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Supply and Demand of Flexibility in European Electricity Systems

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"Cultivo una rosa blanca
en julio como en enero,
para el amigo sincero
que me da su mano franca"
– José Martí

Acknowledgments

Through these two years in my study programme and the masters thesis, it has been a winding journey, a challenging and exciting one at that.

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Resumo

O aumento da contribuição de fontes de energia renováveis para a produção de eletricidade que se tem vindo a observar na Europa exige uma maior flexibilidade por parte dos próprios sistemas de produção eléctrica. Esta flexibilidade é justificada pela necessidade de uma maior adaptabilidade dos sistemas a uma eventual rápida alteração imposta por factores característicos de fontes consideradas intermitentes.

Os objetivos promovidos pela União Europeia (UE) para o desenvolvimento de energia renovável até 2020 levaram já à criação de uma política de energia. Sete países Europeus foram tidos em conta para o estudo desenvolvido.

Flexibilidade foi definida no contexto de sistemas de produção de eletricidade e quatro aspectos fundamentais para o desenvolvimento do seu conceito foram enumerados. O contexto geral utilizado para a análise correspondeu aos objetivos traçados para 2020 no que diz respeito à contribuição de fontes de energia renovável para o mix de produção de energia em cada estado membro.

Foi possível concluir que, dos quatro aspectos fundamentais para a caracterização de flexibilidade, dois apresentaram resultados semelhantes entre os país em estudo. Foi, então, possível concluir que existe, de facto, uma correlação entre determinados aspectos da flexibilidade e a quota anteriormente mencionada. A diferença mais significante prende-se com as políticas governamentais que promovam o desenvolvimento de energia renovável, existente em apenas parte dos países. Foi possível concluir que cada um dos aspectos da flexibilidade é caracterizado por um elevado número de factores que, de forma a obter um resultado mais detalhado, devem ser tidos em especial consideração.

Palavras-chave: flexibilidade, mercado de eletricidade, Europa, energia renovável

Abstract

In light of the increasing share of intermittent renewable electricity in Europe's electricity system, the flexibility of the system to adapt to changes is of utmost importance.

The European Union as a whole, and member states have a direction that they are taking with regards to Energy Policy, like the 2020 renewable energy targets and the Energy Union. Seven European countries (including Switzerland) were considered. In this study, "flexibility" as a term was defined, and four aspects of flexibility that were studied here were enumerated. The primary context of this study was the 2020 targets of the share of renewable energy in national energy systems as follows from the European Commission Directive 2009/28/EC. The possible influence of electricity policies on each of the four aspects of flexibility was estimated qualitatively, particularly focusing on infeed of intermittent renewables.

Four aspects of the power system were studied, focusing on the data available from the Day-Ahead markets, and power system data. The demand of some of these aspects of flexibility as well as the corresponding supply, were compared quantifiably.

In two aspects, namely in residual load variations and in the price peak response, there was a difference between certain countries. It was concluded that correlations between certain aspects of flexibility with the share of intermittent renewables do exist. The difference between countries often was the renewable energy support policies that certain countries had and others did not. It was found that some aspects had many influencing factors, and more insight would be useful.

Keywords: flexibility, electricity market, Europe, renewable energy

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Chapter 1

Introduction

Europe as a collective bloc as well as individual european countries have generally been at the forefront of efforts to increase the share of renewable energy in its electricity system. Many renewable energies, most popularly solar photovoltaic (PV) and wind power are intermittent by their nature, and this intermittency is a challenge at various levels. In addition, the political and economic union of several european countries adds another dimension to the challenge of integrating intermittent renewables in europe's electricity system.

Indeed, much of Europe's countries have banded together to form the European Union (EU). It establishes not only an economic union of sorts through a single market, a customs union and a monetary union (with some opt-outs), but also a political union, through the establishment of a European Parliament, and an executive body in the European Commission, and a judiciary in the European Court of Justice. In addition, certain other countries like Norway and Iceland participate in the economic union through the European Economic Area (EEA), and Switzerland through bilateral agreements with the EU [1].

