature can be caught by Mean reverting process such as

$$dS = \alpha(\mu - S(t))dt + \sigma dW(t)$$

(3.21)

Or

$$\frac{dS}{S(t)} = \alpha(\mu - S(t))dt + \sigma dW(t)$$

(3.21bis)

Where $\alpha$, $\mu$ and $\sigma$ are respectively the strength of the mean reversion, the long term mean level, and the volatility. The drift term (the first term on the right side) includes the mean regression: when prices are above the long term mean level, they will tend to move downward, and the other way round. Another version (from Schwartz-Ross) uses the log of the price in the drift term:

$$\frac{dS}{S(t)} = \alpha(\mu - \ln(S(t)))dt + \sigma dW(t)$$

(3.22)

Spot prices revert to the long term mean reversion level: $S_{\text{mean}} = e^\mu$
Here again with Itô’s lemma applied to (3.22) and for \( X = \ln(S) \) we obtain:

\[
dX = \alpha(\mu^* - X)dt + \sigma dW
\]

With \( \mu^* = \mu - \frac{\sigma^2}{2\alpha} \)

**Jump Diffusion models:**

These models first described by Merton incorporate the jumps or spikes that can occur in prices and that are not caught by a mere Brownian process. A way to integrate these sudden jumps is to add a Poisson process into the classical Wiener process:

\[
dS = a(S,t)dt + b(S,t)dW + \phi dq
\]

Where \( q \) is a Poisson process defined by \( dq = 0 \) with probability \( \lambda \) and \( dq = 1 \) with probability \( 1 - \lambda \). \( \phi \) is the size of the jump which can be a stochastic variable. Although other models have been created to catch the different features of energy and particularly electricity prices (with stochastic volatility, regime switching,…), jump diffusion models have been widely used and constitute an interesting class of models for electricity prices. The jump part can be represented by other process but the Poisson process is the most frequent and probably the most intuitive.

**Poisson Process:**

A Poisson process with intensity \( \lambda \) has the following features:

- The number of changes occurring in two distinct intervals are independent:
  \( \forall t_1 \leq t_2 \leq ... \leq t_k \) the variables \( (N_{t_k} - N_{t_{k-1}}), ..., (N_1 - N_0) \) are independent

- The probability of a change in a short interval of length \( \Delta t \) is \( \lambda \Delta t \):
  \[
P(N_{t+h} - N_t = 1) = \lambda h + o(h) \text{ with } h \to 0^+
  \]

- The probability of more than one change is negligible
  \[
P(N_{t+h} - N_t > 1) = o(h) \text{ with } h \to 0^+
  \]
This process counts the number of events $N(t)$ occurring up to time $t$. $N(t)$ is following the Poisson probability law with the distribution:

$$P(N(t) = k) = e^{\lambda t} \frac{\lambda^k}{k!} \quad (3.25)$$

**Jump Diffusion process with mean reversion:**

After a spike, electricity prices usually tend to return to a “normal regime” and to revert to their long term mean value. Thus it is logical to combine jump diffusion and mean reverting model:

$$dS = \alpha(\mu - S(t))dt + \sigma dW(t) + J_P dP_t \quad (3.26)$$

Or another version, using log of prices and geometric Brownian motion:

$$\frac{dS}{S(t)} = \alpha(\mu^* - \ln(S(t)))dt + \sigma dW(t) + J_P dP_t \quad (3.26 \text{ bis})$$

With $J$ the jump amplitude and $P$, a standard Poisson process with associated intensity $\lambda$. By taking the log: $X_t = \ln(S_t)$ we obtain the following formulation:

$$dX_t = \kappa(\mu - X_t)dt + \sigma dW(t) + Q_P dP_t \quad (3.27)$$

With $\mu = \mu^* - \frac{1}{2\kappa} \sigma^2$ the long term mean of the logarithmic price and $Q_t = \ln(1 + J_t)$

This formulation is simple and is part of the Affine Jump Diffusion Models where the parameters (drift, volatility and jump intensity) follow affine functions of time and $X_t$.

**Estimation method:**

As we explained earlier on, to investigate the convergence process of the prices in the CWE markets, we suggest to analyse the evolution of the model parameters through the time by iteratively estimating these constant parameters on a several intervals ($[T_k, T_{k+1}]$). To do so, we will use the maximum likelihood estimation method when an analytic formulation of the probability distribution of the model is known.

