TÉCNICO
LISBOA

RENEWABLE ENERGY PRICE INDICATOR

Analysis of the Effect of Variable Renewable Energy Generation on Power Prices

Yousif Ahmed Eltayeb Abdalla Mohamed

Thesis to obtain the Master of Science Degree in

Energy Engineering and Management

Supervisors: Prof. Carlos Augusto Santos Silva
Dr. Barbara Breitschopf

Examination Committee

Chairperson: Prof. José Manuel Costa Dias de Figueiredo
Supervisor: Prof. Carlos Augusto Santos Silva
Member of the Committee: Prof. João José Esteves Santana

December 2017

List of Acronyms

Acronym	Meaning
RES	Renewable Energy Source(s)
VRE	Variable Renewable Energy
EU	European Union
PV	Photovoltaic
EEG	Erneuerbare-Energien-Gesetz (German)
EWEA	European Wind Energy Association
OTC	Over The Counter
TSO	Transmission System Operator
EEX	European Energy Exchange
kWh	kilowatt-hour
MWh	megawatt-hour
TWh	terawatt-hour

List of figures

List of Tables

Contents

Abstract

The level of integration of variable renewable resources (VRE) in any power system tells how much flexibility is in it, how much integrated is the system, and how much room for more VRE is available.

This thesis investigates the effects of VRE variation in the generation and its impact on the power prices in the intraday and spot markets in 2015 and 2016. The study aimed to assess the level of integration of the variable renewable energy resources in the power systems of several EU countries using data of generation and demand.

The sample group of countries was selected to represent different scenarios of VRE shares and load behavior in the EU.

The method considers the critical hours, which are the hours when the actual generation and actual load deviate significantly from their forecasted volumes. At those points the prices were examined to see how much they are affected.

The results show different level of integration, where some countries experience very high volatility of prices while in other countries the effect was minimal. This is due to the level of VRE penetration, degree of integration of the system and the availability of other flexible generation or capacities.

Resumo

O nível de integração de energias renováveis variáveis (ERVs) em qualquer sistema de energia é um indicador de quanta flexibilidade existe, qual o nível de integração do sistema, e quando existe espaço disponivel para mais ERVs.

Esta tese investiga os efeitos da variação na geração das ERVs no preço de energia, nos mercados de energia intradiários, em 2015 e 2016. O estudo visou avaliar o nível de integração dos recursos variáveis de energia renovável nos sistemas de energia de vários países da UE, usando dados de geração e procura.

A amostra de países foi escolhida de forma representar diferentes cenários de comportamento em termos de quotas e capacidade das ERVs na UE.

O método considera as horas críticas, ou seja as horas em que a geração real e a capacidade real variam significamente dos volumes previstos. Os preços foram examinados nesses pontos para perceber o quanto eles são afectados.

Os resultados mostram diferentes níveis de integração, onde nalguns países existe uma alta volatilidade de preços, enquanto outros países o efeito foi mínimo.

1. Introduction

Pushed by internal interest and/or the global movement towards clean and green energy, many countries around the world are increasing the share of renewable energy sources (RES) in their energy mix.

Some of those countries have a very ambitious goal which is to transform their energy production entirely into renewable energy. To achieve that they need to redesign and modify the structure and operation of the entire energy system.

The EU countries are in the leading position for the deployment of the renewable resources; since the mid-nineties of the past century the EU commission began to promote the generation of energy from renewable resources and to reduce the utilization of fossil fuels.

In 2009 the EU issued the Renewable Energy promotion directive [1] which sets national binding targets for all EU countries. The overall aim of the directive was to make renewable energy sources accounting for 20% of EU energy and for 10% of energy specifically in the transport sector by 2020 (both measured in terms of gross final energy consumption, i.e. total energy consumed from all sources, including renewables) [1].

The other two targets of this directive were:

- Reduce GHG emissions by 20% from 1990 levels and
- Improve energy efficiency by 20% [1].

From here on, each EU member state was to set a localized action plan to achieve its own set target by 2020.

Those targets were updated for the 2030 Framework for climate and energy to be:

- A 40% cut in greenhouse gas emissions compared to 1990 levels;
- At least a 27% share of renewable energy consumption;
- At least 27% energy savings compared with the business-as-usual scenario[2].

[1] DIRECTIVE 2009/28/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC.

[2] A scenario for future patterns of activity which assumes that there will be no significant change in people's attitudes and priorities, or no major changes in technology, economics, or policies, so that normal circumstances can be expected to continue unchanged [36]

The main goal of these targets is to help EU achieve more secure and competitive energy systems and to get closer to the ambitious goal of full decarbonization by 2050 [2].

The following graph represents the actual growth of the energy generated from renewable resources (by type) in the EU.

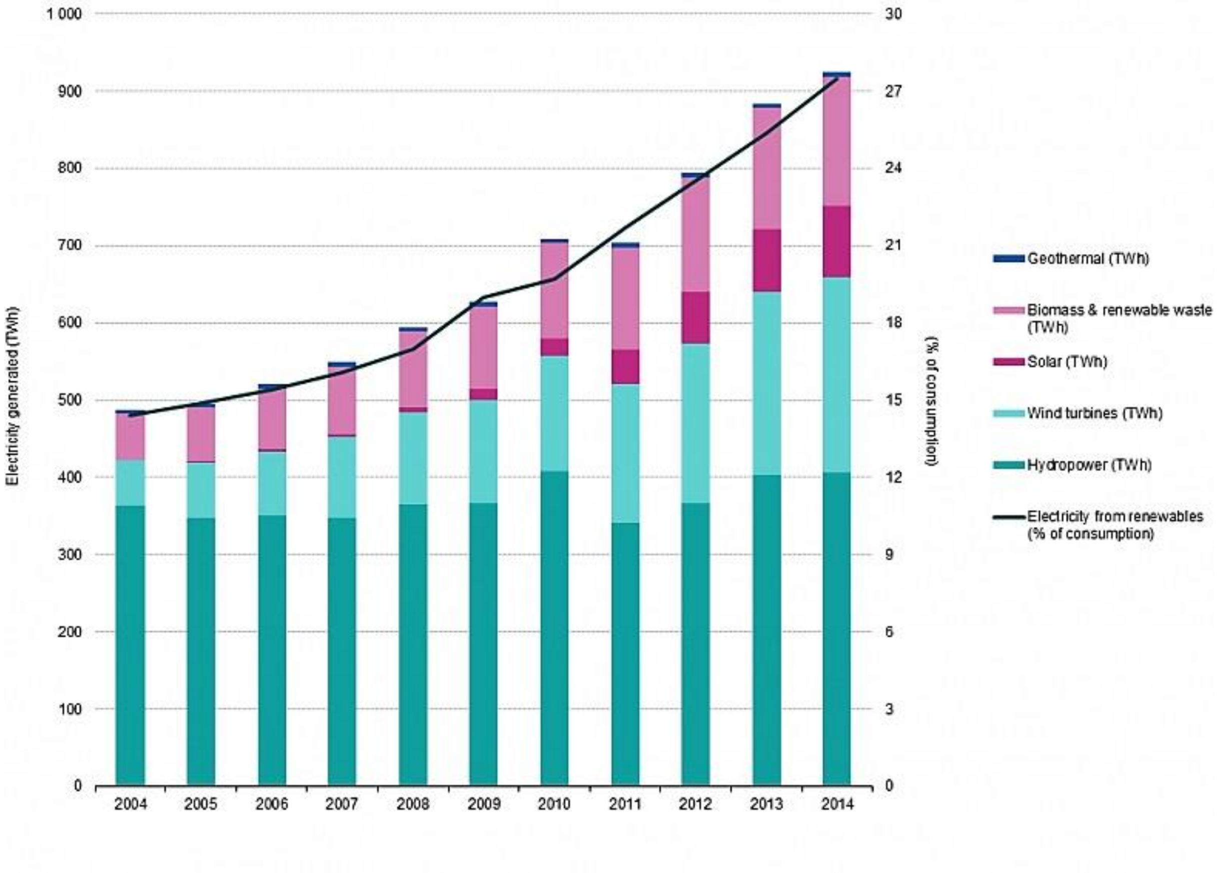


Figure 1: Electricity generated from renewable energy sources, EU-28, 2004–2014 *[3]*

RES are divided into two main categories:

- Dispatchable; where the power produced can be predicted controlled and utilized at the requested time such as biomass, concentrated solar thermal power with storage, and hydro power plants;
- Non-Dispatchable resources, which are divided into :
    - Non-Dispatchable with constant supply, such as geothermal power and run of river power plants [4];
    - Intermittent sources where the energy generation is variable according to the weather, those kinds of sources are called Variable Renewable Energy sources (VRE). The two main VRE sources are wind and solar energy as well as ocean and tidal power [5].

Wind and solar PV power plants possess some specific features; such as uncontrollable variability, partial unpredictability and they are very location dependent.

As availability of wind and sunlight is a weather dependent and can vary from a moment to another, this variation causes fluctuation in their power output which requires an energy balance supply to generate energy whenever the wind and solar energy is less than forecasted and to absorb the extra generated energy [6].

Figure 2 below illustrates the fluctuation and mismatch between forecasted and real-time generated wind energy in Portugal in an ordinary day.

The best wind and solar resources are found in specific locations, and as the resources is not transferable (in contrast to conventional fuels) the production facilities have to be built at the place of the resource. That means the generated electricity need to be transformed and transferred to the near places of consumption. So usually installation of new wind and solar plants require new transmission capacities. These transmission capacities are costly and sometimes very expensive; for example in offshore wind installations the cost will be very high due to the type of technology needed for transmission.

Figure 3 illustrate the variation in wind diversity in Europe, in terms of full-load hours[1] per location.

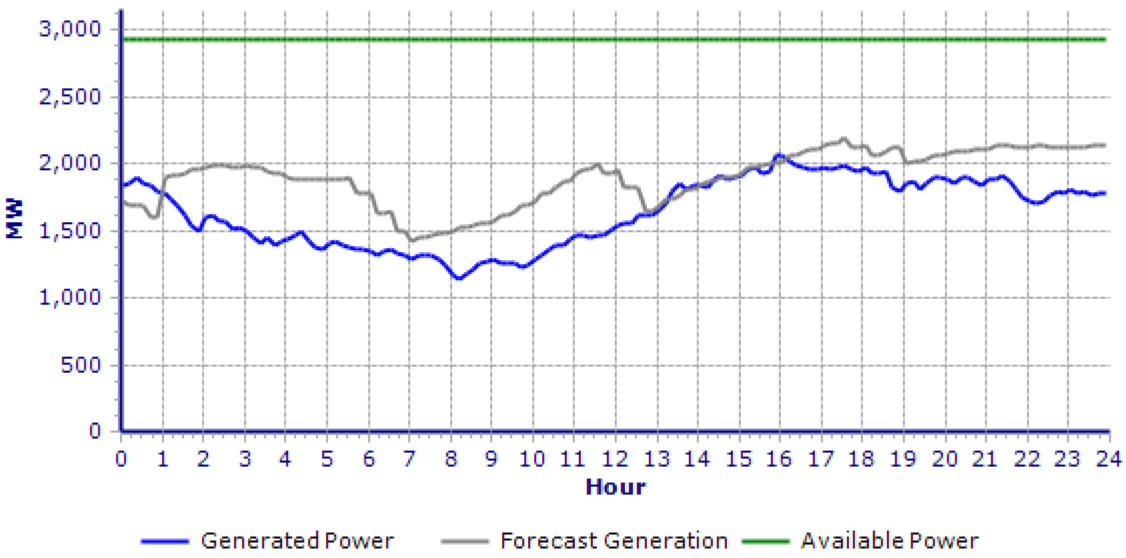


Figure 2: Difference between forecasted and actual generated wind power - 27.02.2016 - Portugal *[7]*

[1] Full load hours are the number of hours in one year during which the turbine would have to run at full power in order to generate the energy delivered throughout a year (i.e. the capacity factor multiplied by 8760) [38].

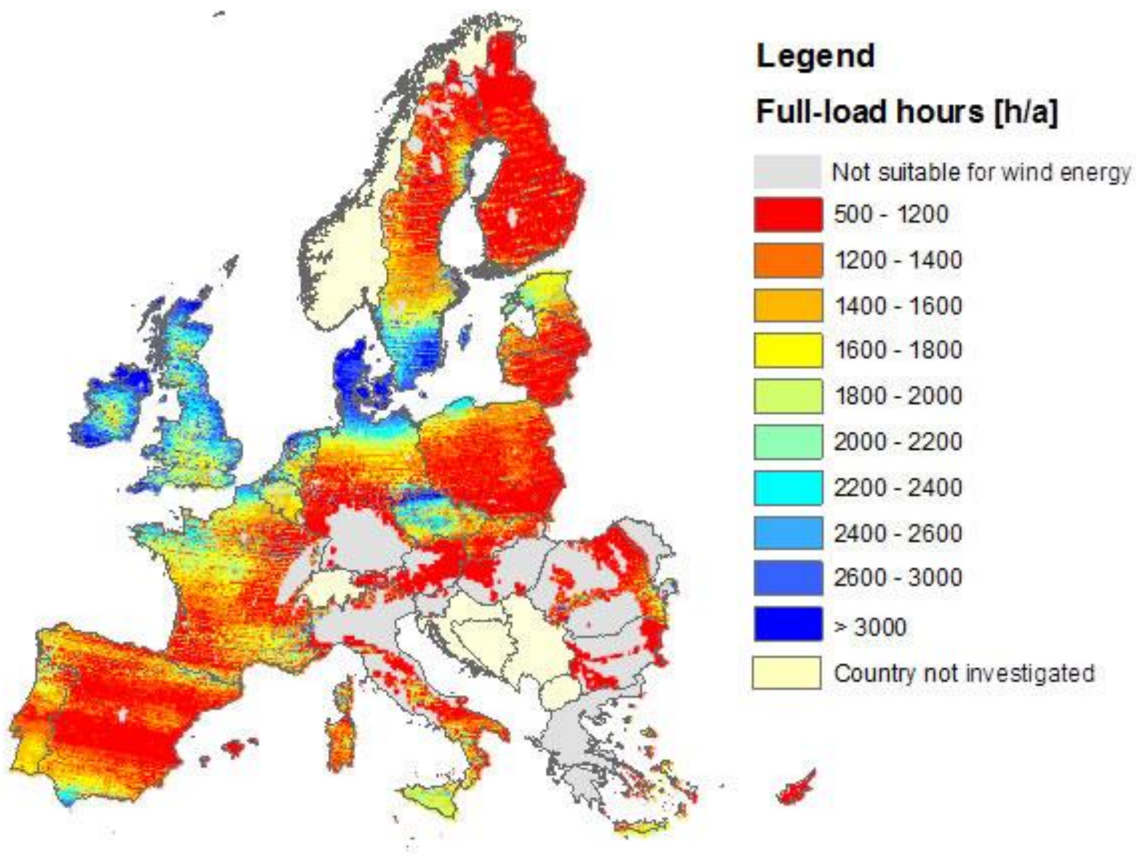


Figure 3: Annual full-load hours for onshore wind energy in the EU *[8]*

To assess the integration of variable renewable resources VRE into the grid systems of the EU, this work will analyze the relation between the renewable energy generation variations in certain EU countries with electricity prices in their power markets. The analysis will be carried out for both Spot market and intraday market.

The selection of the study cases will consider different parameters including:

- VRE penetration in the energy mix.
- Percentage of solar to wind in the VRE portion.
- VRE ratio to the total installed capacity.
- VRE capacity compared to the peak load.
- Availability of data.

Next chapter will provide a background of the power systems and markets and will also discuss the findings from the reviewed literature the effects of renewables on markets and prices.

Chapter three will discuss the selection procedure and gives a brief description about the energy system in each of the selected countries. Furthermore it will elaborate the methods used in the analysis.

Chapter four will discuss the results while chapter five will draw conclusions and recommendations.

2. Concept Review

The reduction of the electricity prices by the introduction of renewables is always used as a justification for renewable support schemes in the countries that adopted it [9]. Renewable power plants are expected to bid their production in the market at zero price (zero marginal cost). This act causes other conventional power plants to be pushed to the right of the supply curve and the intersection between supply and demand is then at lower prices. This phenomenon in the power market is called the merit order effect [10].

The merit order curve is used to optimize the cost in the power spot market. As illustrated in the figure below, lower marginal cost generation plants are bided first with the higher marginal cost ones being brought later on the line [10].

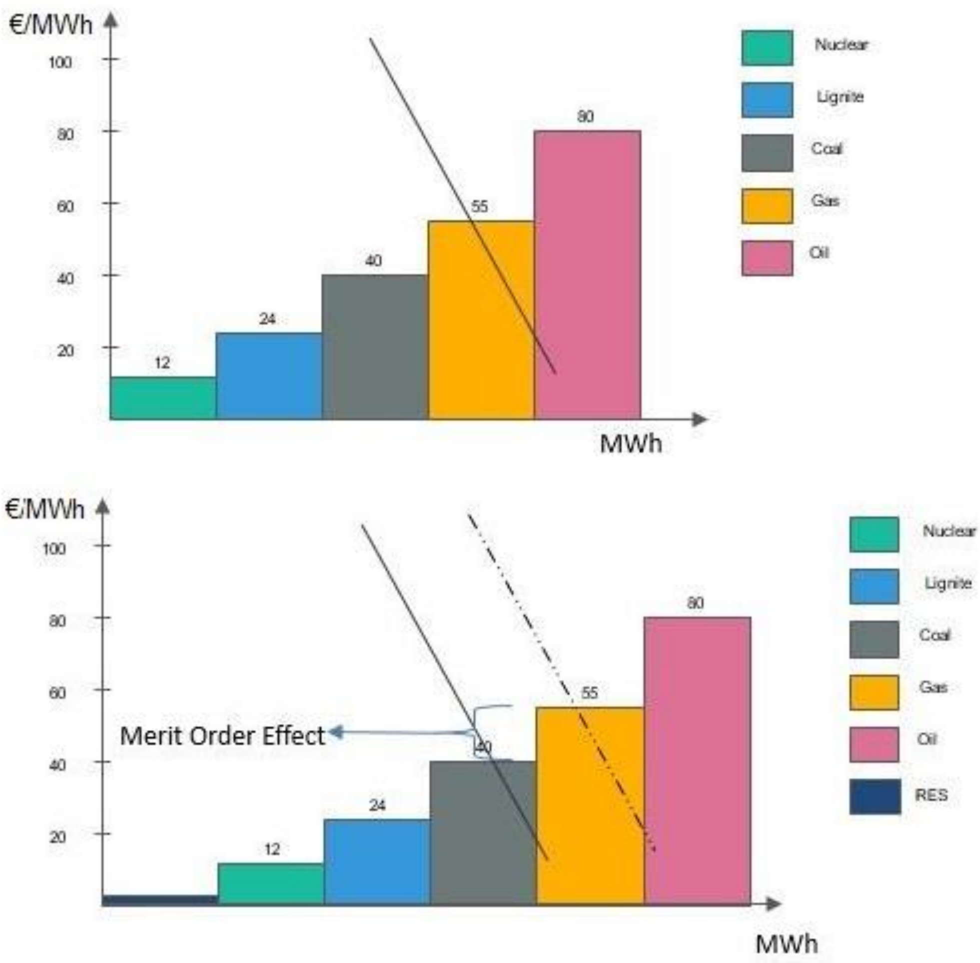


Figure 4: Merit Order Effect (own elaboration based on *[12]* and *[13]*)

2.1. Power Market

On the physical side, the electricity system consists of generation facilities, transmission and distribution networks and consumers, while it has on the organizational side the electricity market to link players on the generation side with the demand side and ensure transaction of power trading [11].