The european electricity situation at present is at its place due to various developments over the years. Agreements like the Kyoto protocol were a push towards introducing more renewable energies in the electricity system. At the same time, the European Union drove in the necessity to create and maintain an internal market for electricity through the Internal Market in Electricity Directive (96/92/EC) (subsequently superseded by Directives 2003/54/EC and 2009/72/EC). The establishment of the so called "2020 targets" for renewable energy through the Renewable Energy Directive in 2009 (2009/28/EC) calls for the EU as a whole to use 20 % of its gross energy from renewable sources in 2020. Each country is set national targets to achieve, as well as sub-targets, for **Heating and Cooling**, **Electricity** and **Transport**. Each member state was obliged to present a plan in 2010 to achieve these targets, along with progress reports every two years [2].

Geopolitical necessities have also often played a role in shaping Europe's energy policy. Europe imports gas and other petroleum from many countries around the world, and in recent years, geopolitics in relation to Russia has often been cited as a reason driving the further integration and drive towards self-sufficiency of the european energy system [3].

When the context of a european "electricity system" or a "power system" is to be defined in this study, it refers to this combination of the technical power system (power plants, grids, etc.), the economic system (Energy Union, market integration, etc.) and the political background (common targets, regulations, and directives). When the topic is being studied, it is aimed to look at each aspect of the system in relation to the others, particularly focusing on the generation and the market aspects of the system and the interplay between them.

An important part of the operation of energy markets in Europe is the transparency of market data. The EU in 2011 introduced a regulation, the Regulation on Wholesale Energy Market Integrity and Transparency (REMIT) to increase the transparency of the energy markets and to prevent market manipulation. So, in accordance with REMIT, market participants are legally obliged to publish certain details of their transactions.

This data is one of the primary sources of data used in this study, a large portion of data relevant to this report being published through the European Network of Transmission System Operators for Electricity (ENTSO-E)'s Transparency Information Platform.

The framework of this study is the Directive 2009/28/EC, or the 2020 Renewable Energy Directive that applies to each EU country. Switzerland, although not part of the EU, is heavily interconnected with its EU neighbours and operates in the same market as Germany, Austria and France. It does, however, have its own renewable energy targets independent of the EU.

1.1 Objectives

The first objective of this study is to give a definition and interpretation of "Flexibility" in this context and establish technical parameters and measurements. Then, after collection of the data required, to analyse this data for each country to obtain the indicators of flexibility required.

Then the objective is to compare these indicators across countries, simultaneously considering the state of renewable electricity penetration as well as individual policies of countries to attempt to establish a correlation between these factors.

1.2 Thesis Outline

After the introduction section to the report, a **background** is given to the various electricity markets and countries that are part of them. Each country is given a short introduction with a presentation of its electricity generation mix.

In the **analysis** section, flexibility as used in this study is first defined. Then the methodology of the analysis is established with explanations.

The results of the individual country analyses are presented in the **country by country analysis** chapter, where the analysis of the four aspects of flexibility are applied to each country/market. Each country's analysis is followed by a view into the country's renewable electricity policy and support schemes.

Finally, the **comparisons and conclusions** chapter opens with comparisons between the countries with respect to each of the aspects of flexibility, and concludes with the major conclusions gathered from the analysis performed in the report.

Chapter 2

Background to Electricity Markets in Europe

2.1 Choosing Focus Regions

For the purposes of this thesis, certain focus regions were defined for which the above mentioned measurements make sense. A logical option would be to choose focus regions based on national borders, since Transmission System Operators (TSO)s typically operate within national borders. This may be suitable for countries such as France, Belgium or the United Kingdom. For some regions, this might not be the best way to demarcate regions: Portugal and Spain, for example, are heavily integrated with each other, operating a single market. In this case, although the TSOs are different, the interconnection is typically high, and it may not make sense to analyse them separately.

There also exists a rather complicated mix of various markets operating in different regions. For instance, the Nordpool Intraday market operates not only in the Nordic and Baltic regions, but also in Germany whereas the Nordpool Day-Ahead market operates only in the Nordic and Baltic regions. In the United Kingdom, there is competition between the N2EX (Nordpool) and APX (EPEX SPOT) Day-Ahead Markets which operate in parallel. And in the end, all the Western European markets are, in theory, coupled using the Price Coupling of Regions (PCR) mechanism. This makes price signals not very reliable indicators of the situation in a national context, particularly while analysing policy which is set nationally.