For a probability distribution $D$, the associated density function $f$ and the unknown distribution parameter $\theta$, the likelihood function is defined by:

$$L(\{X_t\}_{t=1}^N, \theta) = f(X_1 | \theta) f(X_2 | \theta) \ldots f(X_N | \theta) \quad (3.28)$$

for $\{X_t\}_{t=1}^N$ a set of data from the observations.
The likelihood function can actually be considered has the joint density function where the observed values \( \{X_t\}_{t=1}^N \) are fixed and the variable is \( \theta \). Therefore, finding the best estimate for \( \theta \) is equivalent to maximising the likelihood function. Usually the log-likelihood function is used because it is more convenient. Thus the best estimate is:

\[
\hat{\theta} = \arg \max_{\theta} \ln(L(\{X_t\}_{t=1}^N, \theta)) = \arg \max_{\theta} \left( \sum_{i=1}^{N} \ln(f(X_i|\theta)) \right)
\]  

(3.29)

In order to obtain an analytical form of the characteristic function for an affine jump diffusion model leading to an analytical expression for the likelihood function, we follow the procedure defined by Ball and Torus [34], explained in [22], and implemented with Matlab [23] and [25]. We convert the continuous formulation of the model into a discrete one by simply approximating \( dt \) by \( \Delta t \).

We assume that during a small interval \( \Delta t \) the probability that two or more jumps are occurring is negligible. The probability that one jump is occurring is given by \( \lambda \Delta t \) and the probability that there is no jump is given by \((1 - \lambda \Delta t)\) : the jumps are described with a Bernoulli model in the interval \( \Delta t \). The jump amplitude is considered to follow a normal distribution with mean \( \mu_j \) and variance \( \delta \). This considerably simplifies the problem since we can now write the model as a Gaussian mixture: by approximating the continuous model with a discrete one on a small interval \( \Delta t \), we obtain the density function as the product of two Gaussian density functions with and without a jump, weighted by the jump probability:

\[
g(X_{t+1}|X_t) = \tilde{\lambda} \Delta t \times f_{\Delta X - \kappa(\mu - X) \Delta t + \mu_j} + (1 - \Delta t \tilde{\lambda}) \times f_{\Delta X - \kappa(\mu - X) \Delta t}
\]  

(3.30)

With \( f_{\Delta X - \kappa(\mu - X) \Delta t + \mu_j} \) and \( f_{\Delta X - \kappa(\mu - X) \Delta t} \) being the density probability functions of \( \Delta X - \kappa(\mu - X) \Delta t + \mu_j \) and \( \Delta X - \kappa(\mu - X) \Delta t \) with respective mean and variance: \((0, \sqrt{\delta^2 + \sigma^2})\) and \((0, \sigma^2)\).

There the log likelihood function, for the parameters: \( \theta = (\kappa, \mu, \sigma, \tilde{\lambda}, \mu_j, \delta) \) is:

\[
\log L(\theta | \{X_t\}_{t=1}^T) = \sum_{i=1}^{T} \ln(\tilde{\lambda} f_{\Delta X - \kappa(\mu - X) \Delta t + \mu_j} + (1 - \tilde{\lambda}) f_{\Delta X - \kappa(\mu - X) \Delta t})
\]  

(3.31)

85
Therefore estimating the parameters is equivalent to maximizing the likelihood function. This is done using the optimization function with Matlab.

A preliminary estimation for jump part is performed as followed:

\[
R_i = \ln\left(\frac{S_i}{S_{i-1}}\right) = X_i - X_{i-1}
\]  

(3.32)

And then we count the number of jumps on the sample length. We consider that a jump occur if \( R_i > 3\sigma \) (each value above three standard deviations).

Then the probability to obtain one jump during the small interval \( \Delta t \) is approximated as:

\[
\hat{\lambda}_0 = P(\Delta N = 1) \sim \frac{N}{T}
\]  

(3.33)

Now that we have described the model used for spot prices and the parameter estimation method, we will briefly describe the approach we will implement for a “dynamic” estimation of the parameters. The underlying idea behind this approach is the fact that it is not easy to estimate model with time dependant parameters. Moreover, the goal is to obtain diagrams of the evolution of the different parameters in order to compare them with the four price series. Here the notion of convergence is perceived as the convergence of the model parameters.