The EU electricity industry was subjected to a great movement of market liberalization since the beginning of the nineties of last century, and hence a number of power market are now operated in a congruent way; such as power markets in Germany, France, the Iberian Peninsula and the Nordic countries [12].

The typical power system would have four types of power markets:

- **Bilateral electricity trading OTC (Over The Counter)**

The trading happens between the suppliers and buyers directly- bilaterally – outside the power exchange, prices and amounts are privately discussed and agreed between the two participants.

It can be either long term contracts which usually involves fulfillment of large amounts of electricity over a relatively long period of time, or it can also be in form of small amounts OTC.

Another type of OTC is electronic trading where many players can bid their needs with the price they can pay and suppliers accept and make counter offers with their desired prices.

In all cases the terms, amounts and prices are discussed privately and the identities of the two parties are not disclosed to any third party. [13]

- **The day-ahead Market (Spot Market)**

Spot market is defined in economy as: "In a spot market, the seller delivers the goods immediately and the buyer pays for them on the spot. No conditions are attached to the delivery" [13].

The day-ahead market (Spot Market) of electricity is a physical market where prices and amount are settled based on the supply and demand and the resulting prices and the traded amounts are publicly demonstrated with high transparency in market process and figures. The entire bidding, awarding and financial settlements are supervised by the market operator.

It is a called day-ahead market because bidding gate usually closes at noon for fulfilment in the coming day starting from midnight [12].

- **The intraday market**

The intraday market is a supplement for the day ahead market where system members (suppliers and buyers) can continue to trade power on hour long contracts and also with agreed blocks of hours.

The benefit of the intraday market is that it allows fine tuning and matching of supply and demand, the prices and amount traded are also settled by bidding and are publicly disclosed [14].

The intraday market is gaining more importance as more renewables with their variation in generation are introduced to the grid, which leads to variation in supply with respect to demand fulfillment that leads to instant need of power or power reduction.

- **The regulating power market (Balancing and Ancillary Service)**

This market refers to the situation after the markets closes where the transmission system operator (TSO) acts to secure the matching between demand and supply.

Efficient balancing markets ensure the security of supply at the least cost and can deliver environmental benefits by reducing the need for back-up generation [15].

It is a real market working within the hour acting to regulate the imbalances between supply and demand.

In this market the only buyer is the system operator (TSO) while the supply side includes both producers and consumers to supply negative and positive reserves [12].

Some literature mentions a post-day market where the TSO settles the imbalances that happened in the previous day.

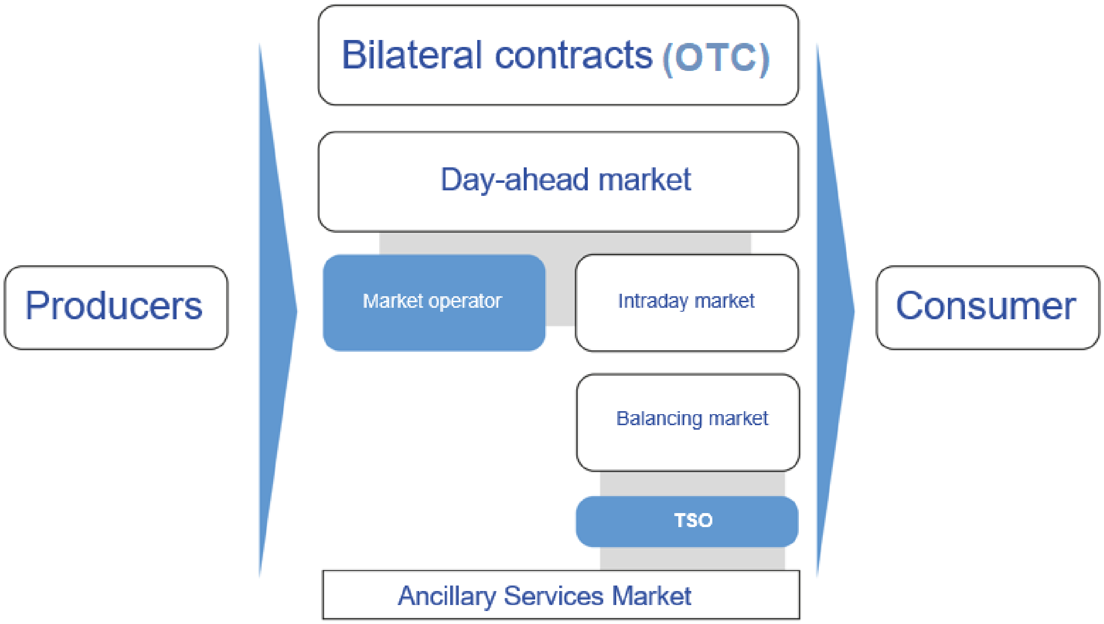


Figure 5: Power Market Architecture (own elaboration based on [13])

Figure 6: European Power Markets Operators [16]

2.2. Supply and Demand Curves

This section will describe briefly the supply and demand curves in the power system and the balance between them.

Electricity is a commodity that is expected to be demanded at any time, and its demand varies according to user behavior (cooking and washing times, etc.), weather conditions (heating in winter and cooling in summer), and it also varies between day and night.

As it is difficult and expensive to store electricity efficiently the demand and supply need to be matching all the time, to keep the system running and avoid the interruption of the supply.

The demand is described by load duration curve which illustrates the number of hours during which the total load is at or exceed any given value [17].

The load duration curve is constructed for any region by measuring the total load at hourly basis for every 8760 hours in a year, sorting in descending order starting from the peak load, as represented in atypical load duration curve in figure 7 below.

From the curve it is clear that the system is always above a small amount of electricity called “Base Load”, while the system never exceeds the highest load “Peak Load”.

The load duration curve is very informative as it tells exactly how much – percentage – of time is the system above certain level of load.

The Load duration curve typically has three stages:

- Base Load: which exists most of the time.
- Peak load: this is when the load is on the high side and it typically exists at less than 20 % of the time.
- Intermediate load where the system is between the base and peak loads [18].

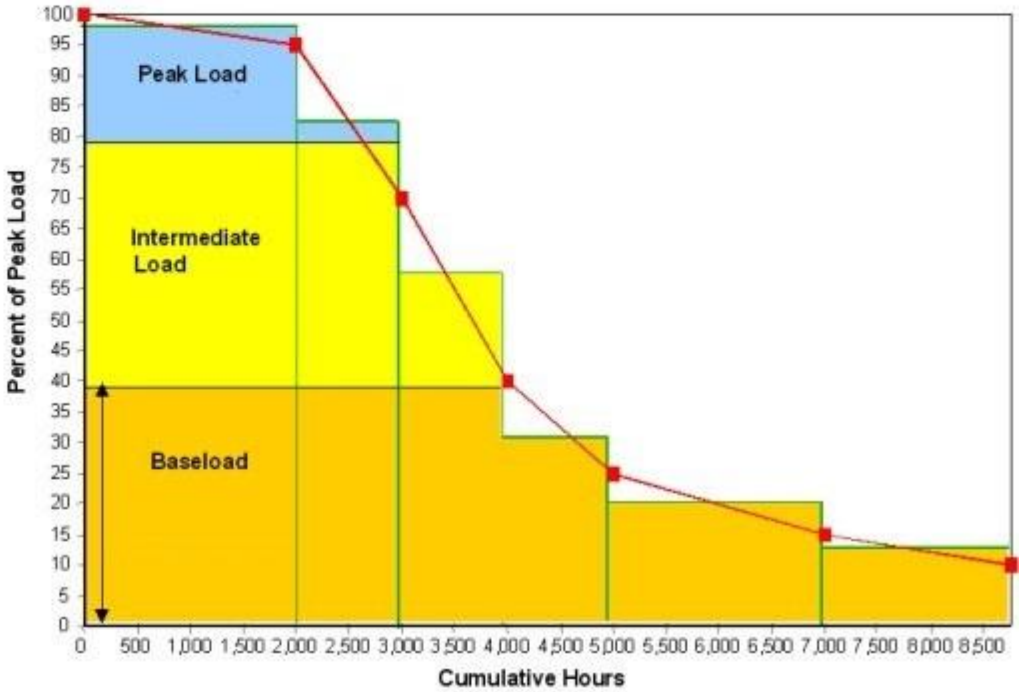


Figure 7: Typical Load Duration Curve [19]

In a regulated (non-liberated) market the load duration curve was convenient to use. After the liberalization movement and the introduction of the free market price factor the demand side is expressed by how much load at which price. However the load duration curve is still used to find equilibrium between supply and demand and also to find the most efficient energy mix for certain period of time.

To supply the demand each power plant will bid its generation based on its marginal cost. Marginal cost is defined as "The increase in the total cost that arises by producing one additional unit of a product or service" [17].

For an ideal competitive market, products would be sold at their marginal cost. In power market each power supplier will bid production at their marginal cost, and adding each power plant horizontally to the last it will yield what we call supply curve. [17]

If the number of power plants is small, the curve will not be smooth, however it will have steps. On the other hand with a large number of power plants the supply curve will be smooth.

Figure 8 below shows a typical Load Price Curve: Load is shown to be steep because the electricity load is known to be relatively inelastic to price changes.

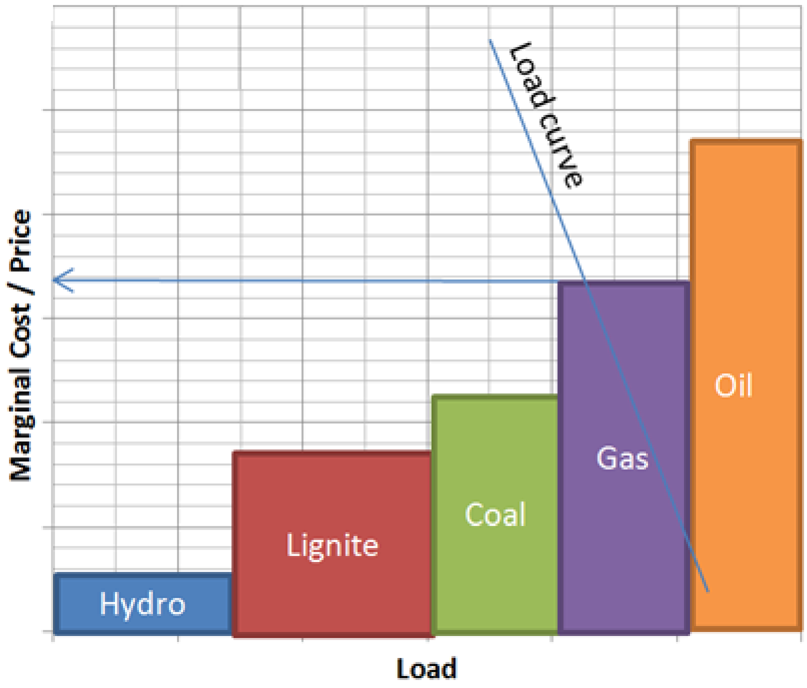


Figure 8: Typical Supply and Demand Curve with the Intersection the price (own elaboration based on [13] and [17])

2.3. Literature Review

There is a wide range of literature and research work that involves the investigation of the different effects of renewable energy technologies and adoption on the various components of the power systems.

The effect of variable renewables on the power market is an interesting and frequently visited research area.

The research usually follows model based approaches to predict the future based on certain assumed conditions. Some other researchers investigate the historic data to explore the relations between actual figures and hypothetical studies.

In most of the literature reviewed, the researchers tend to take the spot market price as the indicator for the electricity price, which is acceptable as in the EU usually the spot market accounts for the major portion of the electricity trading volumes [20].

The modeling approaches that are usually used are:

- Fundamental Models;
- Financial mathematical models;
- Econometrics time series models.

Those three are usually used for short to medium time span, however game theory approaches are used for the long time periods.

In fact all of those can be found combined in the research practice [20].

The public opinion often tend to believe that the introduction of renewables is increasing the power prices as a result of adding the economic burdens of the support schemes such as Feed in Tariff and Feed in Premium to the normal consumer's bill. Yet many studies and researchers came to a conclusion that the prices in the spot market price are either lowered or does not show much change with the introduction of renewables. [20]

For example in (Mulder & Scholtens 2013) study of the impact of renewable energy on electricity prices in Netherlands. They built a model based on historical data from 2006 to 2011 and they found that the supply and demand intersection is hardly altered by the renewable energy generation.

They confirm that although the supply curve moved to the right, this movement was too small to change the price significantly.

In addition to this they state that although the prices didn't change it can be reduced with the percentage of renewables in the energy mix increasing further more [21].

(Paraschiv, Erni, and Pietsch 2014) study investigated the impact of renewable energies on EEX day-ahead electricity prices. They showed that although the prices in the spot market incurred serious reduction yet the ordinary consumer wasn't affected by it as the added value of support schemes made up the gained gap.

Their paper investigated the instant variation that happen on the daily market prices (Spot Market Price) and the intraday market prices, to give detailed estimation on the variation that takes place in an hourly basis of intermittency.

They found that the sensitivity of power prices to fossil fuel prices decreased – especially gas – due to the introduction of renewable power plants which lead to shifting of the supply curve to the right. Yet the sensitivity to coal is still strong, which means that the support scheme for renewables resulted in replacing the low CO2 emission technologies first because they are the most expensive.

Although the normal consumers did not get any benefits from this change yet, the paper argues that intensive industrial consumers are the main winners here as they are exempted from the EEG[1] burden.

Another point is that the PV generation is important as it gets to its highest values at the peak load hours during the day, while wind generation is higher during night when the wind blows stronger. That also led to very low prices during the nights which sometimes reach negative values in the German spot market.

The paper suggest a cut in the Feed in tariff after the renewables reach a certain level to allow the normal consumers to benefit from the transition directly. The paper goes further to suggest a renewable energy policy that consider storage and distribution, to allow for the surplus of generation in the northern part to be equalized by the high demand in other parts of the country [22].

Running alongside with more evidence, is the study of (Clò, Cataldi & Zippoli 2014) where they examined the Italian power market for the effects of Solar and Wind power generation on the wholesale price.

Italian power system undergone one of the highest support schemes for renewables energy which just came at the same time of the economics recession there; so Italian power system had simultaneously large expansion of renewable energy with a steep decrease in load. The paper goes on describing the situation and investigating the effect in the whole market price alongside the comparison between the profit gained from the renewables and the cost of the support scheme.

The papers found strong evidences of alteration in the supply curve and thus the merit order effect of renewables. However further investigation shows that in contrary to the previously mentioned studies, this one claims that the effect on the price decreases with the increase in the renewable energy share. This is explained to be due to the difference in increment rate in savings and deployment cost, as the later increases much faster than the first.

[1] EEG (German: Erneuerbare-Energien-Gesetz) is The Renewable Energy Sources Act. It is a series of German laws that originally provided a feed-in tariff scheme to encourage the generation of renewable electricity [37].

Another very interesting finding is that the solar energy savings doesn't cover the cost of its support scheme, while wind energy easily overcome the cost and is an actual economics addition to the consumer's surplus [23].

One unique study is the one accomplished by EWEA (The European Wind Energy Association) to estimate the merit order effect of wind energy in Europe. The study is done by a modeling approach to investigate the change in wholesale market price of electricity by the year 2020. The target is to investigate the pathway to reach the EU set target for 2020.

The model compares two different scenarios; one reference scenario of all the renewable resources levels are fixed at the level of 2008, and the wind scenario, that assumes Wind installed capacity to increase to 265 GW in the whole EU by the year 2020 compared to 65 GW at 2008 with fixing all other types of renewable energy including solar at their level in 2008.

The findings of the study show lower prices for the wind scenario than the reference scenario. And the merit order effect is quantified to be 10.8 €/MWh; this is explained by the difference in capacities and the difference in CO_2 prices for the fossil fuels electricity generation that happens in the two scenarios [10].

Though there are many studies for the merit order effect on the spot market prices, using modeling and historic data analysis, yet there is scarcity in the studies considering the intraday market alteration due to renewables energy variable generation. This lack of interest can be explained by the traded power volumes difference. The volume of the spot market is larger than the intraday market which makes it an interesting field of study. However the intraday market prices would be directly impacted by the errors in forecast which usually leads to high price spikes and also sometimes negative prices in the countries where the system allows the prices to go negative, or at least zero prices in other countries.

The third market which is directly affected by the errors in forecast and variation in renewable generation is the balancing energy market. This market is the first defense line for the TSO to mitigate the change in supply due to generation oscillation.

This work is considering the spot market and the intraday market for five different countries in the EU. For these countries numbers are investigated in hourly basis for the two years of 2015 and 2016.

3. Methodology and Data

This section will go through the procedure used to select the study sample countries, sources of data, and the analysis methodology applied to them.

The data about the installed capacity and actual generation is mainly taken from the EU Eurostat database[1] and also form the Entso-e transparency platform[2].

Other data about prices, and bidding procedures are taken form the respective countries TSO's, market operators, and regulatory authorities official websites.

Firstly all the installed capacity, load profile, and actual generation data from all the EU countries were analyzed and classified to select a reasonable sample of five countries, in order to give plausible results for the entire EU.

The following factors were took into consideration to choose the sample countries:

- Current energy mix and percentage of VRE (wind and solar energy);
- The development of wind installed capacity from 1990 – 2015;
- The development of solar installed capacity from 1990 – 2015;
- The percentage of VRE to the peak load registered in 2015;
- The type of VRE resource in the mix; solar to wind percentage;
- Availability of data.

[1] Eurostat is the statistical office of the European Union situated in Luxembourg. Its mission is to provide high quality statistics for Europe.

[2] ENTSO-E, the European Network of Transmission System Operators, represents 43 electricity transmission system operators (TSOs) from 36 countries across Europe

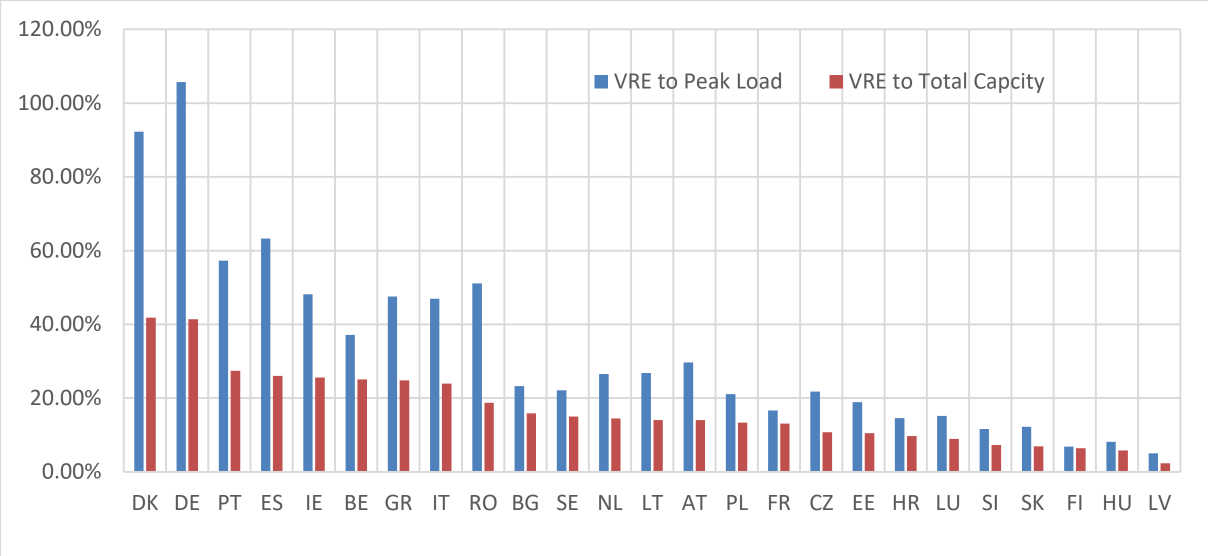


Figure 9: Percentage of VRE to Total Capacity and to Peake load per country (2015) (own analysis based on *[24]* and *[3]*).