After taking the data availability and suitability aspects into consideration, the following countries were chosen to be a part of this study (Figure 2.1):

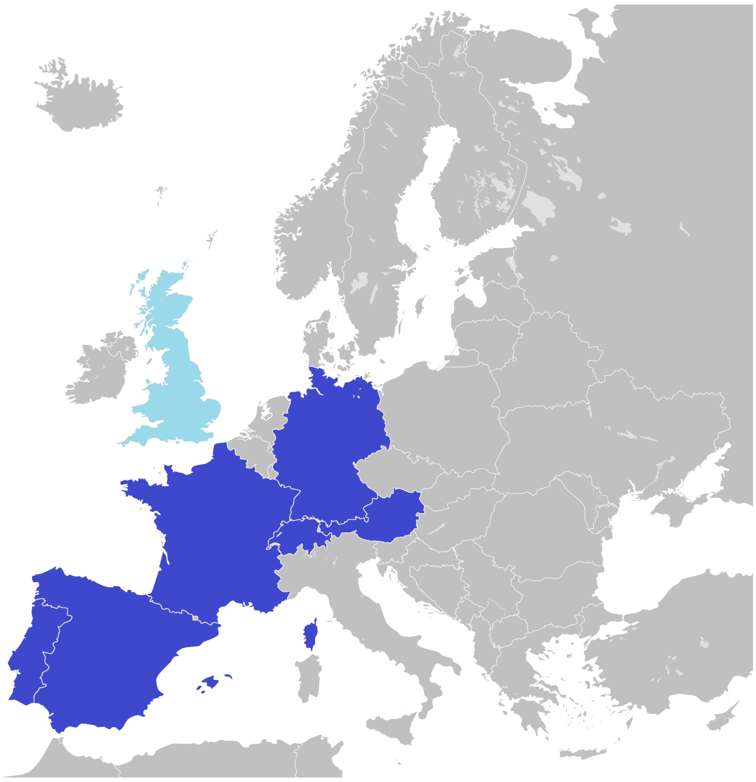

Figure 2.1: Countries considered in this study (marked in blue); countries considered, but for which full data was not available (marked in light blue) (Map base source: Public Domain)

- Germany
- Austria
- France
- Switzerland
- Spain
- Portugal
- Great Britain (data partially available)

Since the study is to focus on the primary electricity system in each country, areas not part of the main grid were not considered. For instance, the grid system of Northern Ireland, a constituent country of the United Kingdom, is part of the grid network of the Republic of Ireland. Similarly, areas like the Azores and Madeira islands of Portugal or the Canary islands of Spain were not considered.

2.2 EPEX

The European Power Exchange (EPEX SPOT SE) operates its spot markets in Germany, Austria, Switzerland, France and Luxembourg. The company is owned by EEX (European Energy Exchange) AG with a 51% controlling stake with the rest being owned by various Transmission System Operators (TSOs) including RTE (France), Elia (Belgium) and TenneT (The Netherlands). EPEX also owns APX which operates in the Netherlands, Belgium and the United Kingdom.

EPEX SPOT operates Day-Ahead Electricity markets for Germany, Austria, Switzerland, France and Luxembourg. In this study, the markets of Germany, Austria and France will be studied. The markets are coupled on a market coupling basis, with each country/region operating its own market, the prices being computed for each region. There is price convergence as long as there is sufficient transmission capacity [4].

In 2014, with the cooperation from the respective TSOs, EPEX SPOT coupled its Day-Ahead Markets as part of the Price Coupling of Regions (PCR) project, with those of APX, Belpex, GME and Nordpool Spot in order to create what is known as the Northwest Europe Price Coupling (NWE) region. It was extended to the Southwest Europe (SWE) region operated by OMIE operating in Spain and Portugal [5].