This analysis will be done in several steps. First we will estimate, for each price series, the dynamics of the five parameters:

For a price series \((S_t)_{0 \leq t \leq N}\), modelled by (3.26) or (3.26 bis), we implement the maximum likelihood estimation method described above on an interval \([k, k+I]\) with I being the fixed interval length, and k moving from 0 to N-I. Therefore we obtain k estimation of the parameters:

\[
(\theta_k)_{0 \leq k \leq N-I} = (\kappa_k, \mu_k, \sigma_k, \lambda_k, \mu_{k+1}, \delta_k)
\]  

(3.34)

But first, we estimate the parameters for the whole data set for each prices (k=0 and I=1250 ie a single interval). Then we plot several simulated paths with the estimated parameters (see [25] for Matlab simulation code).

We plot two different models:
Simulated series using model (3.26 bis) to represent prices, which is equivalent to use model (3.27) with natural log of prices

- Simulated series directly using model (3.26) to represent prices (ie: no log in the formula).

![Figure 3.18: Real PNX prices series and 2 simulated series using model 3.26 bis](image1)

![Figure 3.19: Real PNX prices series and 1 simulated series using model 3.27](image2)

There are several differences in these two models: model (3.26 bis) with logarithm included in the formula leads to more spikes and longer reverting time to the long term mean level while model (3.26) without log in the formula seems to be more stationary due to a quicker reversion to
the long term mean: during peak period, it seems to represent more accurately the behaviour of prices with really “sharp” spikes, but during normal state, the variations seems to be larger than the reality.

In order to compare more accurately these two models we simulate 1000 series for each model and compute the difference between the simulations and the real series. We calculate the mean difference (ie: two series of 1000 mean). The following results are obtained:

![Figure 3.20: Mean difference with real series for 1000 simulations](image)

The difference is clearly smaller with model (3.26), this is why we choose this one for the next part of the thesis.

Using a jump diffusion model allows catching non Gaussian characteristics of prices thanks to the mixture distribution of the model that shows longer tails and thinner peak than a normal distribution. The Quantile-Quantile plots also show that model (3.26) is more adapted to the price series:
Figure 3.21: QQ plot for PNX prices series

Figure 3.22: QQ plot for simulation with model 3.26
We notice that model (3.26) and the real price series PNX are similar while model (3.26 bis) is rather different: the far right tail is longer than for a normal distribution (thus diverging from the red dashed line). For model (3.26 bis), this right tail is diverging too early from a Gaussian distribution. Therefore we decide to use model (3.26) in the next parts of the thesis.

We can now proceed to the dynamic estimation of the parameters. Following (3.26) for spot prices $S$, we estimate the parameters:

$\kappa$: mean reversion rate

$\mu$: mean reversion level

$\sigma$: stochastic diffusion volatility

$\lambda$: jump intensity

$\mu_j$: mean jump amplitude

$\sigma_j$: jump volatility

We decide to choose $I=250$ for the interval length of the estimation because it corresponds approximately to one year of week-days ($5*50$). Since we have 1250 data, there will be $k=1000$
intervals, therefore 1000 estimations for the parameters from the interval $I_0 = [1 \ 250]$ up to $I_{1000} = [1000 \ 1250]$. Due to the great number of optimisations that Matlab has to perform, the time to get the results can be quite long. Here are the results for the 4 price series:

Figure 3.24: Parameters for PNX

Figure 3.25: Parameters for EEX
Apart from some small disruptions, the four price series show the same dynamics for each parameter. We can notice that there is a big discontinuity for the mean reversion rate, the volatility and the mean jump amplitude of PNX around $k=500$ which correspond to the exceptionally high price level reached in 2009 on the French power exchange.

Figure 3.26: Parameters for BLX

Figure 3.27: Parameters for APX
We also observe that the volatility as well as the jump intensity and standard jump deviation seem to decrease through the time for each market which could be a sign of better integration. It is however harder to find a common pattern for the mean jump amplitude which is the parameter that reflects the most the erratic behaviour of prices.