According to the analyzed data and also the availability of data the following countries were selected for the study:

- Germany (DE); representing the country with the largest power system and the highest capacity of VRE;
- France (FR); as country were the power system is dependent on nuclear power, with relatively low penetration of VRE;
- Denmark (DK); as a country with high penetration of wind but low solar penetration.
- Portugal (PT); as the unique power system with high hydro power and also high penetration of wind energy;
- Spain (ES); as the country with relatively balanced penetration of solar and wind with significant share also of solar thermal energy.

3.1. Germany

Germany has the largest power system in the EU and the largest share of renewables installed capacity in the energy mix. Globally Germany is in the third place in the world considering share of renewables installed capacity (excluding hydro following China and the US [25].

The major players in the energy market are large utilities like E.ON, RWE, EnBW and Vatten-fall. Yet recently competition began to evolve in the country. With the expansion of Renewables, only 5% is owned by the four companies, while 46% is owned by private citizens, including farmers, and the rest is owned by project developers, industry, and even banks [26].

In 2015 the renewables accounted for 30% (194 TWh) of the total energy generated in Germany, where wind represents 12% of the total generation while solar energy comes in the third place with 6% following biomass with 8%.

The following figure shows the energy mix in Germany in 2015, which shows that combustible fuel makes around 50% of the total installed capacity followed by wind with 22% and Solar 19%. Only 5% of the capacity is nuclear power.

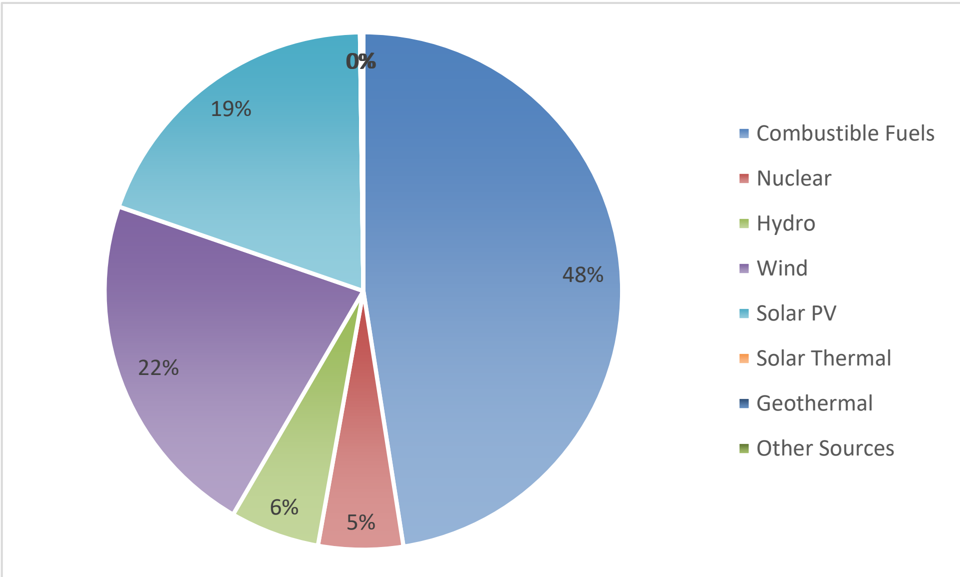


Figure 10: German Power Mix (Installed capacity) - 2015 (own analysis based on [3]).

Germany initiated an ambitious energy transition program called Energiewende[1], the program has been developing for two decades and aims to decarbonize the power system while phasing out the nuclear power by 2022.

The Energiewende consist of many regulations such as:

- The Renewable Energy Act (EEG) to support and promote the utilization of the renewable energy resources using different measures like feed in tariff and tax exemption;
- The Nuclear Phase out by 2022 which was emphasized after the disaster of Fukushima in 2009 in Japan [27].

With many other regulations and schemes to lead the energy transition the result appeared in the rapid increase in the installed capacity of renewable energy in Germany and considerable change in the energy mix.

[1] Energiewende defined by the Federal Ministry of Economics and Technology (BMWi) as “The Energiewende (German for energy transition) is the transition by Germany to a low carbon, environmentally sound, reliable, and affordable energy supply”

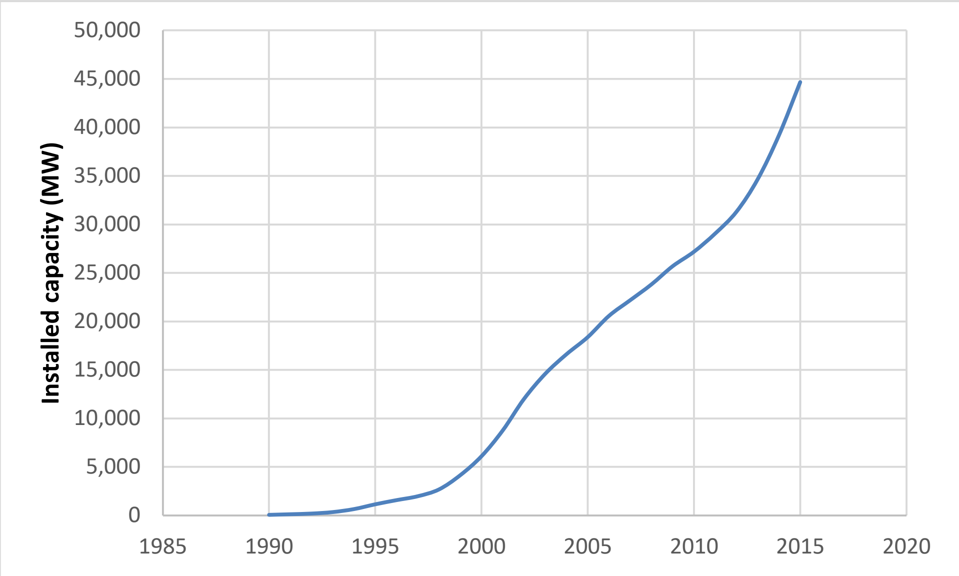


Figure 11: Cumulative of Wind Installed Capacity in Germany (own analysis based on [3]).

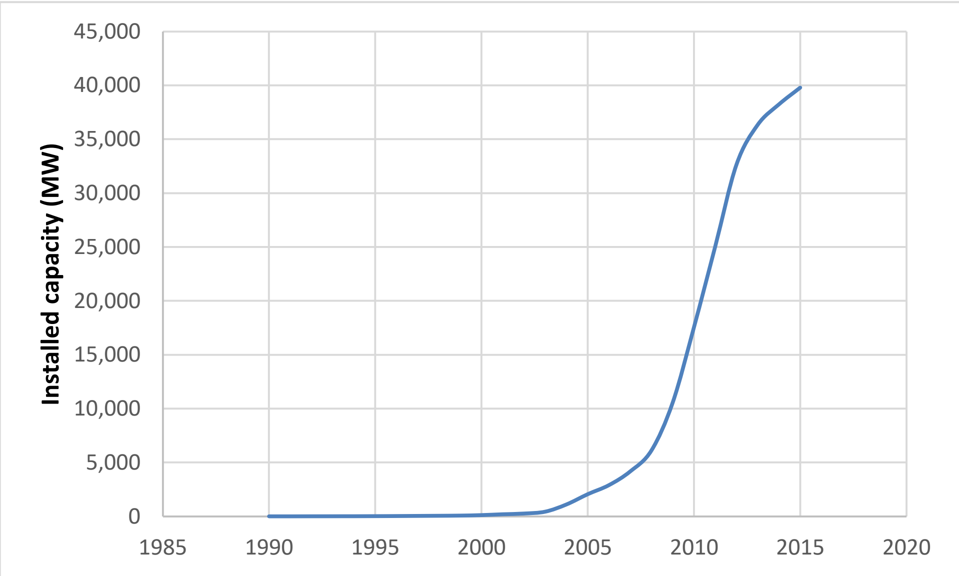


Figure 12: Cumulative of Solar Installed Capacity in Germany (own analysis based on [3]).

Figures 11 and 12 above shows the effect of the Energiewende in terms of the increase in the installed capacity of wind and solar energy from 1990 till 2015.

The German wholesale electricity market as a typical power market consist of three parts:

- Bilateral OTC market, usually trading of energy derivatives up to one year;
- Spot market;
- Intraday Market [28].

Most of the trading happens via the bilateral contracts, although sizable volumes go through the day ahead spot market.

Though the price of electricity in the wholesale market is continuously decreasing due to the low marginal cost of renewables and the increase in energy efficiency, as well as the recent global economic recession, yet the retail market price has increased for the normal an industrial consumer with the increase in the other fees especially the EEG Surcharge and the power tax.

The following figure shows a typical household bill breakdown in Germany in 2014, the figure shows that more than 50% of the bill is actually governmental fees and taxes [26].

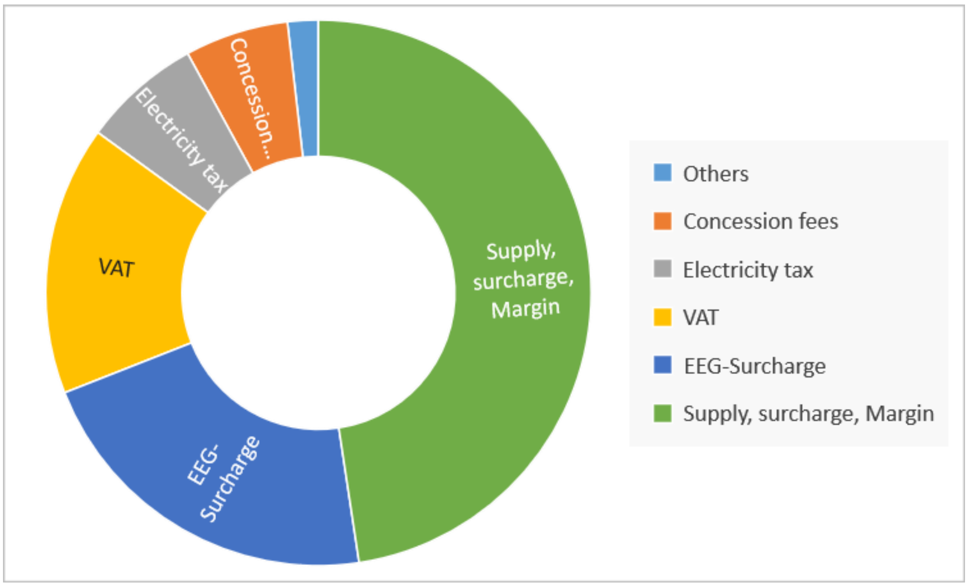


Figure 13: Breakdown of an average household electricity bill in Germany 2014 [26]

3.2. France

The French power system is dominated mainly by nuclear power which in 2015 accounted for 49% of the installed capacity and 77% of the total generation. While renewables in France generates only 16.6%, mainly hydro power whith 10.4%, followed by wind and solar with 3.7% and 1% respectively. The following figure illustrates the energy mix of France in 2015.

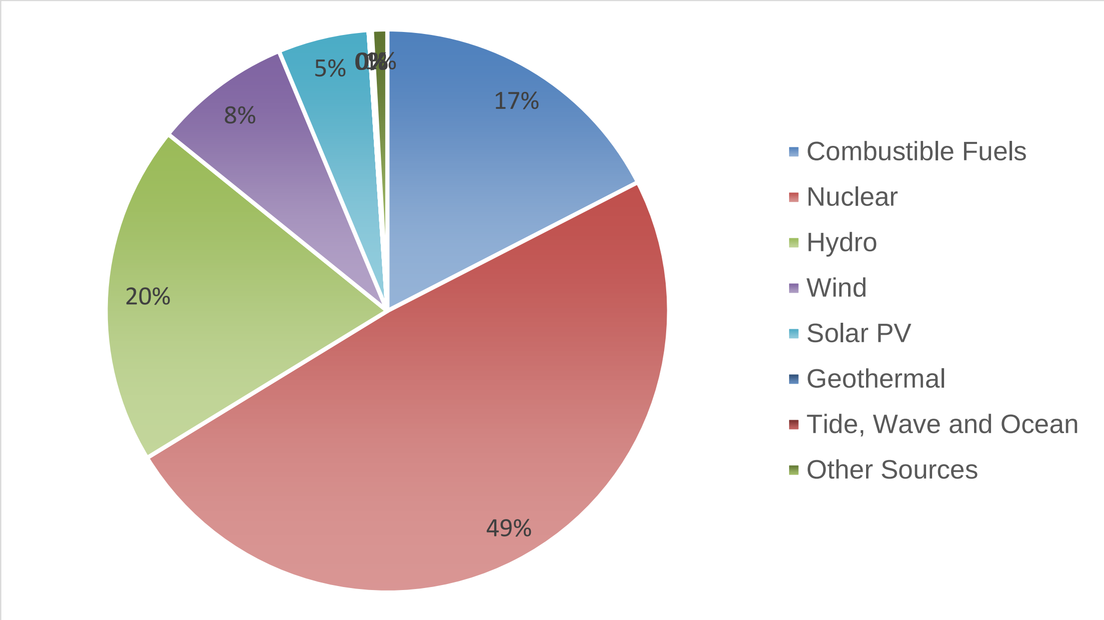


Figure 14: French Power Mix (Installed capacity) – 2015 (own analysis based on (3)).

In 2014 the French government adopted an ambitious legislative package called Energy Transition Bill for Green Growth, which included several goals:

- Reduction the share of nuclear energy in power mix to 50% by 2025;
- Increase the percentage of renewables in the final energy consumption to 32% by 2030;
- Reduce CO2 emissions by 40% by the year 2030 compared to the level in 1990;
- Reduce fossil fuels consumption by 30% by 2030;
- Reduce final energy consumption by 50% by 2050 [29].

Despite the nuclear dominance in the French power system, yet the recent years saw some increase in the wind and solar energy installed capacity as it is clear from the two following two graphs.

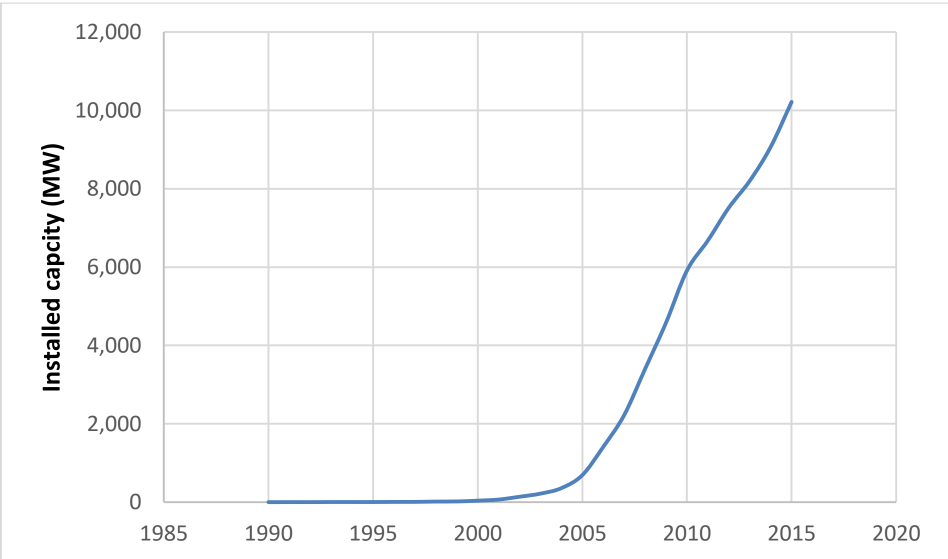


Figure 15: Cumulative of Wind Installed Capacity in France (own analysis based on [3]).

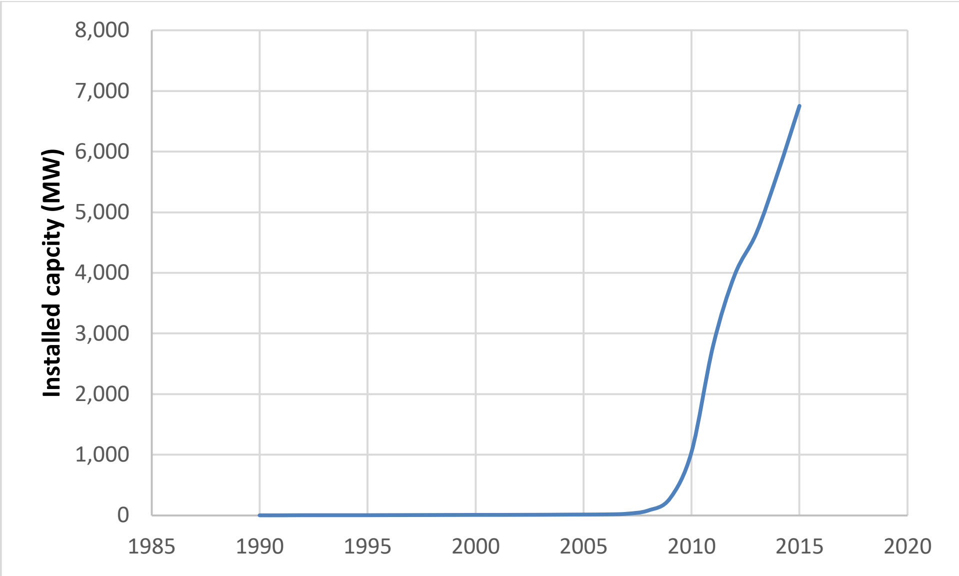


Figure 16: Cumulative of Solar Installed Capacity in France (own analysis based on [3]).

The Power market in France is well concentrated in the hands of Electricité de France (EDF), which is 85% owned by the government.

EDF is responsible for the most generation and retail market in France and it also owns the transmission system operator (TSO) RTE. Although there is a room for choice yet household costumers who get their power from alternative suppliers are blow 10% [29].

The French wholesale market takes a very typical shape of the German one and it is also well connected with the regional central west European regional market CWE.

Nevertheless, the retail market is still regulated, however a movement of deregulating it is going on since 2007 [29].

3.3. Denmark

The power system in Denmark is one of the leaders in Europe in terms of energy transition and renewables integration.

The EU target for Denmark was to get to 30% renewables by 2020 compared to 17% in 2005, yet the government of Denmark took it even further and set a local target of 50% wind energy by 2020 as a step toward the big target of 100% renewable energy mix in electricity and heat sectors by 2035 [30].

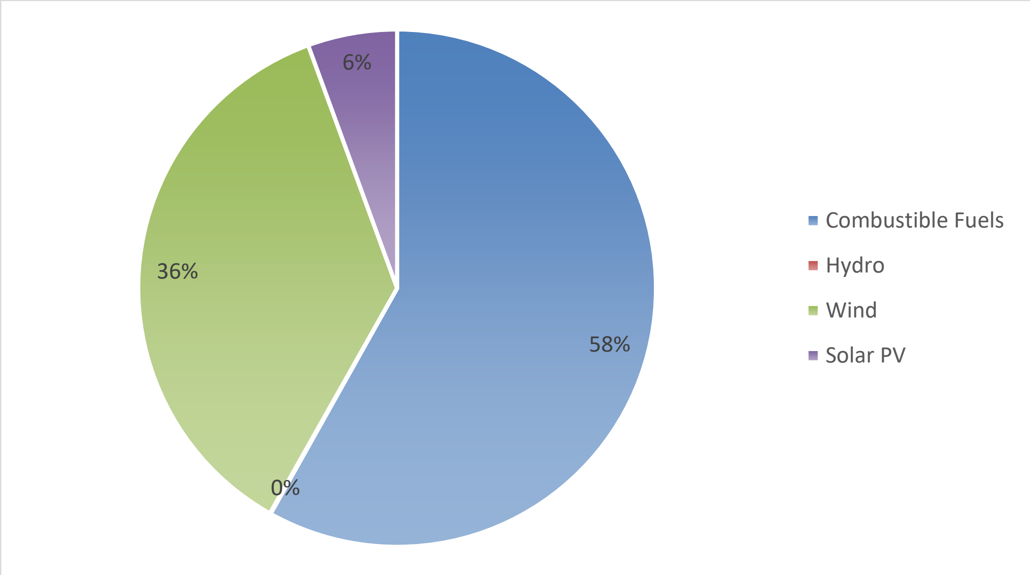


Figure 17: Danish Power Mix (Installed capacity) – 2015 (own analysis based on [3]).