2.2.1 Germany

To give a broad overview of the electricity mix in Germany, the country has seen a strong marked increase in the share of renewable electricity, with a share of up to 26,8 % of total consumption in 2014 as compared to a 17,6 % in 2010 /[6]/. Coal and other solid fuels have remained relatively stable despite the focus on cutting carbon emissions, possibly due to the decreasing share of nuclear energy which in turn was due to the so called *Automausstieg* (nuclear phase-out). Going by the installed capacity, 39 % of the installed capacity consisted of intermittent electricity sources like wind and solar PV (Figure 2.2) /[7]/.

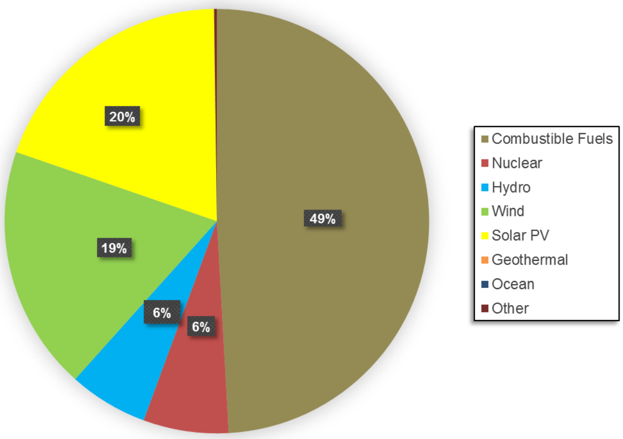

Figure 2.2: Shares of electricity sources by installed capacity in Germany

At the centre of recent energy policy in Germany is the Erneuerbare-Energien-Gesetz (EEG), or the Renewable Energies Act. The first version of the EEG was introduced in 2000, which offered fixed feed-in tariffs to new installations of renewable electricity sources. It was modified several times through the years in 2004, 2009, 2012, 2014 to make several changes including setting market premiums, switching to direct marketing, and in 2016, announcing a shift from feed-in tariffs to auctions for certain sources [8] [9]. The shift from fixed tariffs to auctions seems to signal that the government is ready to expose renewables more to market forces.

2.2.2 Austria

Austria is known for its high share of renewables in its electricity mix, with about 49,2 % of electricity (final) coming from renewable sources. It is known for its high amounts of hydroelectric electricity, consisting 13,1 MW of a total 23,6 MW (56 %)installed capacity (Figure 2.3) [6]. There is also a significant share of wind power in the mix, with 1,6 MW installed, chiefly in the eastern parts of the country.

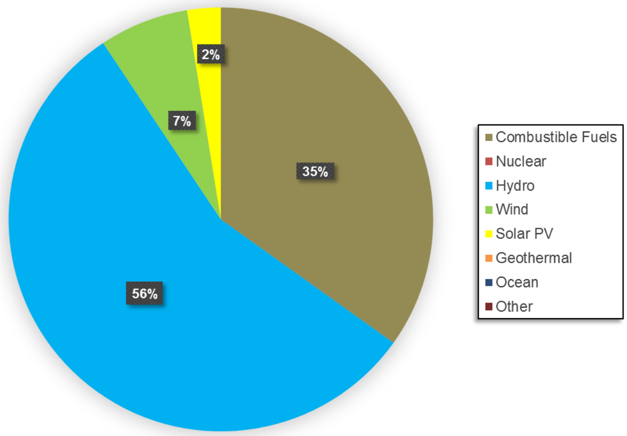

Figure 2.3: Shares of electricity sources by installed capacity in Austria

The neighbouring countries of the Czech Republic, Slovenia and Hungary are coupled with each other, but not with the rest of the PCR (Price Coupling of Regions) regions, and a coupling would be seen as very beneficial [10]. Austria forms a single price zone with Germany, and as such, has the same price on the market as Germany.

2.2.3 France

The French electricity mix is based heavily on nuclear energy with nearly 74 % of the generated electricity (2013) coming from nuclear energy [6]. Renewable electricity production takes up the next largest share in the electricity mix with 17,7 %. To break it up by installed capacity, it is evident that the three major sources of installed electricity generation are nuclear (49 %), combustible fuel-based (21 %), and hydroelectric (20 %), with a smaller but significant share from wind, as seen in Figure 2.4.