The shape of the mean reversion levels are very similar: from $k = 0$ to $k = 250$, they are increasing, which is logical because it corresponds to the rise observed in energy prices between 2006 and 2008. Then they decrease and reach their lowest level for $k = 500$, which corresponds to the end of 2008 and the beginning of 2009 so that these parameters are estimated for the year 2009, when the economic crisis weighed on demand and prices.

In order to compare more accurately these parameters, we compute their difference:

![Figure 3.28: Parameters difference between PNX and EEX](image)

First we compute the difference between the PNX and EEX parameters. The most relevant parameter is the mean reversion level because it symbolises the spot electricity price during normal condition by taking apart the stochastic shocks of supply and demand that are encompassed in the jump parameters. We observe that this difference is globally decreasing and
converging toward zero, as highlighted by the red line which is a quadratic fitting of the curve. Therefore, we can conclude that EEX and PNX are converging toward common mean reversion levels. However, when looking closer at the curve we notice that such a convergence is “stepwise” since we can distinguish different levels as showed by figure 3.29:

![Figure 3.29: Difference between mean reversion levels of PNX and EEX](image)

For the other parameters, it is harder to perceive a clear pattern but we observe that their differences, apart from the mean reversion rate, generally tend to stabilize around 0 which is obviously a sign of convergence. Similarly to the previous approach with Kalman we decide to plot the max difference of the parameters in order to assess on the convergence process for the four price series simultaneously. This is why we compute for each parameter $\theta_{i,j}$ (with $i \in \{pnx, eex, apx, blx\}$ and $j \in \{1, 2, 3, 4, 5, 6\}$):

$$\theta_{\text{max spread}}(t) = \max_{i \in \{apx, eex, pnx, blx\}} (\theta(t)_{i,j}) - \min_{i \in \{apx, eex, pnx, blx\}} (\theta(t)_{i,j})$$  \hspace{1cm} (3.35)

8 If we neglect the sudden but temporary increase that appears in the mean reversion rate, jump amplitude and volatility due to the price spike of PNX in 2009.
This means that, at time t, and for one parameter type (i.e., mean reversion level, jump amplitude, ...) we calculate the maximum difference between the four series (APX, EEX, PNX, BLX). These maximum differences are plotted in figure 3.30:

From this point of view, it is rather clear that the four markets are converging since, for most of the parameters, the maximum difference is heading toward zero. It is obvious for the mean reversion level: prices in normal condition, neglecting the temporary stochastic shocks, are getting closer. The Standard Deviation of Jumps, and to a certain extent (although less clearly) the Volatility also seem to converge. For the three remaining parameters, it is less clear because: they are impacted by the big price spikes that disturb estimation (especially the mean reversion rate for k around 500, 750 and 900), or because they represent the jump part that is to say the temporary unpredictable shocks that can occur in one country independently from the others.
Figure 3.31 shows the maximum difference for the mean reversion rate more in details:

![Figure 3.31: Maximum difference between each parameter](image)

Here again, we observe (although the dashed lines have been placed a bit arbitrarily) several steps and several levels for the mean reversion. In particular, the last step for k around 750 to the end, coincides with the implementation of the market coupling.

To conclude, this second approach is quite satisfying because it distinguishes normal mean conditions and jumps. Convergence among the four markets is clear, but subject to shocks and not constant. Through this method we do not observe significant impacts of the recent events such as Fukushima but we can distinguish steps of convergence that support the results given by the Kalman approach.

Finally, using the estimates for the last interval, we simulate the spot prices for the next 250 days to the end of August 2012. We compute 10,000 simulations of PNX, EEX, APX and BLX with the last historical data we have as starting points (ie September 7th 2011). We obtain for each market, 10,000 simulations of prices between September 7th 2011 and August 22nd 2012 (corresponding to 250 week days). For each market, table 3.4 gives the mean value obtained.
As we can see the mean value of Powernext (PNX) remains below those of EEX as observed recently. The maximum difference is equal to 1.07€/MWh and the difference between EEX and PNX is equal to 0.59€/MWh. These values are close to the differences between futures for delivery 2012 given in table 3.5 (for the last day of data sample 09/09/2011).