As it can be seen in figure 17 the Danish power system depends mainly on combustible fossil fuels and wind energy with 58% and 36% respectively. The rest of the capacity is solar power with 6% share in the energy mix and negligible hydro power capacity.

Despite the difference in installed capacity, yet renewables generated around 66% of the total generation in Denmark in 2015, with 49% of the total generation from wind alone.

Denmark has two power systems, the western and eastern Denmark. The western one is connected to mainland Europe through Germany and the eastern one is connected to the Noord pool powers system which includes Sweden, Norway and Finland. The two systems are operated in the same market, the Noord pool power market [31].

Due to difference in resource availability, Denmark wind energy generation increased much faster and stronger than solar energy.

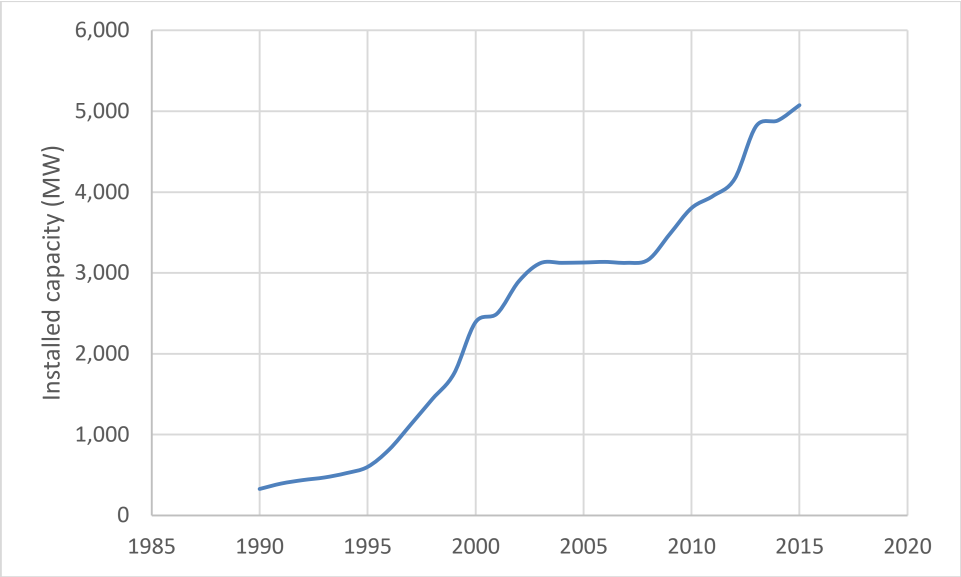


Figure 18: Cumulative wind installed capacity in Denmark (own analysis based on [3]).

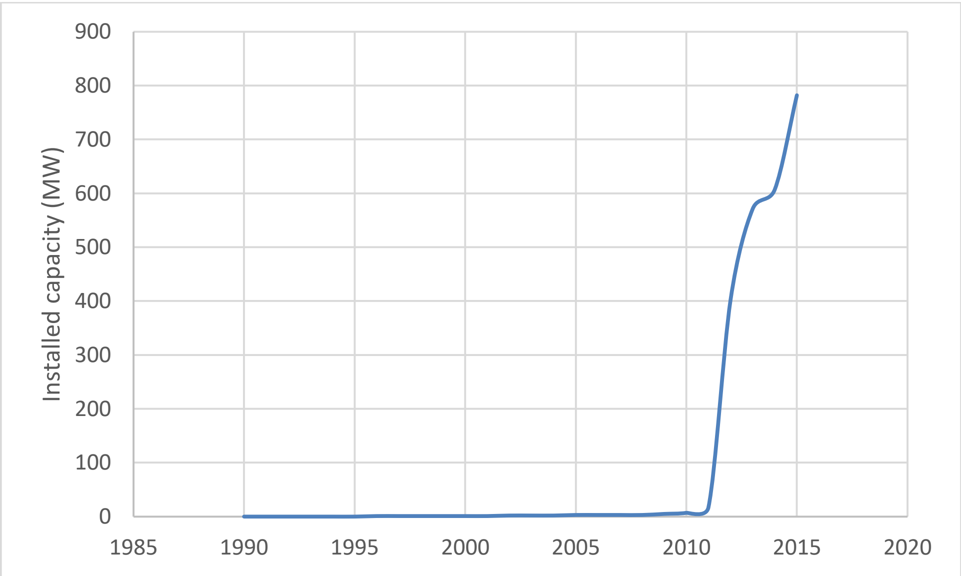


Figure 19: cumulative Solar Installed Capacity in Denmark (own analysis based on [3]).

From the above two figures it is clear that wind energy is improving faster. By the year 2015, while wind energy is surpassing 5 GW solar energy is still blow 1 GW of installed capacity.

3.4. Spain

The peak of electricity generation in Spain happened in 2008 with 311 TWh but after that the country went into economics recession which led to reduction in electricity generation.

The Spanish electricity generation mix is well balanced between fossil fuels and renewables as shown in figure 12 [32].

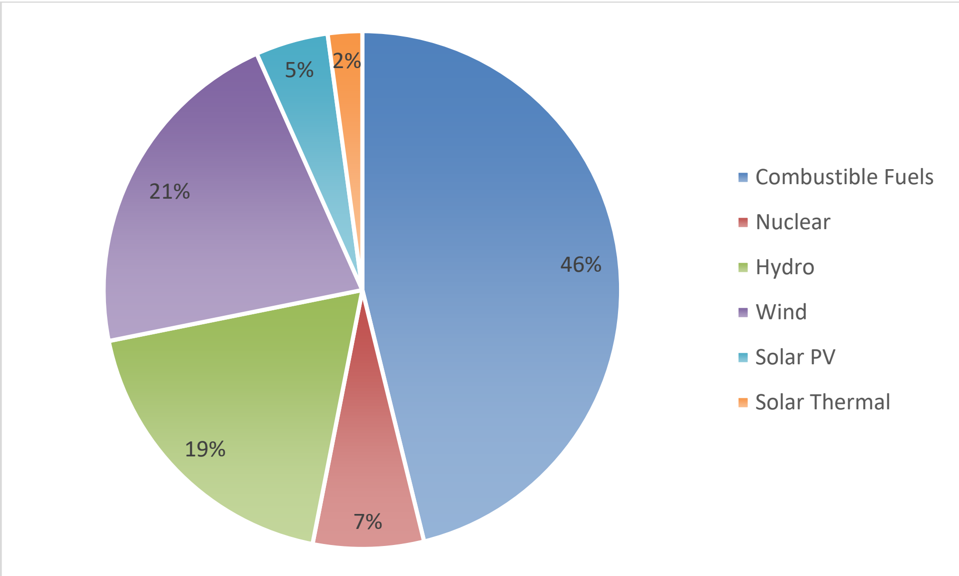


Figure 20: Spanish Power Mix – 2015 (own analysis based on [3]).

With a strong support program, wind and solar power boomed in Spain in the last decade, while coal and oil-fired generation nearly halved, with hydro and nuclear power generation oscillating around their averages of 11% and 20% respectively.

According to the government projections the electricity generation will go up to reach 312.5 TWh in 2020 with wind and solar increasing in a lower rate than before [32].

As a result of the cooperation of the Portuguese and Spanish power systems the MIBEL power market established to operate the electricity trading in the Iberian Peninsula.

The Iberian electricity market MIBEL consists of two bodies:

- OMIP, the Portuguese partner which manages the forward derivatives market;
- OMIE, the Spanish partner which is responsible of the daily and intraday markets (Spot Market).

The trading at OMIE happens in day-ahead spot market and six intraday auctions, in addition to capacity trading and ancillary services [32].

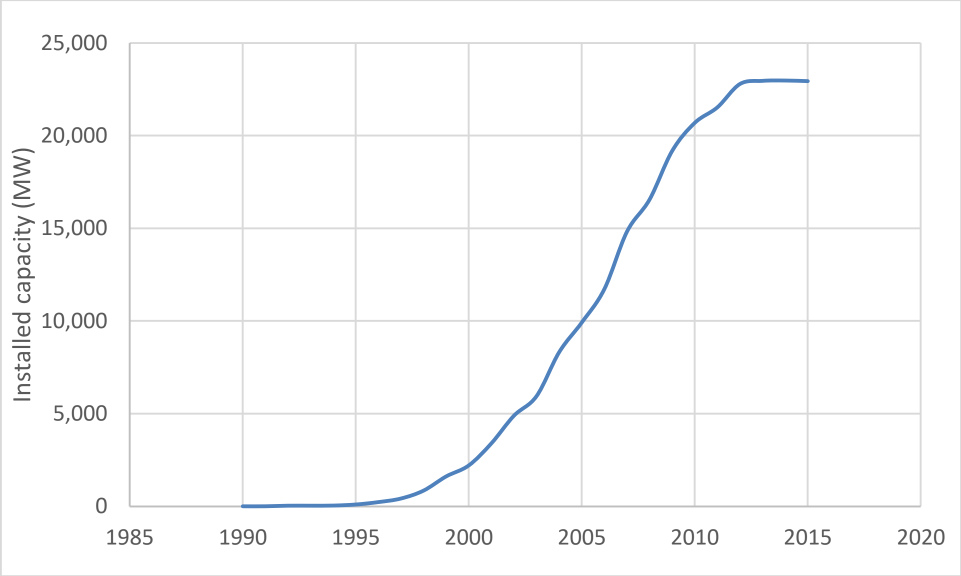


Figure 21: Cumulative wind installed capacity in Spain (own analysis based on [3]).

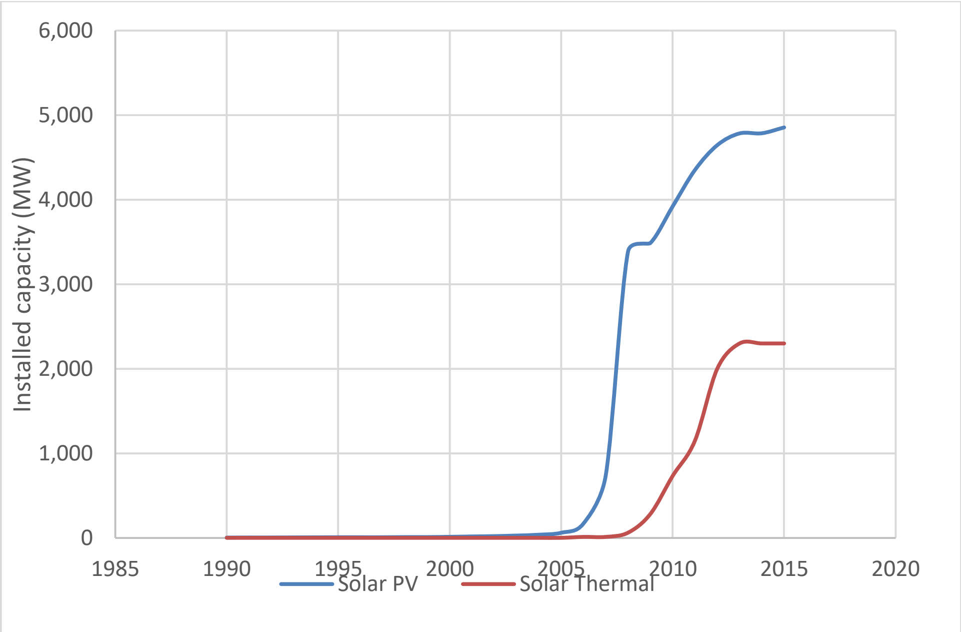


Figure 22: Cumulative Solar installed capacity in Spain (own analysis based on [3]).

3.5. Portugal

The annual electricity generation in Portugal is volatile due to the seasonal change of hydropower. The electricity generation mix in Portugal is diverse as in the past decade it undergone an increase in variable renewables, led by wind energy. At the same time the fossil fuel generation saw a significant decline.

The wind energy expanded from 1.8% of total generation in 2004 to 23.3% in 2014 which makes the share of wind energy in the energy mix the second highest in Europe after Denmark [33].

Figure 15 below shows the energy mix for Portugal in 2015, where Hydro power is the second in capacity, but it is the first in total generation with nearly half of the power generated in Portugal.

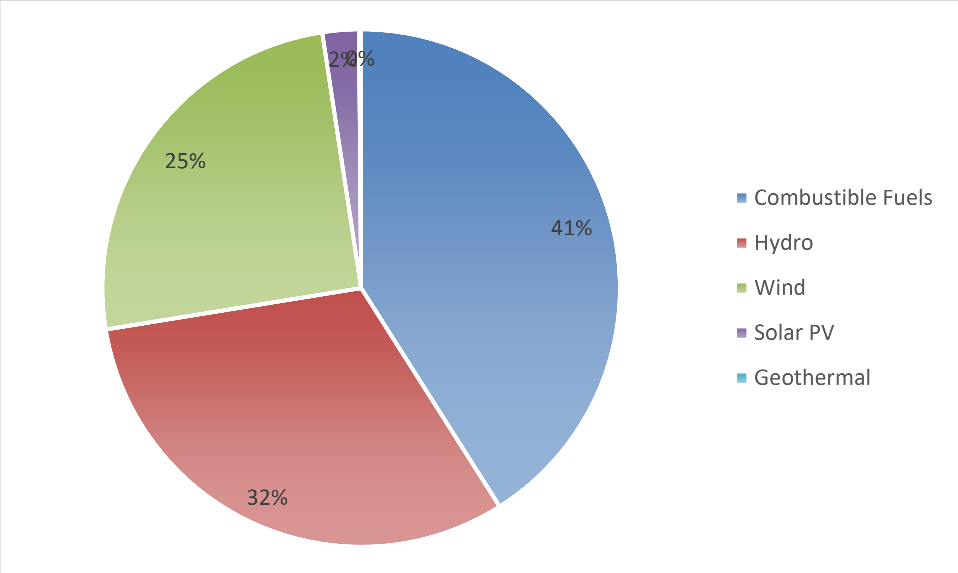


Figure 23: Portuguese power mix (Installed capacity) – 2015 (own analysis based on [3]).

In generation market, the share Energias de Portugal (EDP) Group - who is the main player in the market- has fallen largely in terms of installed capacity due to the rapid increase of renewables (excluding hydro), a field of which EDP holds a limited share.

In 2015, the market shares and sales volume for the wholesale market was 51% for EDP and small shares for REN Trading, Iberdrola and Endesa, while renewable energy generators represent 40% of volume in wholesale physical trades. Several other market participants were active in the wholesale market [33].

The increase of wind and solar power installed capacities in Portugal is shown in the following two graphs.

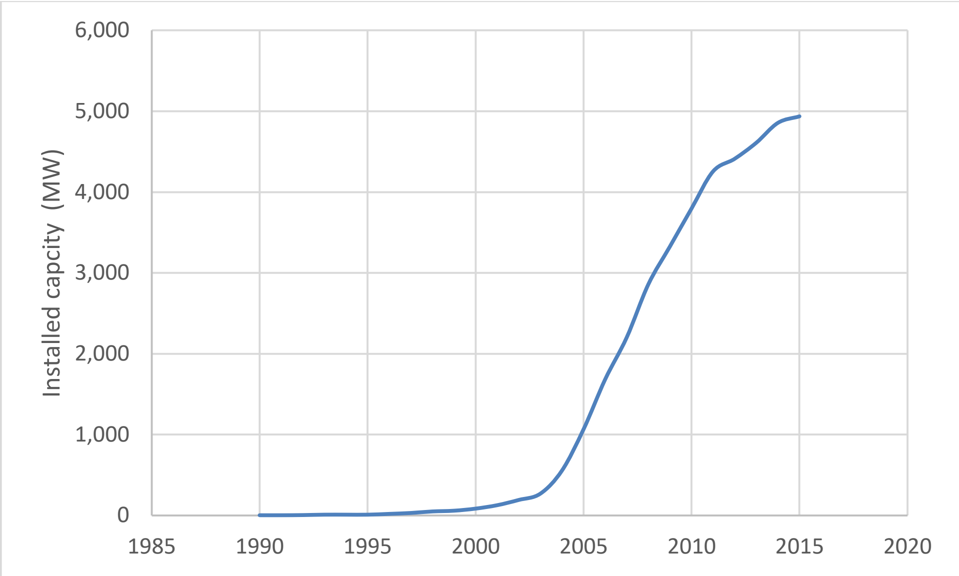


Figure 24: Cumulative Wind installed capacity in Portugal (own analysis based on [3]).

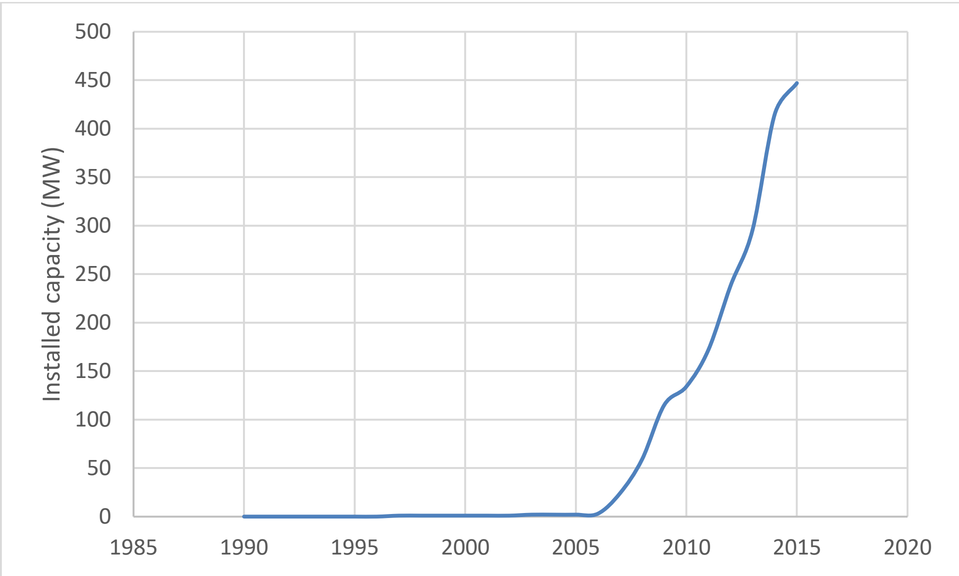


Figure 25: Cumulative Solar installed capacity in Portugal (own analysis based on [3]).

In contrast to Spain, Portugal focused more on wind energy which is clear from the two graphs. By year 2015, wind installed capacity is more than ten times the installed capacity for solar power.

3.6. Method of Analysis

After the determination of the study sample countries, those countries data was carefully considered and analyzed as follows.

First, we did the determination of critical hours, when the system flexibility is examined. Critical hours are those hours of the year where:

- Load is larger than forecasted with the generation form the VRE (wind and solar) being lower than expected (Top Hours) or,
- Load is lower than forecasted, with a generation higher than the forecasted from VRE (Bottom Hours).

In those critical hours, the prices in the spot and intraday markets are expected be different than the normal averages.