The French company EDF owns a significant share of the French electricity market, exploiting nearly 91,5 % of installed capacity in France (2014), leaving the market highly concentrated. In addition, the market has low liquidity, with nearly 87 % of the trading taking place over-the-counter (OTC) [11]. An important concern that has been raised is the lack of interconnection capacity between France and the Iberian peninsula (Spain and Portugal), this has been cited as a key to a more integrated european power system.

2.2.4 Switzerland

Switzerland, like its alpine neighbour Austria, is heavily reliant on hydroelectric and nuclear power for its electricity needs. Intermittent renewables make up quite insignificant amounts of power generation,

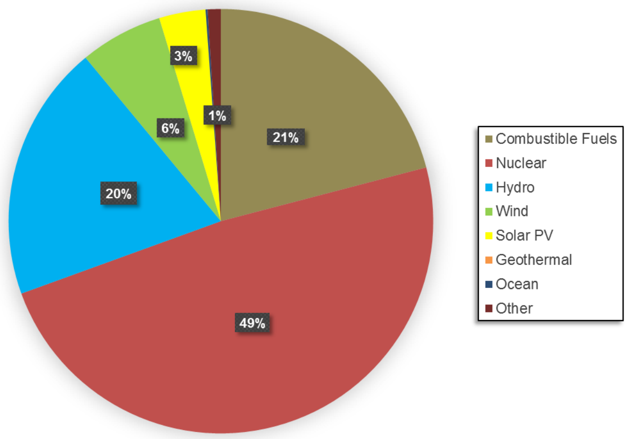

Figure 2.4: Shares of electricity sources by installed capacity in France

with about 0,1 % of the electricity generation in 2013 coming from solar PV, and 0,8 % from wind power (2013). As seen from Figure 2.5, hydroelectric and nuclear power make up almost all of the generation in Switzerland.

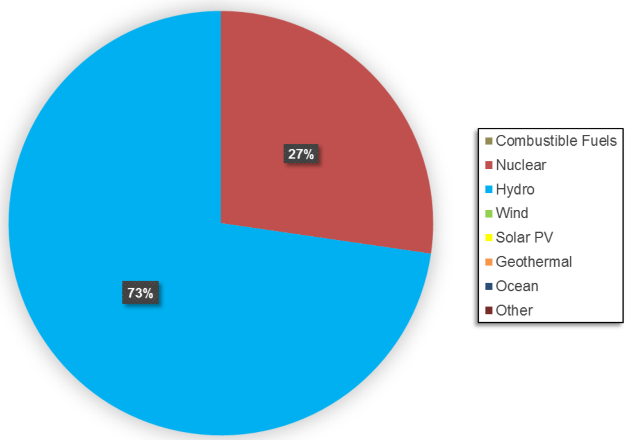

Figure 2.5: Shares of electricity sources by installed capacity in Switzerland (Source: ENTSO-E)

2.3 MIBEL

The *Mercado Ibérico de Electricidade* (MIBEL), the Iberian electricity market, began operations in 2007, covering the countries of Portugal and Spain. The two entities OMIE (*Operador del Mercado Ibérico de Energia Español* S.A.) and the OMIP (*Operador do Mercado Ibérico de Energia Portugal* S.A.) operate the Spot market and the derivative markets respectively. The establishment of this combined market was the result of long discussions right from the 1990s between Portugal and Spain [4].

The market works on a market splitting basis, with there existing only one market operator. Bids are allowed to be placed in either country, with each country having the same price as long as the interconnection capacity is not reached. Only when the interconnection capacity is reached, the market splits, and the two regions have different prices. In 2014, the price convergence was 94,3 %, meaning that the price was equal 94,3 % of the time [12].

2.3.1 Spain

Spain is one of the larger countries in Europe which currently has a majority of its electricity share coming from renewables, with up to 39,84 % of the electricity consumption mix composed of renewables (2013). This could largely be attributed to its high installed capacities of wind power and solar PV (23,0 GW and 4,8 GW respectively in 2013) (Figure 2.6) [6].