<table>
<thead>
<tr>
<th>Mean Value: €/MWh</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PNX</strong></td>
</tr>
<tr>
<td><strong>EEX</strong></td>
</tr>
<tr>
<td><strong>APX</strong></td>
</tr>
<tr>
<td><strong>BLX</strong></td>
</tr>
</tbody>
</table>

*Table 3.4: Mean Values for prices estimated through simulations*

<table>
<thead>
<tr>
<th>APX</th>
<th>EEX</th>
<th>PNX</th>
<th>BLX</th>
</tr>
</thead>
<tbody>
<tr>
<td>58,01</td>
<td>58,15</td>
<td>56,89</td>
<td>56,17</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MAX diff</th>
<th>EEX–PNX</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.98</td>
<td>1.26</td>
</tr>
</tbody>
</table>

*Table 3.4: Last values of cal-12*

According to the estimations, the spread is thus supposed to narrow and to be lower than the difference on the future market. From the last quotations of the future prices (after September 2011), prices seem to decrease and to come closer to the estimated values.
4 What can we conclude for a manager who needs to hedge his electricity portfolio?

This study was dedicated to explore the convergence process and to analyse its evolution through the time. In the first part, we focused on the market structures. We saw that European regulations lay the ground for a real market integration. Regional Initiatives are the intermediary steps before the creation of a single European market. The market coupling launched in the CWE market is an example of this will for integration. We saw that it was efficient by deleting incoherent cross border flows. However, the market structures present strong differences that could slow down the convergence process: different production portfolios (nuclear vs thermal production unit), different rate of renewable integration, and last but not least different consumption profiles with a high seasonality for France. We could therefore say that convergence of the market structures is not achieved yet and that, given the recent decisions of nuclear shut down taken by Germany (and very recently Belgium), a risk of divergence still exits. In the second part, we presented three different approaches to analyse price convergence and market integration. They all conclude that a single European market was far from being achieved but they show evidences for regional convergence especially among the CWE market.

In the third and main part, we first performed a graphic analysis for spot and futures historical prices. We observed convergence but also influence of peculiar events (Fukushima, Market Coupling). The Fukushima event, for instance, caused the inversion of the spread between France and Germany on futures prices. We observed high level of correlation particularly between France and Belgium on the one hand (large share of nuclear in the production mixes) and Germany/Netherlands on the other hand (large share of thermal units). We then suggested analysing more in details the convergence process by carrying out two methods. The first approach was based on a Kalman filter to establish the evolution of the relation between the maximum and the minimum price. For the spot prices, we observed that the relation was getting steadier as the parameters were stabilizing, therefore we could conclude that convergence was clear. However we distinguished several steps with more or less steady parameters, sign of a “stepwise convergence”. The relation between prices can evolve to equilibrium and this must be considered in hedging strategies: a model can no longer be correct if the relation between prices has changed. The Market coupling impact on spot prices cannot be really observed through this analysis. Convergence of future prices is even clearer. The impact of Fukushima is easily observed but the parameters are still stable, indicating that a steady relation
still exists. The second method tests for convergence under a more original approach: estimating the evolution of the fundamental parameters of spot electricity prices. We used a Mean Reversion Jump Diffusion model and estimated its related parameters (mean reversion level, mean reversion rate, volatility, jump intensity, jump amplitude, jump volatility) on a constant length interval along the historical price series. Here again, prices clearly show signs of convergence especially through the mean reversion level. Computing the maximal and minimum differences between each parameters, we observed that the difference in mean reversion levels is decreasing, while standard deviation and jump diffusion are converging. It was however harder to observe significant moves in the other parameters. In addition, the hypothesis of a stepwise convergence process is strengthened by the observation of the difference in mean reversion levels. A steady step, closer to zero is noticed for the last 250 data which could be perhaps explained by the market coupling implementation.

From these two approaches, we can conclude that there is convergence among the CWE countries. The relation between prices is getting steadier. The dynamics of the convergence process is stepwise: jumping from one convergence state to another although impacts of external events is not clearly identified in both methods, and cannot be directly related to these changes. Using the Mean Reversion Jump Diffusion model, we finally realised forecast for the next 250 data and observed that mean prices and mean price differences are below the last values for futures (which represent the expect value of spot prices for the next year).