- The forecasted and actual VRE generation were taken from ENTSO-E platform for all the five countries, along with the same data for load;
- All the data was normalized to hourly basis, because some countries TSOs provide data on half hourly or sometimes quarter hourly numbers;
- The difference between forecasted and actual load and variable generation was taken and then the top 20 hours and bottom 20 hours was determined. Those critical hours are the numbers that were actually analyzed as they show the extreme variation that happens in the system;
- The prices in those hours were taken from the respective markets and transmission systems operators' websites.

Sample of the tables is shown below with the rest in the appendix. Analysis for these data is done and the results are discussed in the following chapter.

Table 1: Determination for top and bottom critical hours for Germany in 2015

Number	**Top 20 Hours**	**Date and Time**	**Bottom 20 Hours**	**Date and Time**
	lower generation and higher demand (MW)		higher generation and lower demand (MW)	
1	17219.75	24.6.15 11:00	-13526.25	24.12.15 7:00
2	17042.25	24.6.15 12:00	-13083.5	25.12.15 23:00
3	15772	24.6.15 10:00	-13075.25	24.12.15 8:00
4	14914.5	24.6.15 13:00	-12642	24.12.15 6:00
5	14556	24.6.15 9:00	-12356.5	24.12.15 15:00
6	14217.5	24.6.15 14:00	-11896	24.12.15 14:00
7	14142	24.6.15 8:00	-11800.25	26.12.15 0:00
8	13132	19.11.15 8:00	-11333.25	24.12.15 10:00
9	12729	24.6.15 15:00	-11311.25	24.12.15 9:00
10	12648.5	24.6.15 7:00	-11122.75	24.12.15 11:00
11	12504.75	13.5.15 15:00	-11051.5	25.12.15 22:00
12	12491.75	18.11.15 9:00	-11011.75	24.12.15 13:00
13	11795.25	18.11.15 1:00	-10901.5	12.12.15 23:00
14	11761	18.11.15 2:00	-10822.25	24.12.15 16:00
15	11728.25	13.5.15 14:00	-10491.75	24.12.15 12:00
16	11580	30.11.15 8:00	-10196.25	24.12.15 19:00
17	11535.5	18.11.15 3:00	-9994	25.12.15 21:00
18	11517.5	17.6.15 16:00	-9743	2.10.15 13:00
19	11504.5	13.5.15 16:00	-9709.75	24.12.15 20:00
20	11478.75	17.6.15 13:00	-9493.5	28.12.15 8:00

Table 2: Top 20 hours with the respective prices of Spot Market and Intraday Market prices in Portugal (2016)

Number	Top 20 Hours lower generation and higher demand (MW)	Date & Time	Spot Market Price	Intraday Market Price
1	1361	27.2.16 12:00	€ 5.59	€ 8.02
2	1332	27.2.16 11:00	€ 6.50	€ 9.41
3	1280	31.3.16 0:00	€ 23.34	€ 22.30
4	1275	5.1.16 13:00	€ 36.98	€ 36.23
5	1268	25.11.16 22:00	€ 52.00	€ 50.30
6	1267	28.2.16 2:00	€ 4.00	€ 5.25
7	1265	27.2.16 14:00	€ 5.10	€ 6.50
8	1263	27.2.16 21:00	€ 10.50	€ 10.50
9	1243	27.2.16 23:00	€ 5.40	€ 7.20
10	1242	5.1.16 21:00	€ 34.42	€ 34.92
11	1219	6.1.16 15:00	€ 12.40	€ 14.00
12	1198	26.6.16 23:00	€ 30.35	€ 33.75
13	1197	6.9.16 21:00	€ 51.19	€ 52.47
14	1187	28.2.16 1:00	€ 5.09	€ 9.09
15	1184	5.1.16 22:00	€ 32.99	€ 32.99
16	1178	6.1.16 16:00	€ 12.40	€ 12.55
17	1171	25.11.16 21:00	€ 58.78	€ 56.78
18	1161	27.2.16 10:00	€ 7.60	€ 11.10
19	1158	28.2.16 3:00	€ 4.00	€ 5.05
20	1148	27.2.16 0:00	€ 6.50	€ 9.50

4. Results and Discussion

The results for the five countries showed wide spectrum of variation, indicating the differences in their power system characteristics, starting from countries where the effect was clear, to other countries where the impact was minimal.

This chapter will discuss findings of each country results for the two years and then compare the five countries results.

4.1. Germany Results

The German power system showed very high prices variation in the top and bottom hours as shown in the figures below.

In general the prices vary between 93.5 €/MWh and -19.9 €/MWh for top hours, while for bottom hours it varies between 38.8 €/MWh and – 70 €/MWh.

The Intraday market is more affected by the critical hours as it reaches a peak of 93.5 €/MWh in the top hours of 2015 while it hits – 70 €/MWh in the bottom hours for the same year.

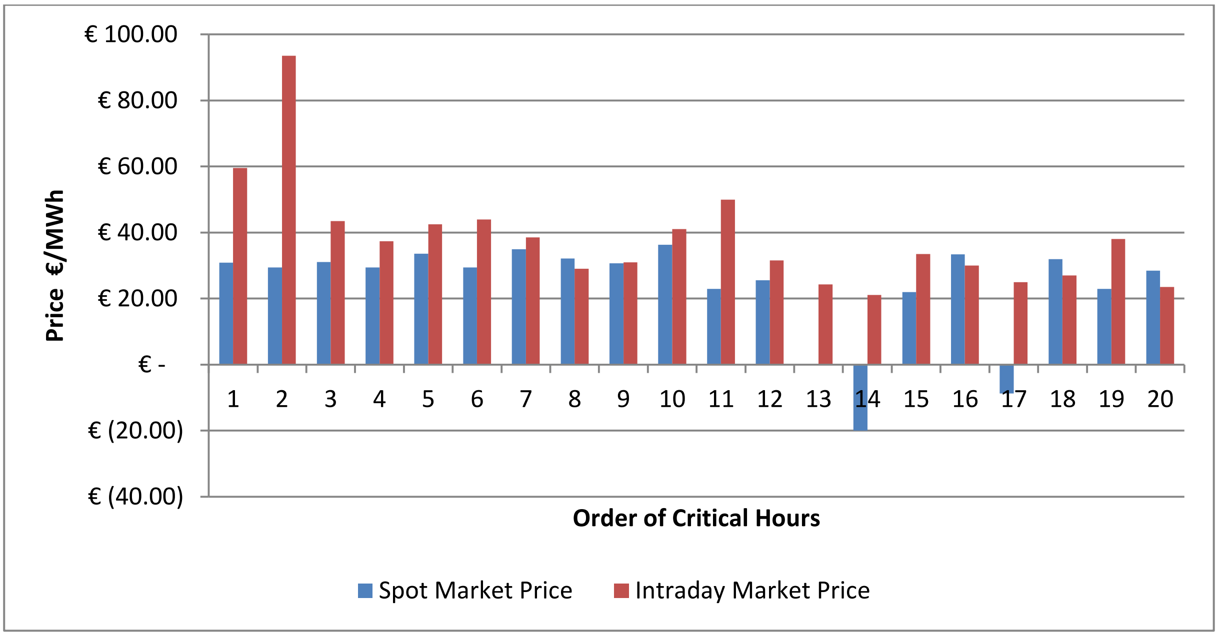


Figure 26: Prices for top critical hours in 2015 for Germany (own analysis based on *[24]* and *[3]*).

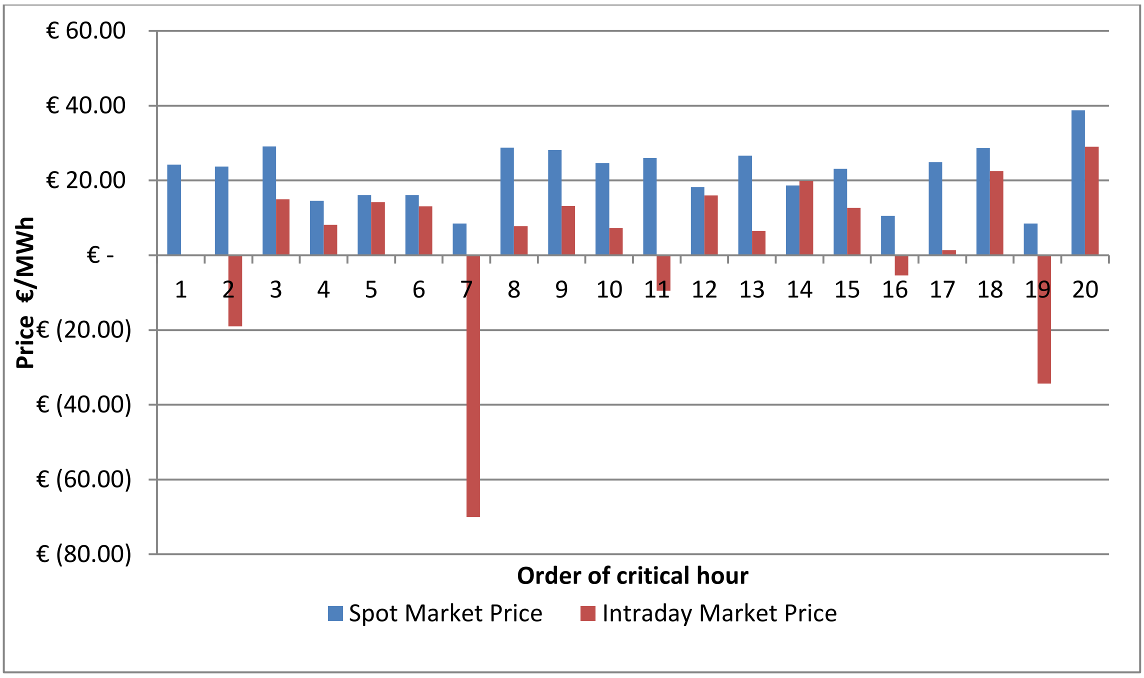


Figure 27: Prices for bottom critical hours for 2015 in Germany (own analysis based on *[24]* and *[3]*).

For 2016 the Intraday market prices spread was a bit lower as the highest peak for top critical hours was 61.95 €/MWh and the lowest for bottom hours was -25.01 €/MWh only.

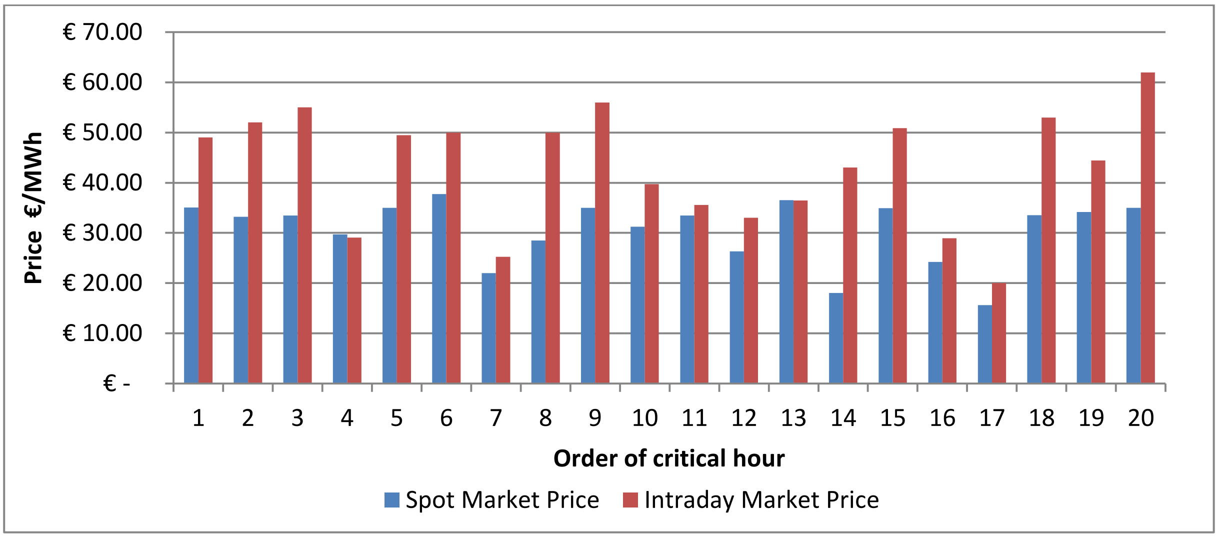


Figure 28: Prices for top critical hours in Germany – 2016 (own analysis based on *[24]* and *[3]*).

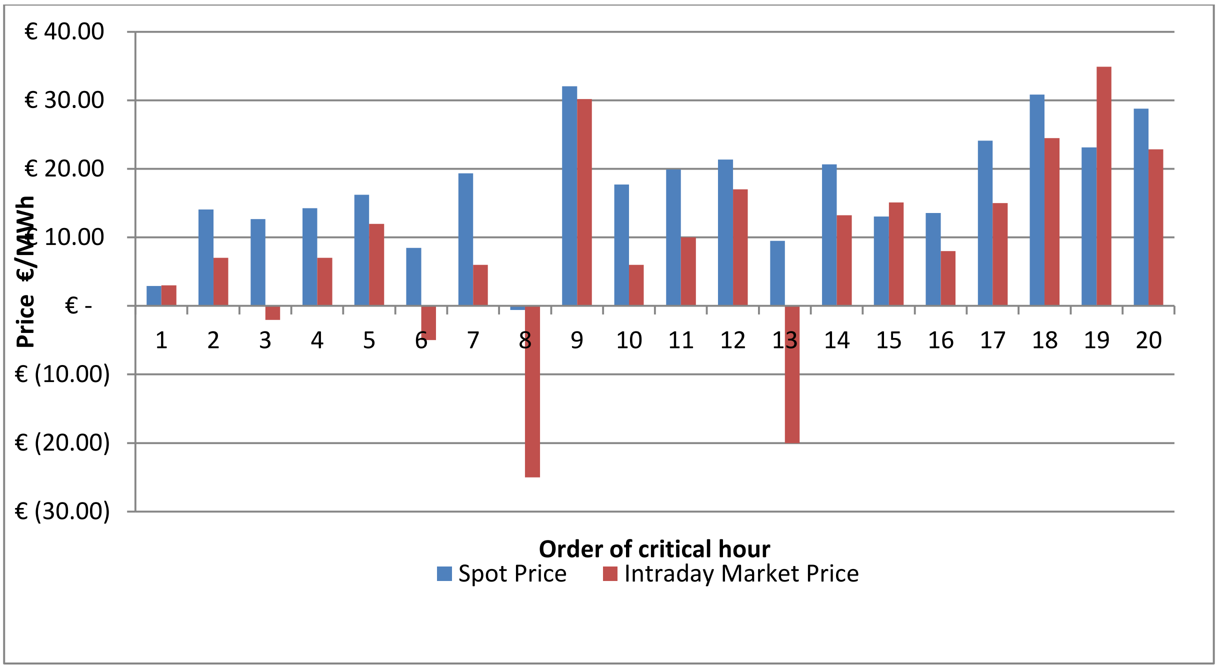


Figure 29: Prices for bottom critical Hours for Germany – 2016 (own analysis based on *[24]* and *[3]*).

From the summary for the two years shown in the table below, the numbers show higher volatility in 2015 compared to 2016.

Table 3: summary for Germany Results

Summary	2015	2016
Range for intraday market prices (Highest – Lowest)	163.50 €	86.96 €
Range for spot market prices (Highest – Lowest)	56.29 €	35.60 €
Average difference between Spot and Intraday Prices	17.75 €	10.34 €

The ranges for the German market are high, and the average difference between the two markets is also on the high side, this indicates the high impact of the VRE variable generation.

These results may be interpreted as a better integration of VRE in the grid in 2016, yet this claim needs more investigation regarding the relevant weather data for the investigated hours and more focus on the load profile, export power and other market factors.

4.2. France Results

As shown in the previous chapter the French power system has a relatively low penetration of VRE while it relies highly on the non-flexible nuclear power generation.

The results for the French system shows lower variability in the spot and intraday market prices compared to Germany. Even though the prices are allowed to go negative in France yet no negative values were recorded in the two years of the study period, and the lowest recorded price in the French intraday market is 0.1 €/MWh which happened in one of the bottom critical hours in 2016.

The following graphs show the French results for 2015 and 2016.

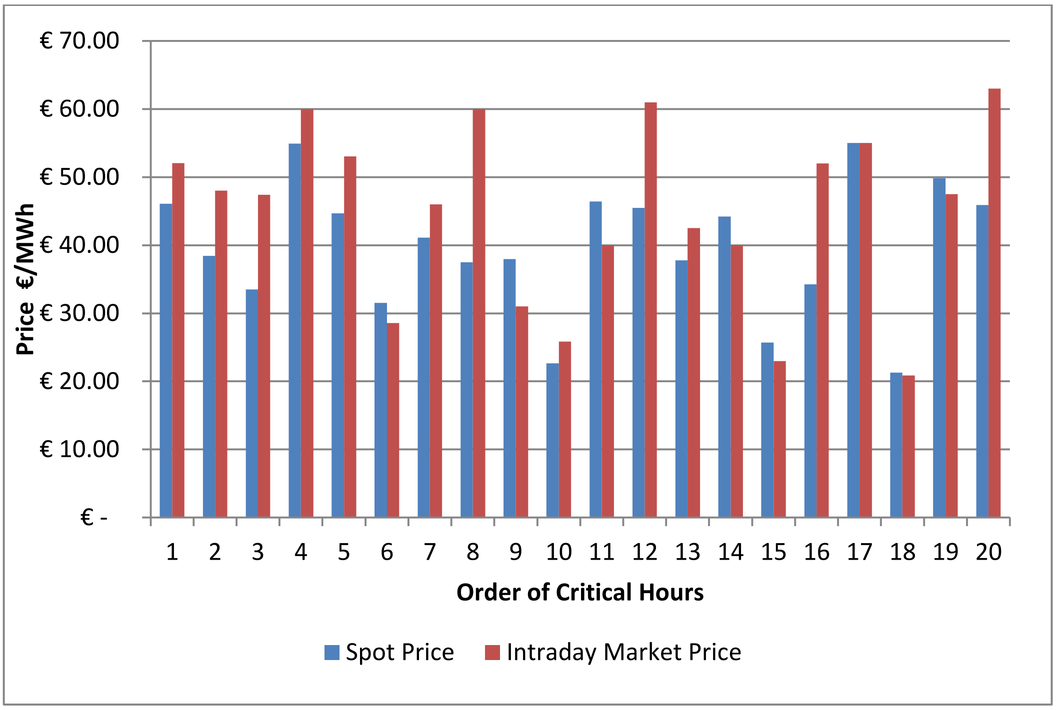


Figure 30: Prices for top critical hours for France – 2015(own analysis based on *[24]* and *[3]*).

Figure 31: Prices for bottom critical hours for France – 2015 (own analysis based on *[24]* and *[3]*).

Figure 32: Prices for top critical hours for France – 2016(own analysis based on *[24]* and *[3]*).

Figure 33: Prices for bottom critical hours for France – 2016 (own analysis based on *[24]* and *[3]*).

From the above shown results it is clear that the average of prices in the top critical hours is higher than the average in the bottom one, with the intraday market being a little more affected. However the difference between the spot market and intraday market is small which mainly a reflection of the low penetration of VRE.

Table 4: Summary of France Results

Summary	2015	2016
Range for intraday market prices (Highest – Lowest)	52.00 €	78.48 €
Range for spot market prices (Highest – Lowest)	44.48 €	66.08 €
Average difference between spot and Intraday prices	5.74 €	6.01 €

As shown in the summary table, the average offset between Spot and Intraday market prices is limited to around six Euros, with the range of prices in 2016 a bit bigger. This can be explained as the share of VRE higher in 2016 compared to 2015.

4.3. Denmark Results

The main two characters of the Danish power system as mentioned before is that:

- It consists of two adjacent power systems of east and west parts of the country;
- It is highly penetrated by wind power.

To deal with the first one, in this work, the average of the numbers between the two parts is taken in consideration.