A real convergence among these four markets can give the opportunity to develop new hedging strategies. In particular, a hedger can choose to benefit from higher liquidity in Germany by using EEX German futures to hedge his electricity consumption/sale in France. Indeed, the French power exchange still lacks of liquidity, therefore hedging on the German power exchange can reduce the liquidity risk and optimize the hedging strategy. This, however, requires steady relations between spot prices and between futures. We saw earlier on, many evidences supporting the convergence. However, we also observed that the relation that links prices together can be subject to changes related to external factors. The energy sector have been subject to major events these last years, especially in 2011 with the Fukushima event that dealt a severe blow on the future of nuclear generation in Europe (with for instance the German decision to phase out nuclear power plants by 2022 and by already disconnecting eight of the seventeen plants still in activity). Meanwhile, 2011 was also a year of massive integration of renewable production, especially solar in Germany. On the other hand, France is applying a completely
different policy regarding energy mix by maintaining a major share of nuclear power in its portfolio ensuring theoretically low prices compare to other thermal units. Therefore, we could say that, to a certain extent, in the coming years, a relative divergence in the production portfolios could appear. More renewable energy could imply for instance a higher variability in the spot price differences although this has not been observed through our analysis. The coming winter will be very interesting to observe: France generally imports electricity from Germany, this could give rise to tight supply situations and higher prices, therefore the convergence will have to be closely watched.

It is also necessary to notice that the risk taken by adopting such a hedging strategy is smaller than the basis risk implied when hedgers use “local” future contracts. Indeed, table 4.1 shows the error (ie: the basis=spot price of underlying asset - future price) between the average spot price for a year and the price of the corresponding calendar (the settlement price) and table 4.2 shows the average absolute error.

<table>
<thead>
<tr>
<th></th>
<th>APX</th>
<th>EEX</th>
<th>PNX</th>
<th>BLX</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>NA</td>
<td>-4,57</td>
<td>-5,05</td>
<td>NA</td>
</tr>
<tr>
<td>2009</td>
<td>20,78</td>
<td>17,44</td>
<td>17,55</td>
<td>14,26</td>
</tr>
<tr>
<td>2010</td>
<td>-1,05</td>
<td>-0,12</td>
<td>0,22</td>
<td>-1,34</td>
</tr>
<tr>
<td>2011</td>
<td>0,19</td>
<td>-0,19</td>
<td>5,61</td>
<td>5,19</td>
</tr>
</tbody>
</table>

Table 4.1: Error between the annual mean spot price and the last quotation for the corresponding calendar contract

<table>
<thead>
<tr>
<th></th>
<th>APX</th>
<th>EEX</th>
<th>PNX</th>
<th>BLX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>10,9160938</td>
<td>7,37665117</td>
<td>7,60999638</td>
<td>7,80171231</td>
</tr>
</tbody>
</table>

Table 4.2: Average absolute error (on 2008-2010 for EEX and PNX and on 2009-2010 for APX and BLX

We can notice that the average absolute error is around 7€/MWh for PNX which is much more than the current spread between France and Germany for calendar 2012 (between June 1st 2011
and October 12th 2011, the average spread is equal to 1.10€/MWh) while the average difference between maximum and minimum prices for calendar 12 (ie: the series we worked on in this thesis) is equal to 1.98€/MWh. The error calculated for 2011 is of course not accurate since the year is not over but with winter coming, low temperatures and high prices are likely to reduce the error for PNX and BLX and to increase for EEX, (hence the arrow on figure 4.1).

Figure 4.1: Error between the annual mean spot price and the last quotation for the corresponding calendar contract

To conclude, the CWE markets seem to be well integrated. The convergence is reinforced by the launching of the market coupling (with high level of correlation and high percentages of equal spot prices). Apart from temporary variations, the convergence can also be impacted by deeper structural evolutions that can modify the relation between prices. Such modifications may imply risks for a hedger who wishes to benefit from the most liquid market and hedges abroad. However, the basis risks that exist between future contract and its underlying asset seem to be higher than the previous one. Therefore, such a strategy could be implemented. One must nonetheless observe the prices behaviour in the coming months in order to know whether the current state of convergence remains stable.
The next step for the development of the CWE markets could be to create a common financial futures power exchange with common futures contracts. This could be a solution to improve liquidity on the futures markets. A system inspired by the Nordic power exchange Nordpool could be used with contract for differences in order to hedge against price differences among countries…

Future studies should be carried out to observe the evolution of convergence after the winter 2011, a crucial season with peak periods (especially) in France and tightening supplies. A more sophisticated model for spot prices could also be implemented and adapted to the second approach. Finally it could also be interesting to analyse the impact of renewable productions on the prices, although this is far from being easy…
References:


[18] “Rules for capacity allocation by explicit auctions within Central Western Europe Region (CWE Auction Rules)”, reglementary paper, CASC.


ANNEX:

A- The Kalman Filter

The Kalman filter is a statistical approach which principle is to correct the model trajectory using observations and the information contained in the model in order to minimize the error between the true state and the filtered state.

For a stochastic state representation:

\[ X_{k+1} = M_k X_k + B_k u_k + G_k W_k \]  \hspace{1cm} (A.1)

With \( M_k, B_k \) two linear matrices, \( u_k \) an external input vector (that can be null), \( G_k \) the noise entrance matrix and \( W_k \) a white noise vector with covariance matrix \( Q_k \) which symbolises the state model error.

The state is observed through an observation equation:

\[ Z_k = H_k X_k + V_k \]  \hspace{1cm} (A.2)

With \( H_k \) a linear observation matrix and \( V_k \) a white noise representing the error made on the observation (the measurement error) with covariance matrix \( V_k \).

To obtain the state \( X_k \), we combine the observations \( Z_k \) and the information given by the state model. We determine the conditional density probability of the state \( X_k \), knowing \( Z_1, ..., Z_l \).

This iterative process is divided into two steps:

1- The prediction step:

First a prediction of the state is calculated through the state equation:

\[ X_{4k-1} = M_k X_{k-1} + B_k u_k \]  \hspace{1cm} (A.3)
And the covariance matrix of the system is updated:

\[ P_{4k-1} = M_k P_{4k-1} M_k^T + G_k Q_k G_k^T \]  \hspace{1cm} (A.4)

Calculation of the filter optimal gain \( K_k \):

\[ K_k = P_{4k-1} H_k^T \left( H_k P_{4k-1} H_k^T + R_k \right)^{-1} \]  \hspace{1cm} (A.5)

**2- The Correction step:**

The predicted state is corrected using the new observation \( Z_k \):

\[ X_{4k} = X_{4k-1} + K_k (Z_k - H_k X_{4k-1}) \]  \hspace{1cm} (A.6)

And an update of system covariance matrix:

\[ P_{4k} = (I - K_k H_k) P_{4k-1} \]  \hspace{1cm} (A.7)

This requires an initialisation stage, therefore values for \( X_0 \) and \( P_0 \) have to be given.

If not defined, E-views automatically gives initial values usually small for \( X_0 \) and large for \( P_0 \) which are, stage after stage, getting closer to the real values. This is why the very first stages can be more imprecise than the following.

The parameters such as the covariance of the state model error and the observation error are scarcely known but they can be estimated through Expectation Maximisation Algorithm (algorithm used by Eviews and using maximum likelihood estimation but not described here).
B- Itô’s Lemma:

For an Itô process (general diffusion process)

\[ dX_t = \mu dt + \sigma dB_t \]  \hspace{1cm} (B.1)

With \( B_t \) a standard Brownian motion.

For any twice differentiable function \( f \) of \( X \) and \( t \), we have:

\[ df(t, X_t) = \left( \frac{\partial f}{\partial t} + \mu \frac{\partial f}{\partial x} + \frac{\sigma^2}{2} \frac{\partial^2 f}{\partial x^2} \right) dt + \sigma \frac{\partial f}{\partial x} dB_t \]  \hspace{1cm} (B.2)

And thus \( f(t, X_t) \) is also following an Itô process.

Therefore for a geometric Brownian motion:

\[ dS(t) = \mu S(t) dt + \sigma S(t) dW(t) \]  \hspace{1cm} (B.3)

if \( f \) is the natural logarithm:

\[ d(\ln(S_t)) = \frac{1}{S_t}(\sigma S dB_t + \mu S dt) - \frac{1}{2} \sigma^2 dt = \sigma dB_t + (\mu - \frac{1}{2} \sigma^2) dt \]  \hspace{1cm} (B.4)

\( \ln(S) \) is following an arithmetic Brownian motion and:

\[ S_t = S_0 \exp(\sigma B_t + (\mu - \frac{1}{2} \sigma^2)t) \]  \hspace{1cm} (B.5)