In general, the average intraday and spot market prices are lower on average than the prices in the German and French markets. Further there is no recognized difference in the average prices between top critical and bottom critical hours.

The results show more volatility in the Spot market prices than the Intraday market prices; the Spot market price hit negative values several times in 2016 with the lowest at -13.31 €/MWh, while the lowest Intraday prices was zero and recorded in 2015.

The Following graphs illustrate the results for the Danish power market in 2015 and 2016. In 2015, there was no record for negative prices in the critical hours for both spot and intraday market prices, yet the intraday market recorded a zero once. The highest price is around 40 €/MWh in both markets with the spot market a little higher than the Intraday market.

In 2016 the prices look quite similar for Top and Bottom critical hours, and except for the four times of negative Spot market prices, the Intraday and Spot market were very close in values.

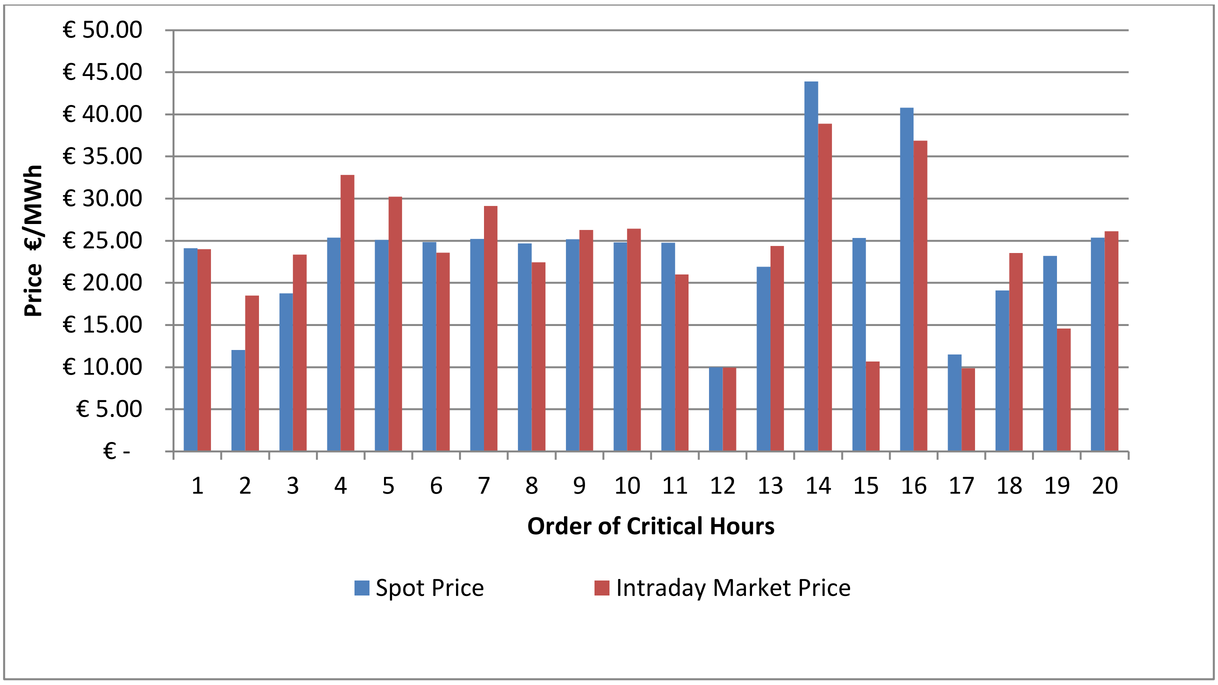


Figure 34: Prices for top critical hours for Denamrk – 2015 (own analysis based on *[24]* and *[3]*).

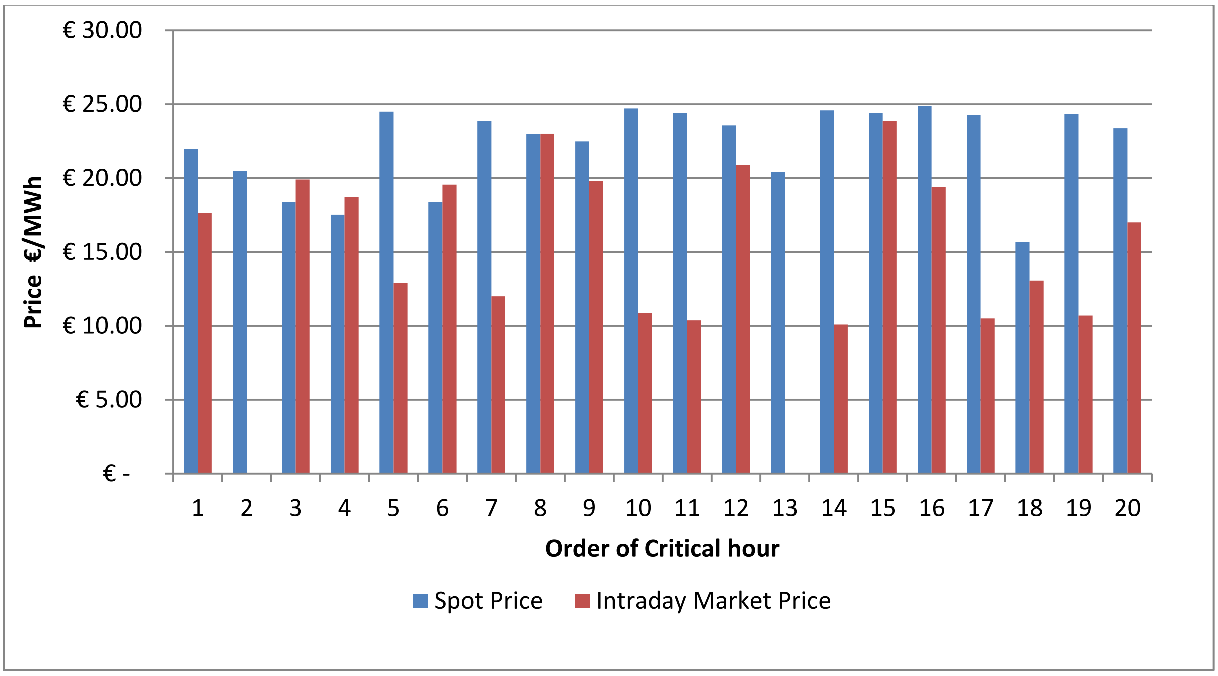


Figure 35: prices for bottom critical Hours for Denmark – 2015 (own analysis based on *[24]* and *[3]*).

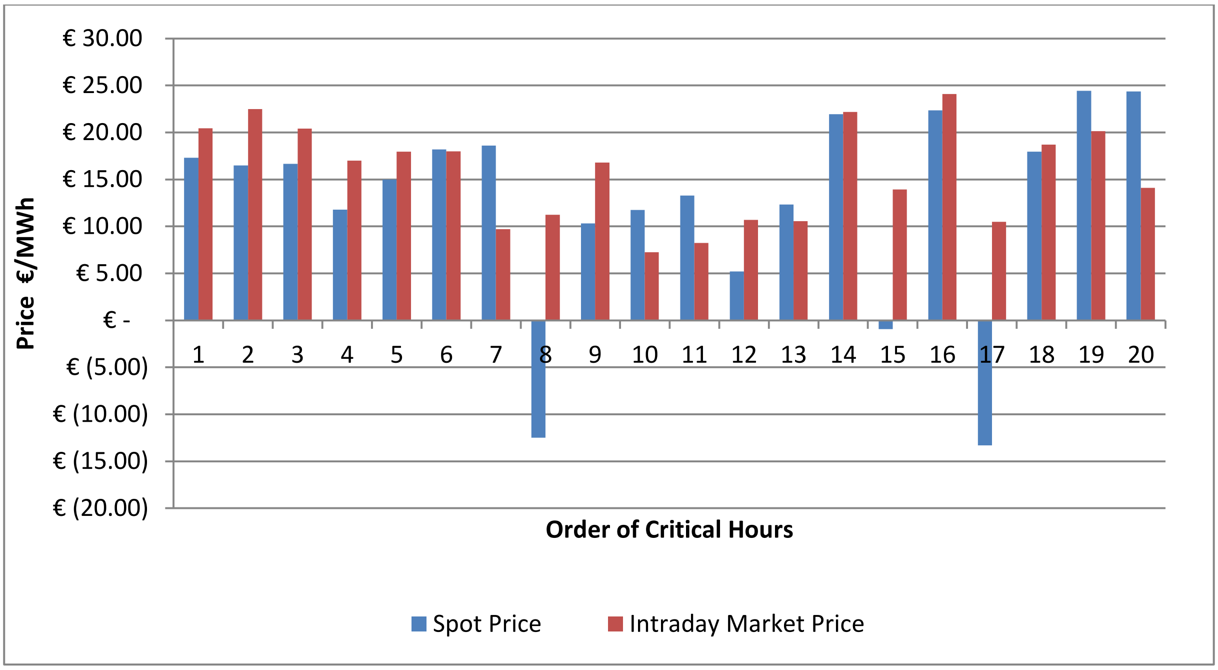


Figure 36: Prices for top critical hours for Denmark – 2016 (own analysis based on *[24]* and *[3]*).

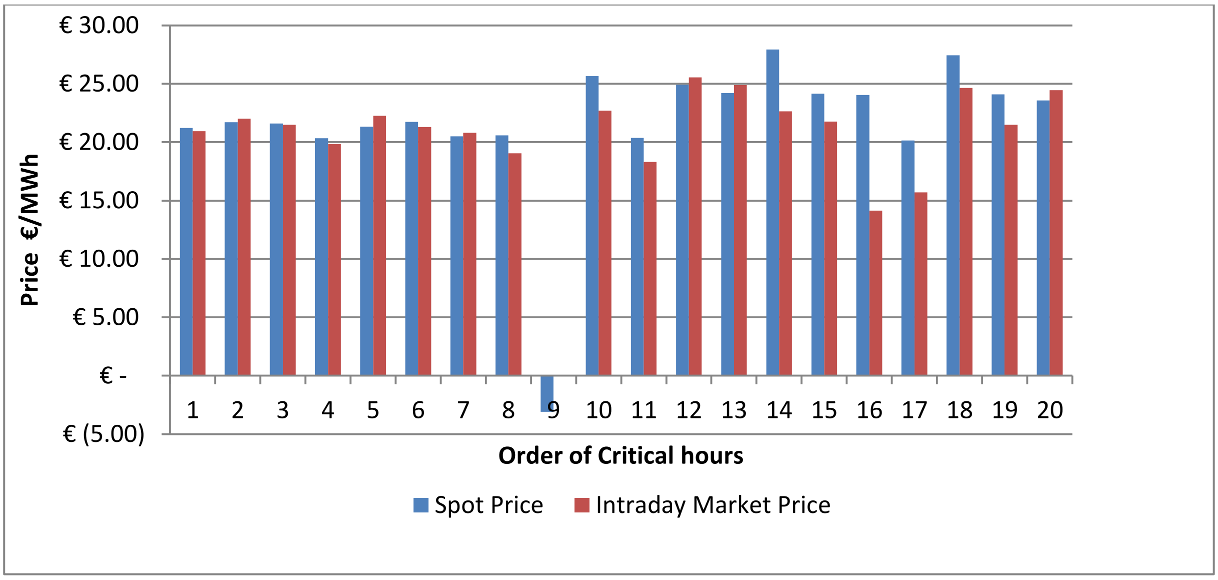


Figure 37: Prices for bottom critical hours for Denmark – 2016(own analysis based on *[24]* and *[3]*).

The Danish power market needs to be studied in more detail. The circumstances of the neighboring power systems in the Noord Pool and Germany need to be considered, because the power system size is relatively small and gets affected more by the import and export of power. Also, the connection between the two parts of the system needs to be investigated and analysis of the net transfer power between them is critical to be considered in any future study for the Danish power system.

Table 5: Summary of Denmark Results

Summary	2015	2016
Range for intraday market prices (Highest – Lowest)	38.88 €	25.55 €
Range for spot market prices (Highest – Lowest)	33.95 €	41.24 €
Average difference between Spot and Intraday Prices	6.05 €	4.38 €

Although the Danish system has high share of renewables yet its results are a bit lower because it is well connected to its neighbor systems with large capacities of import and export.

4.4. Spain Results

The results from the Spanish power system showed much more alignment between the Intraday and Spot market prices in all of the two years in both top and bottom prices.

In general the power prices in Spain are the highest on average compared to the other countries in the study sample.

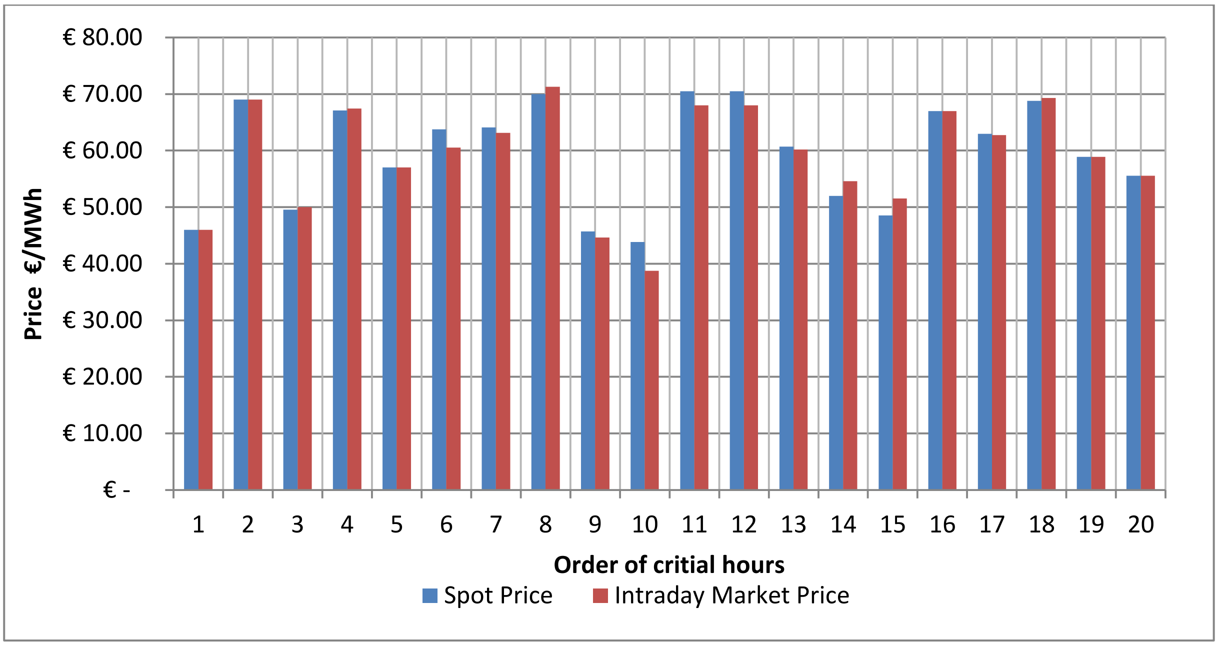


Figure 38: Prices for top critical hours for Spain – 2015 (own analysis based on *[24]* and *[3]*).

The graphs for 2015 show high prices where the minimum of the Intraday market was 29.8 €/MWh and for Spot market 34.8 €/MWh. In the same period the peak for spot market and intraday market were recorded at 70.48 €/MWh and 71.27 €/MWh. Those values show that the prices are just slightly affected by the critical hours; where we find the average in the bottom critical hours is a bit lower than the average in the top critical hours of the system.

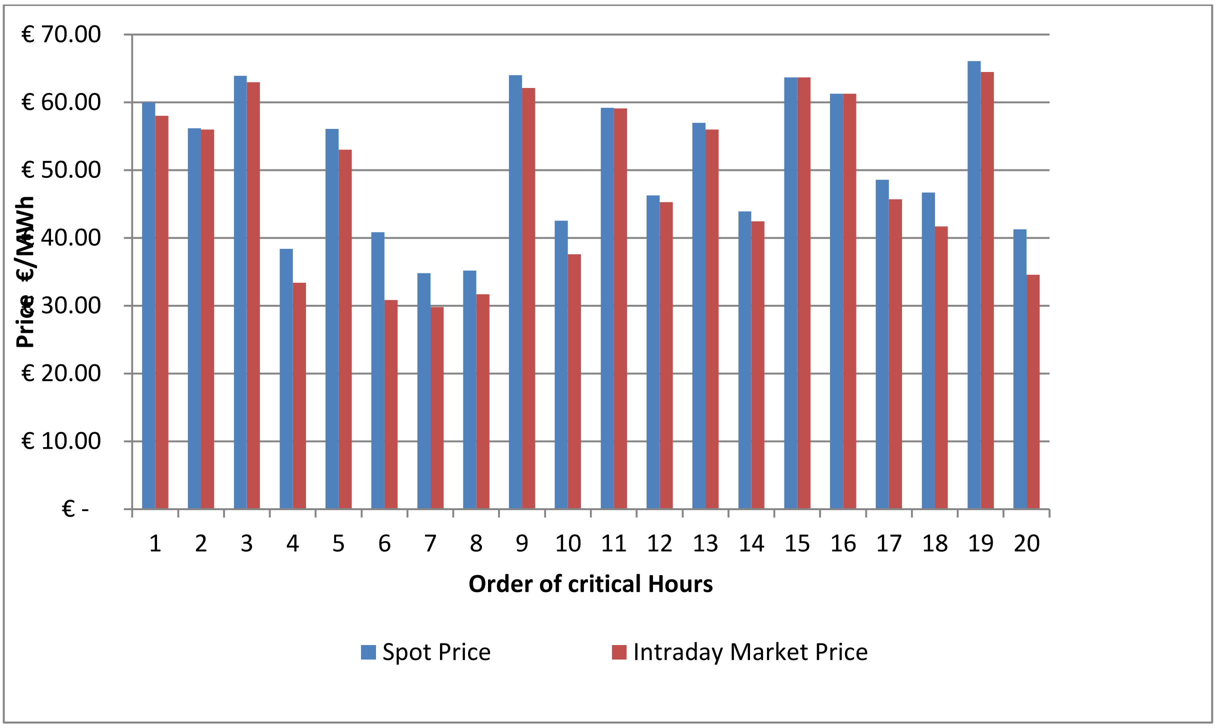


Figure 39: Prices for bottom critical hours for Spain – 2015 (own analysis based on *[24]* and *[3]*).

For 2016 the same argument goes with just small decrease in the average prices for both markets in both to and bottom critical hours.

Figure 40: Prices for top critical hours for Spain – 2016 (own analysis based on *[24]* and *[3]*).

The 2016 graphs show more volatility with the prices hitting a near zero values, where the spot market recorded a value of 2.3 €/MWh and the intraday market recorded a 1.1 €/MWh.

The peak values were lower than those of 2015, which indicates a general reduction in power prices in Spain in 2016 compared to 2015.

Figure 41: Prices for bottom critical hours for Spain – 2016 (own analysis based on *[24]* and *[3]*).

The summary table below indicates the lower volatility in 2015 compared to 2016 shown in terms of the range for the market prices. It also shows the minimal effect of the VRE generation illustrated in the negligible difference between intraday and spot market prices.

Table 6: Summary of Sapin Results

Summary	2015	2016
Range for intraday market prices (Highest – Lowest)	41.47 €	61.38 €
Range for spot market prices (Highest – Lowest)	35.68 €	58.39 €
Average difference between Spot and Intraday Prices	2.02 €	1.33 €

4.5. Portugal results

The results for Portuguese power systems show very similar trends to those of the Spanish power system; the Prices are normally on the high side and the intraday market and spot market prices almost coincide.

The following graphs show the results for Portugal, where in 2015 results the prices were a little bit lower than the Spanish results with the highest prices for intraday and spot markets recorded at 67.81 €/MWh and 69.81 €/MWh respectively.

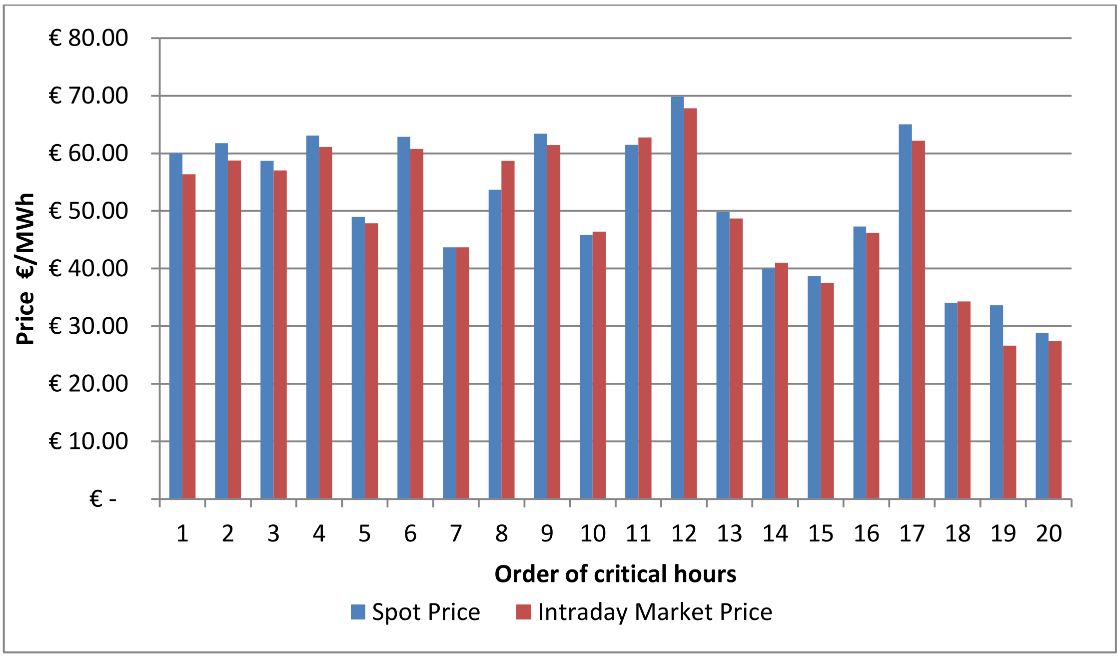


Figure 42: Prices for top critical hours for Portugal – 2015 (own analysis based on *[24]* and *[3]*).

The lowest prices were 26.6 €/MWh for Intraday market and 28.69 €/MWh for Spot market which is marginally lower than the values for Spanish power system in the same period.

Figure 43 : Prices for bottom critical hours for Portugal – 2015 (own analysis based on *[24]* and *[3]*).

For 2016 the system shows more diversity in the prices, especially in the top critical hours, with several occasions the price hit values below 10 €/MWh.

Figure 44 : Prices for top critical hours for Portugal – 2016 (own analysis based on *[24]* and *[3]*).

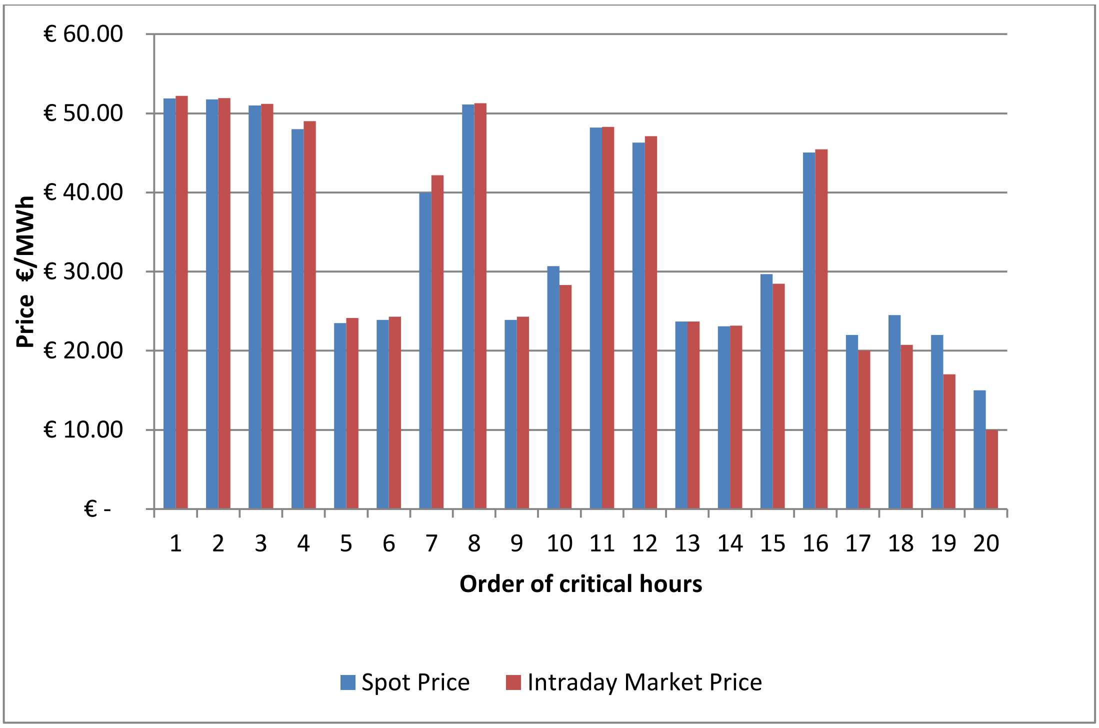


Figure 45 : Prices for bottom critical hours for Portugal – 2016 (own analysis based on *[24]* and *[3]*).

The price was never above 60 €/MWh for both markets in all the top and bottom critical hours with the highest value in 2016 for spot market 58.78 €/MWh and for intraday market 56.78 €/MWh.

The lowest values were 4 €/MWh and 5.05 €/MWh for Spot and intraday markets in that order.

The summary table below illustrates the high range in 2016 compared to 2015 and it also shows the similarity between intraday and spot market prices represented by the minimal average difference in prices between them.

Table 7: Summary of Portugal Results

Summary	2015	2016
Range for intraday market prices (Highest – Lowest)	41.21 €	51.73 €
Range for spot market prices (Highest – Lowest)	41.02 €	54.78 €
Average difference between Spot and Intraday Prices	1.88 €	1.50 €

This result indicates very low impact of the VRE generation on the power market prices in Portugal, yet the system needs more research considering the very crucial connection to Spain. It is highly advised to consider the two countries power systems as one island power system with a connection to France.

4.6. Discussion on Results

The spot market prices compared for all the five countries with respect to their relative VRE percentage to total capacity show diverse values from which we can read:

- Spanish and Portuguese system has almost the same prices which shows the integration of their power systems and the fact that they trade in one market;
- Power prices in Spain and Portugal are the highest of the study group while Denmark has the lowest prices;
- German and Denmark have almost the same percentage and they also have almost same prices in Spot market;
- In France despite the lower VRE penetration the prices are comparable to Denmark and Germany.

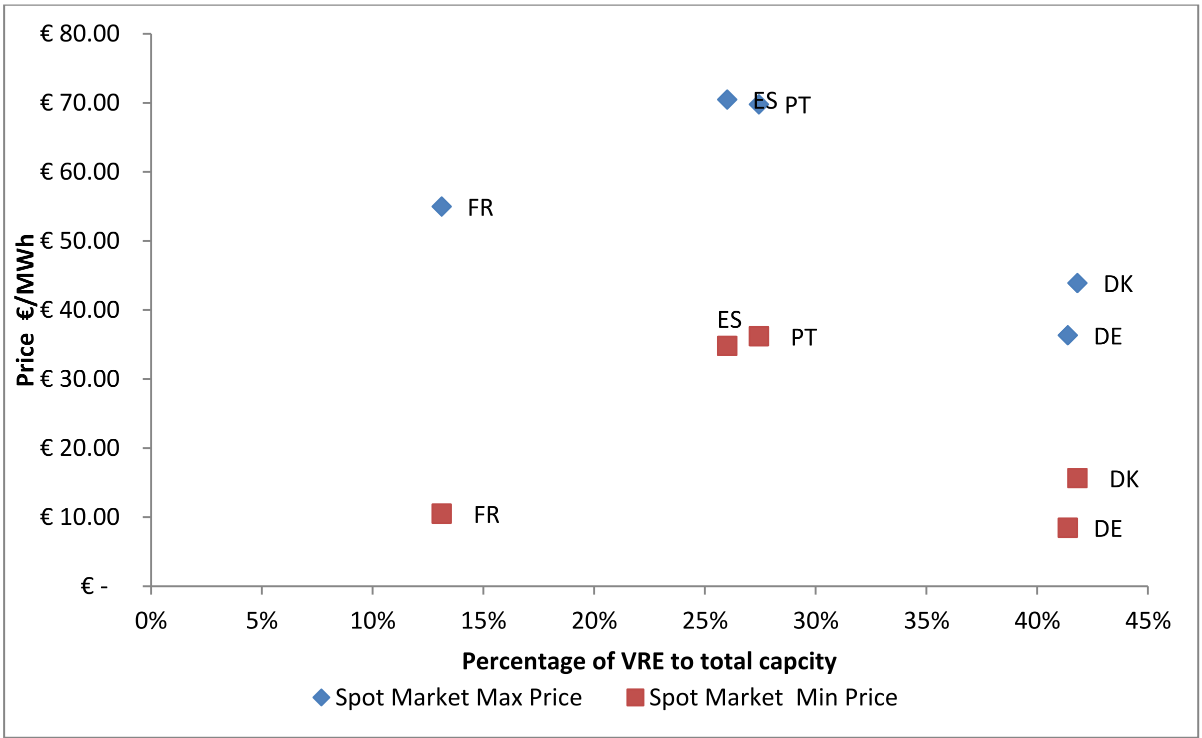


Figure 46: Comparison of Spot market results for the five countries (own analysis based on *[24]* and *[3]*).

Comparing the Spot market graph with the intraday market graph below

- Germany has the highest volatility and price change due to VRE variable generation in the Intraday market, as the prices oscillates in a range more than 160 €/MWh;
- Denmark indicators show that despite the high share of renewables yet they are well integrated so the effect on the prices is not as high as German market due to its high import and export of power with its neighbors;
- France, Spain and Portugal are more or less on same spots on both graphs;

- For France this can be explained because of low VRE share, so the variable generation doesn't affect the system significantly;
- For Spain and Portugal the study procedure doesn't show much effect because the two systems has a very high interaction with diversity in generation types. This diversity in generation makes each one of them a buffer of more flexibility to the other. The high hydro and wind capacity in the Portuguese side adds to the flexibility in the Spanish system where the solar and fossil fuels on the Spanish side are added flexibility and buffer for the Portuguese system. The critical hour's identification needs to be implemented again for the Iberian Peninsula as one system; that means finding points in time when the load and VRE generation in both countries hit peaks and bottoms.

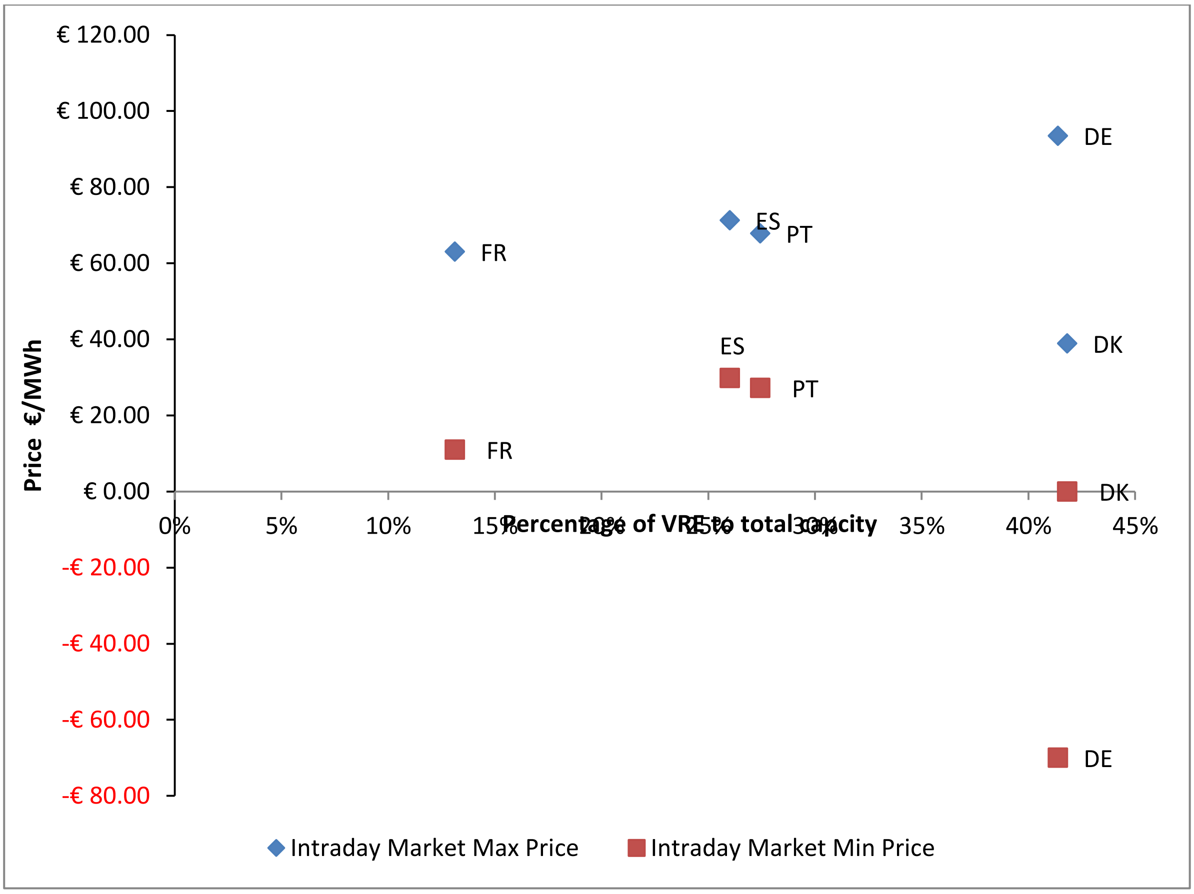


Figure 47: comparison of the intraday market results for the five countries (own analysis based on *[24]* and *[3]*).

5. Conclusion

The regulations and targets set by the EU commission and the local member states governments are the corner stone in the current renewable energy expanded deployment and integration into the power systems.

The recent renewable energy boom led to radical change in the power market due to its impact on the power mix and power prices.

The study for the renewable energy effects on the power markets is vital for the steering of the energy transition movement.

This thesis started with collecting data for all the EU member states to select a suitable study sample which represents as much as possible of the different types of power systems and their characteristics in the EU.

Then VRE actual and forecasted generation data for the selected group was analyzed along with the forecasted and actual load to define critical hours. Those hours on which the system flexibility is challenged. For those hours the intraday market prices and spot market prices were identified and studied to find the patterns.

The study showed strong impacts in the German power system with lower recorded impacts in the Danish, and French power systems, while it recorded only tiny change between the Intraday market prices and spot market prices in the two countries of the Iberian Peninsula.

The study illustrate indicators of the limit of integration of renewables, however for future studies each country power system needs to be considered including its unique characteristics and circumstances.

The price indicators of the renewables might lead to reduction in the investments in the conventional power plants, which brings a risk of lower security of supply in the future.

For the German power system the flexibility of the system needs more attention to minimize the harsh effects on the prices. As illustrated in the results chapter the prices in the German power market had very high and very low values. In Germany the installed VRE capacity scored 105% compared to the peak load. This value might lead to increase in VRE curtailment which is an unwanted economical loss.

In Denmark, each of the two system circumstances need to be considered and the total power import and export to be considered as well in any flexibility and VRE studies in the future. The Percentage of VRE to peak load was recorded at 92.3 %, which makes it on the safe side, but still flexibility issues and curtailment may arise.

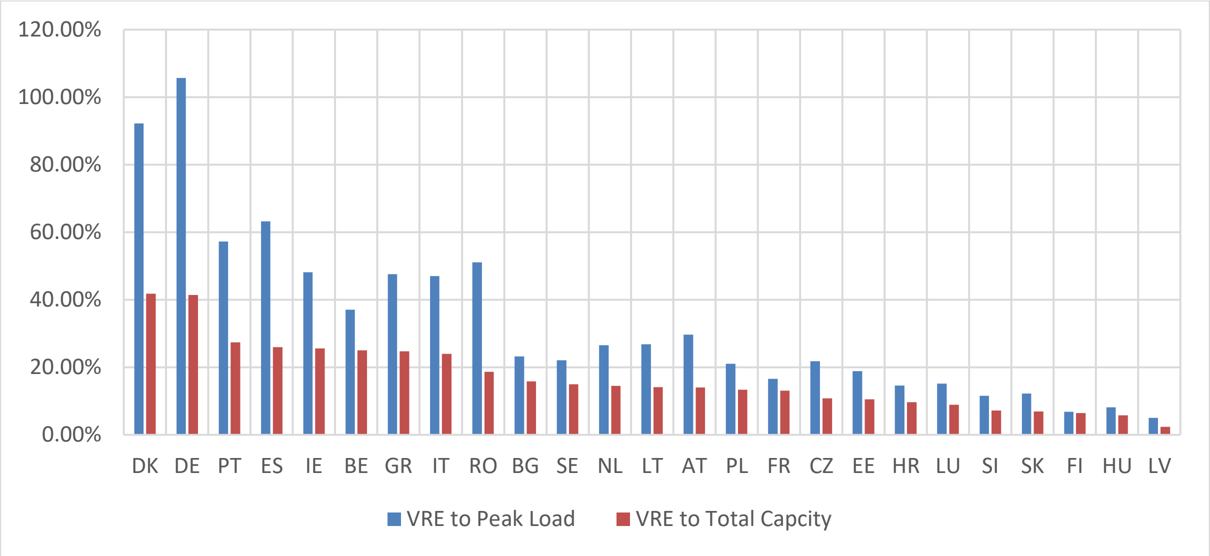
The Portuguese and Spanish systems need a combined study; considering them as a united system with one power market and different system operators. The results from this thesis are only indicative and need more refinement ant further studies to be considered. The percentage of VRE to peak load was very close for both countries as it registered 27.4% and 26% for Portugal and Spain respectively, this mean there still room for more renewables to be installed.

In France the VRE share is minimum but the expansion of renewable technology in general needs to consider the inflexible behavior of the nuclear generation facilities.

For the French power system the percentage of VRE to peak load was the lowest in the group of the study at 16.6%, which shows the gab France has and also indicates the need for much work in this direction.

To conclude, the variable generation of VRE has a recorded impact on the prices and sends some signals of the level of integration and flexibility issues in the power system. However to study the effects and their comprehensive future developments more detailed studies for each country need to be done, considering all the factors and players in the certain power system.

6. Appendices



Appendix 1: Percentage of Installed VRE Capacity to Total capacity and Peak load - All countires (own analysis based on [3]).

Appendix 2: Top and Bottom hours for Germany - 2016

Number	Top 20 Hours lower generation and higher demand (MW)	Date and Time	Bottom 20 Hours higher generation and lower demand (MW)	Date and Time
1	15463.5	4.1.16 11:00	-10453.75	8.5.16 18:00
2	15312.25	4.1.16 10:00	-10201.5	16.4.16 17:00
3	15189.5	4.1.16 9:00	-9509.25	16.4.16 16:00
4	14905.5	19.4.16 9:00	-9364.5	1.5.16 16:00
5	14874.75	4.1.16 12:00	-9291.5	1.5.16 17:00
6	14716	4.1.16 8:00	-9008.5	24.4.16 16:00
7	14410.5	19.4.16 10:00	-8943.75	8.5.16 19:00
8	14052.5	4.1.16 7:00	-8939.25	8.5.16 17:00
9	13874.5	4.1.16 13:00	-8730.5	28.12.16 7:00
10	13637	9.5.16 9:00	-8709	16.4.16 18:00
11	13072	7.1.16 15:00	-8705.25	7.5.16 18:00
12	13040.25	7.4.16 9:00	-8667.5	1.5.16 18:00
13	12936.25	7.1.16 14:00	-8631	24.4.16 15:00
14	12857.75	4.1.16 6:00	-8559.75	5.5.16 18:00
15	12857.25	4.1.16 14:00	-8531.75	24.4.16 17:00
16	12778.5	9.5.16 10:00	-8527.5	1.5.16 15:00
17	12732.25	19.4.16 13:00	-8472.75	18.9.16 13:00
18	12663.25	5.1.16 15:00	-8403	29.4.16 18:00
19	12642	7.1.16 16:00	-8320.5	18.9.16 14:00
20	12562.25	5.1.16 16:00	-8278.25	9.2.16 20:00

Appendix 3: Top and Bottom hours for Denmark - 2015

Number	**Top 20 Hours**	**Date and Time**	**Bottom 20 Hours**	**Date and Time**
	lower generation and higher demand (MW)		higher generation and lower demand (MW)	
1	3538	30.11.15 15:00	-2212	1.12.15 5:00
2	1831	31.3.15 23:00	-2183	1.12.15 4:00
3	1724	31.3.15 22:00	-2102	1.12.15 3:00
4	1720	31.3.15 18:00	-2052	1.12.15 2:00
5	1665	31.3.15 19:00	-2016	1.12.15 8:00
6	1614	10.11.15 10:00	-1846	1.12.15 1:00
7	1581	31.3.15 17:00	-1837	1.12.15 7:00
8	1446	12.4.15 20:00	-1783	1.12.15 6:00
9	1431	31.3.15 16:00	-1775	18.5.15 23:00
10	1398	31.3.15 20:00	-1664	1.12.15 10:00
11	1335	12.4.15 21:00	-1645	1.12.15 9:00
12	1283	27.8.15 4:00	-1612	18.5.15 22:00
13	1276	31.3.15 21:00	-1588	1.12.15 0:00
14	1204	31.8.15 18:00	-1436	1.12.15 11:00
15	1176	12.4.15 19:00	-1430	7.11.15 19:00
16	1153	31.8.15 17:00	-1400	7.11.15 18:00
17	1135	18.8.15 23:00	-1331	1.12.15 12:00
18	1106	1.4.15 0:00	-1269	6.6.15 14:00
19	1105	1.4.15 23:00	-1220	1.12.15 13:00
20	1098	31.3.15 15:00	-1209	7.11.15 20:00

Appendix 4: Top and Bottom hours for Denmark - 2016

Number	Top 20 Hours	Date and Time	Bottom 20 Hours	Date and Time
	lower generation and higher demand (MW)		higher generation and lower demand (MW)	
1	1697	21.2.16 17:00	-1673	16.4.16 22:00
2	1567	21.2.16 20:00	-1625	16.4.16 20:00
3	1519	21.2.16 21:00	-1614	16.4.16 21:00
4	1512	21.2.16 16:00	-1593	16.4.16 23:00
5	1482	21.2.16 22:00	-1538	16.4.16 0:00
6	1453	21.2.16 19:00	-1461	16.4.16 19:00
7	1446	21.2.16 18:00	-1389	16.4.16 18:00
8	1407	24.12.16 23:00	-1368	16.4.16 17:00
9	1386	21.2.16 15:00	-1199	26.12.16 9:00
10	1340	21.2.16 14:00	-1194	27.4.16 10:00
11	1279	21.2.16 13:00	-1160	16.4.16 16:00
12	1258	24.12.16 0:00	-1152	27.4.16 11:00
13	1243	21.2.16 23:00	-1138	27.4.16 12:00
14	1212	29.4.16 15:00	-1137	27.4.16 9:00
15	1186	22.2.16 2:00	-1092	27.4.16 13:00
16	1170	29.4.16 16:00	-1085	12.8.16 17:00
17	1153	26.12.16 14:00	-999	16.4.16 15:00
18	1101	5.1.16 23:00	-988	12.8.16 16:00
19	1096	23.12.16 0:00	-970	24.1.16 19:00
20	1073	30.5.16 20:00	-967	27.4.16 14:00

Appendix 5: Top and Bottom hours for France - 2015

Number	Top 20 Hours	Date and Time	Bottom 20 Hours	Date and Time
	lower generation and higher demand (MW)		higher generation and lower demand (MW)	
1	5762	20.3.15 18:00	-6008	24.12.15 2:00
2	5577	20.3.15 17:00	-5865	21.11.15 3:00
3	5106	20.3.15 16:00	-5812	21.11.15 2:00
4	4992	21.3.15 18:00	-5675	24.12.15 3:00
5	4847	21.3.15 17:00	-5566	21.11.15 4:00
6	4827	15.11.15 12:00	-5533	21.12.15 3:00
7	4820	20.3.15 12:00	-5134	21.12.15 2:00
8	4686	20.3.15 14:00	-5089	28.11.15 13:00
9	4593	11.11.15 12:00	-4983	27.9.15 4:00
10	4583	1.5.15 18:00	-4930	9.11.15 4:00
11	4560	15.9.15 11:00	-4824	22.9.15 4:00
12	4523	20.3.15 22:00	-4802	21.11.15 5:00
13	4508	17.11.15 22:00	-4743	9.11.15 3:00
14	4486	5.1.15 6:00	-4716	29.9.15 3:00
15	4461	23.12.15 6:00	-4714	27.9.15 5:00
16	4450	20.3.15 15:00	-4651	24.12.15 1:00
17	4389	20.3.15 19:00	-4639	21.12.15 4:00
18	4333	1.5.15 17:00	-4629	22.9.15 3:00
19	4301	22.10.15 15:00	-4598	29.9.15 4:00
20	4193	21.3.15 12:00	-4596	24.12.15 4:00

Appendix 6: Top and Bottom hours for France - 2016

Number	Top 20 Hours	Date and Time	Bottom 20 Hours	Date and Time
	lower generation and higher demand (MW)		higher generation and lower demand (MW)	
1	4712	29.12.16 17:00	-6104	6.4.16 12:00
2	4675	20.9.16 5:00	-6036	6.4.16 11:00
3	4636	16.3.16 17:00	-5721	10.4.16 14:00
4	4489	16.3.16 18:00	-5641	19.2.16 13:00
5	4387	29.12.16 22:00	-5597	10.10.16 14:00
6	4360	29.2.16 18:00	-5539	26.2.16 12:00
7	4311	9.2.16 15:00	-5535	25.8.16 13:00
8	4305	16.3.16 16:00	-5475	14.3.16 13:00
9	4111	18.11.16 6:00	-5387	24.9.16 13:00
10	4099	7.10.16 9:00	-5385	22.3.16 15:00
11	4031	2.4.16 17:00	-5372	6.6.16 7:00
12	4005	21.4.16 18:00	-5344	4.10.16 15:00
13	3998	23.10.16 18:00	-5295	21.3.16 10:00
14	3984	9.2.16 12:00	-5259	20.1.16 7:00
15	3976	26.9.16 6:00	-5210	19.2.16 14:00
16	3973	30.12.16 15:00	-5177	18.10.16 12:00
17	3935	9.2.16 14:00	-5175	22.3.16 16:00
18	3913	3.3.16 6:00	-5112	4.9.16 13:00
19	3903	30.12.16 12:00	-5082	11.2.16 12:00
20	3833	28.2.16 18:00	-5042	24.3.16 11:00

Appendix 7: Top and Bottom hours for Spain - 2015

Number	Top 20 Hours	Date and Time	Bottom 20 Hours	Date and Time
	lower generation and higher demand (MW)		higher generation and lower demand (MW)	
1	2055	20.3.15 19:00	-2662	5.1.15 14:00
2	2011	7.8.15 15:00	-2631	26.3.15 20:00
3	1989	6.1.15 8:00	-2481	24.8.15 19:00
4	1980	7.8.15 16:00	-2415	25.3.15 14:00
5	1976	6.1.15 17:00	-2404	2.1.15 7:00
6	1948	2.1.15 18:00	-2357	25.3.15 13:00
7	1948	7.8.15 21:00	-2334	25.3.15 15:00
8	1928	3.8.15 10:00	-2324	25.3.15 16:00
9	1902	20.3.15 9:00	-2322	22.7.15 20:00
10	1898	25.12.15 10:00	-2309	5.2.15 15:00
11	1870	31.8.15 13:00	-2251	24.8.15 17:00
12	1854	31.8.15 11:00	-2174	26.3.15 17:00
13	1851	10.6.15 11:00	-2171	4.9.15 16:00
14	1848	18.3.15 11:00	-2163	5.2.15 16:00
15	1825	6.1.15 15:00	-2141	5.1.15 12:00
16	1801	7.8.15 17:00	-2136	9.6.15 17:00
17	1796	6.1.15 19:00	-2125	5.2.15 17:00
18	1781	3.8.15 9:00	-2095	25.3.15 18:00
19	1780	1.6.15 18:00	-2069	22.7.15 21:00
20	1761	3.1.15 8:00	-2048	25.3.15 17:00

Appendix 8: Top and Bottom hours for Spain - 2016

Number	Top 20 Hours	Date and Time	Bottom 20 Hours	Date and Time
	lower generation and higher demand (MW)		higher generation and lower demand (MW)	
1	6295	25.4.16 2:00	-3546	5.10.16 15:00
2	2270	15.8.16 9:00	-3104	28.3.16 7:00
3	2270	12.10.16 12:00	-3010	7.9.16 20:00
4	2269	12.10.16 13:00	-2361	7.9.16 22:00
5	2188	15.8.16 10:00	-2348	10.8.16 12:00
6	2043	20.7.16 11:00	-2255	31.10.16 10:00
7	2041	20.7.16 10:00	-2106	14.10.16 17:00
8	2022	12.2.16 17:00	-2039	31.10.16 11:00
9	1993	26.2.16 18:00	-2036	28.3.16 8:00
10	1917	12.2.16 15:00	-1985	14.10.16 18:00
11	1911	20.7.16 13:00	-1932	28.3.16 19:00
12	1881	12.2.16 16:00	-1927	7.11.16 13:00
13	1874	20.7.16 12:00	-1926	7.11.16 14:00
14	1869	12.10.16 11:00	-1905	26.12.16 10:00
15	1863	10.1.16 15:00	-1844	13.9.16 17:00
16	1846	12.2.16 18:00	-1833	11.3.16 17:00
17	1826	28.6.16 11:00	-1824	28.3.16 20:00
18	1800	22.5.16 15:00	-1816	29.3.16 19:00
19	1794	6.1.16 13:00	-1796	31.10.16 12:00
20	1794	12.2.16 14:00	-1787	29.3.16 20:00

Appendix 9: Top and Bottom hours for Portugal - 2015

Number	Top 20 Hours	Date and Time	Bottom 20 Hours	Date and Time
	lower generation and higher demand (MW)		higher generation and lower demand (MW)	
1	1483	2.1.15 22:00	-2297	31.12.15 23:00
2	1404	2.1.15 21:00	-1674	31.12.15 22:00
3	1155	2.1.15 23:00	-1577	26.10.15 0:00
4	1108	19.10.15 20:00	-1468	24.1.15 18:00
5	1003	25.4.15 10:00	-1464	31.3.15 0:00
6	996	19.10.15 19:00	-1396	31.12.15 0:00
7	983	21.3.15 14:00	-1372	25.2.15 11:00
8	982	7.2.15 0:00	-1354	28.1.15 13:00
9	932	14.12.15 17:00	-1307	26.10.15 21:00
10	931	21.3.15 13:00	-1295	9.10.15 23:00
11	910	8.1.15 0:00	-1293	23.1.15 20:00
12	905	14.12.15 18:00	-1279	25.2.15 12:00
13	893	25.4.15 11:00	-1279	31.3.15 9:00
14	893	26.4.15 23:00	-1274	31.3.15 10:00
15	890	4.10.15 11:00	-1259	26.10.15 20:00
16	884	25.4.15 9:00	-1254	23.1.15 18:00
17	875	2.1.15 20:00	-1250	9.1.15 3:00
18	837	18.1.15 8:00	-1246	8.3.15 19:00
19	832	18.1.15 7:00	-1237	23.1.15 21:00
20	819	18.1.15 6:00	-1234	9.1.15 4:00

Appendix 10: Top and Bottom hours for Portugal - 2016

Number	Top 20 Hours	Date and Time	Bottom 20 Hours	Date and Time
	lower generation and higher demand (MW)		higher generation and lower demand (MW)	
1	1361	27.2.16 12:00	-1921	28.1.16 20:00
2	1332	27.2.16 11:00	-1906	28.1.16 18:00
3	1280	31.3.16 0:00	-1849	28.1.16 21:00
4	1275	5.1.16 13:00	-1696	28.1.16 22:00
5	1268	25.11.16 22:00	-1663	18.4.16 12:00
6	1267	28.2.16 2:00	-1659	18.4.16 11:00
7	1265	27.2.16 14:00	-1573	28.1.16 23:00
8	1263	27.2.16 21:00	-1556	28.1.16 17:00
9	1243	27.2.16 23:00	-1497	18.4.16 10:00
10	1242	5.1.16 21:00	-1485	2.3.16 19:00
11	1219	6.1.16 15:00	-1483	13.9.16 11:00
12	1198	26.6.16 23:00	-1471	13.9.16 12:00
13	1197	6.9.16 21:00	-1443	7.5.16 11:00
14	1187	28.2.16 1:00	-1438	18.4.16 13:00
15	1184	5.1.16 22:00	-1414	3.3.16 8:00
16	1178	6.1.16 16:00	-1407	13.9.16 13:00
17	1171	25.11.16 21:00	-1389	7.5.16 12:00
18	1161	27.2.16 10:00	-1387	2.3.16 18:00
19	1158	28.2.16 3:00	-1379	18.4.16 23:00
20	1148	27.2.16 0:00	-1377	2.3.16 16:00

Bibliography

[1] EU comission, "DIRECTIVE 2009/28/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL," EU comission, 2009.

[2] EU Comission, "A policy framework for climate and energy in the period from 2020 to 2030.," 2014.

[3] Eurostat, "Renewable energy Statistics," 2016. [Online]. Available: http://ec.europa.eu/eurostat/statistics-explained/index.php/Renewable_energy_statistics. [Accessed 2017].

[4] B. Harack, "Electricity Grid: Key Terms and Definitions," 2010. [Online]. Available: https://www.visionofearth.org/industry/electricity-grid-key-terms-and-definitions/. [Accessed 2017].

[5] IEA-ETSAP and IRENA©, "Renewable Energy Integration in Power Grids - Technology Brief," IEA-ETSAP and IRENA©, 2015.

[6] IEC - International Electrotechnical Comission, "Grid integration of large-capacity Renewable Energy sources and use of large-capacity Electrical Energy Storage," IEC - International Electrotechnical Comission, 2017.

[7] REN - Redes Energéticas Nacionais, "REN - Wind Power Generation," 2017. [Online]. Available: http://www.centrodeinformacao.ren.pt/EN/InformacaoExploracao/Pages/DiagramadeProdu%C3%A7%C3%A3oE%C3%B3lica.aspx. [Accessed 2017].

[8] A. M. Held, *Modelling the future development of renewable energy technologies in the European electricity sector using agent-based simulation,* Karlsruhe: KIT - Karlsruhe Institute of Technology, 2010.

[9] X. L. P. L. Klaas Würzburg, "Renewable generation and electricity prices: Taking stock and new evidence for Germany and Austria," 2013.

[10] E. -. T. E. W. E. Association, "Powering Europe: wind energy and the electricity grid," EWEA, 2010.

[11] European Parliment, *Brifing: Understanding Electricity Markets in the EU,* 2016.

[12] EWEA - The European Wind Energy Assosciation, "Wind Energy and Electricity Prices - Exploring the ‘merit order effect’," EWEA, Brussels, 2010.

[13] G. S. Daniel Kirschen, Fundamentals of Power System Economics, Manchester: John Wiley & Sons Ltd, 2004.

[14] APX Group, "Countinous Markets: intraday and strip," 2017. [Online]. Available: https://www.apxgroup.com/trading-clearing/continuous-markets-intraday/. [Accessed 2017].

[15] Entso-e, "Balancing and Ancillary Services Markets," 2017. [Online]. Available: https://www.entsoe.eu/about-entso-e/market/balancing-and-ancillary-services-markets/Pages/default.aspx. [Accessed 2017].

[16] Eurelectric, "Power Distribution in Europe," 2013. [Online]. Available: http://www.eurelectric.org/powerdistributionineurope/.

[17] T. Pham., Market power in power markets in Europe : the Cases in French and German wholsale electricity markets, Paris, 2015.

[18] S. C. Bhattacharyya, Energy Economics - Concepts, Issues, Markets and Governance, London: Springer, 2011.

[19] energycommunity.org, [Online]. Available: http://energycommunity.org/WebHelpPro/Transformation/Dispatching_Processes_on_a_Load_Curve.htm.

[20] M. J. ,. J. K. Marius Dillig, "The impact of renewables on electricity prices in Germany – An estimation based on historic spotprices in the years 2011–2013.," 2016.

[21] M. M. &. B. Scholtens, "The impact of renewable energy on electricity prices in the Netherlands," 2013.

[22] D. E. &. R. P. Florentina Paraschiv, "The impactofrenewableenergiesonEEXday-aheadelectricityprices," 2014.

[23] A. C. a. P. Stefano Clò, "The merit-ordereffect in the Italian powermarket : The impact of solar and wind generation on national wholesale electricity prices," 2014.

[24] ENTSO-E, "Entso-e Transperncy platform," 2017. [Online]. Available: https://transparency.entsoe.eu.

[25] REN21, "RENEWABLES 2017 - GLOBAL STATUS REPORT," REN21, 2017.

[26] Agora Energiewende , "Report on the German Power system," Berlin, 2015.

[27] M. P. Craig Morris, "THE GERMAN ENERGIEWENDE BOOK," 2017. [Online]. Available: https://book.energytransition.org/.

[28] BNTZA, "Monitoring Report 2013," 2014.

[29] Agora Energiewende, "Report on the French power system," 2015.

[30] IRENA, "30 Years of Policies in Wind energy - Lessons from Denmark," IRENA, 2013.

[31] Z. Xu, M. Gordon, M. Lind and J. Østergaard, "Towards a Danish power system with 50% wind," 2009.

[32] IEA - International Energy Egency, "Spain 2015 Overview," IEA, 2016.

[33] IEA - Internationl Energy Egency, "Portugal 2016 Review," 2016.

[34] U. -. D. o. Energy, "Renewable Energy Integration l Department of Dnergy," 2017. [Online]. Available: https://energy.gov/oe/services/technology-development/renewable-energy-integration. [Accessed 2017].

[35] D. Jayaweera, Smart Power Systems and Renewable Energy System Integration, Springer International Publishing, 2016.

[36] C. Park, Oxford Dictionary of Environment and Conservation, Oxford University Press, 2012.

[37] BMWI - Federal Ministry for Economic Affairs and Energy, "Act on the Development of Renewable Energy Sources - (Renewable Energy Sources Act - RES Act 2014)," http://www.bmwi.de/, 2014.

[38] E. -. t. E. W. E. Association, "The Economics of Wind Energy," EWEA, 2009.