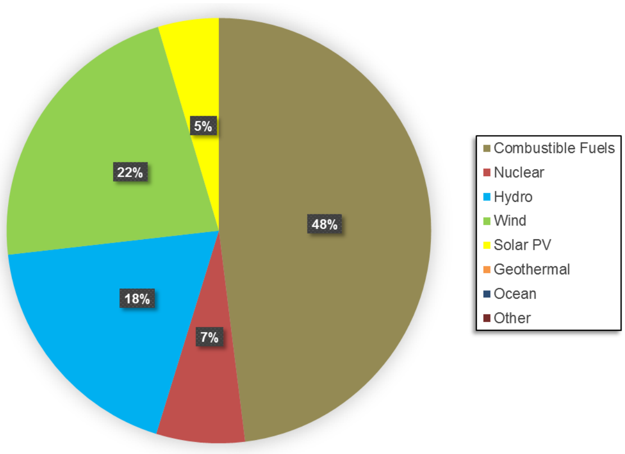

Figure 2.6: Shares of electricity sources by installed capacity in Spain

An important factor to consider is that Spain is one of the countries that was economically most affected by the european sovereign debt crisis in the late 2000s and early 2010s, and as such, the electricity consumption reduced in line with the economic demand. To counter the tariff deficit, the Spanish government has been introducing regulations (often retrospective) that reduce support for renewable sources of electricity production [11].

2.3.2 Portugal

In 2013 in Portugal, the share of renewables in gross electricity consumption was about 49,2 %, with the rest of the mix being filled by natural gas, solid fuels and petroleum products. That figure would have been influenced, however, by trading. To give an idea of the generation capabilities of the country, Portugal has nearly 5,7 GW of installed hydroelectricity generation capacity, and 4,6 GW of installed wind power generation capacity, out of a total of 18,9 GW of installed capacity (Figure 2.7) [6].

While Portugal has also been affected heavily by the european sovereign debt crisis, its renewable policies have not seen such a drastic shift as have Spain's. The only land border the country has is with Spain, and the interconnection capacity has been increasing. EDP S.A. (*Energias de Portugal*), the formerly state-owned energy generation company was privatised in 2013, but still has a 43 % share in the electricity generation market [11].

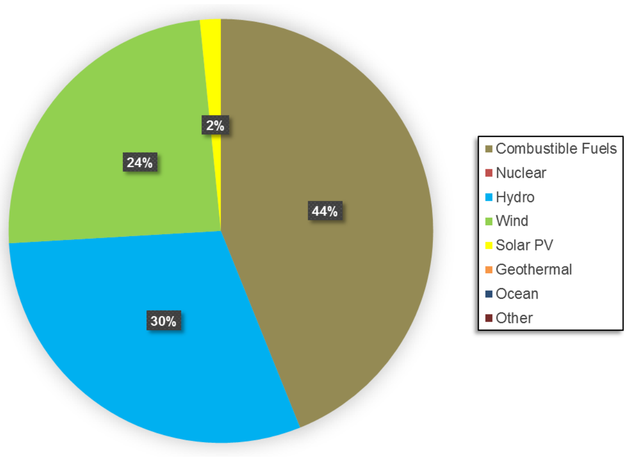

Figure 2.7: Shares of electricity sources by installed capacity in Portugal

2.4 APX

The APX (Amsterdam Power Exchange) started operations in 1999 as the electricity market operator in the Netherlands. In 2001, the APX UK Electricity Spot Market was founded as a separate entity, and in 2005, APX acquired the Belgian market operator Belpex. Today, all the operations of APX are owned by EPEX SPOT, which also operates the Spot markets in Germany, Austria, France and Switzerland.

2.4.1 Great Britain

Previously reliant on coal, Great Britain moved towards producing electricity using natural gas from the early 1990s. Since then, coal, natural gas and nuclear energy have each retained significant shares in the electricity mix till the present day (Figure 2.8). Renewables have been increasing their share in the mix, with about 15,7 % of consumed electricity in 2013 coming from renewable sources. Wind energy is the primary renewable power source, with 11,2 GW of installed capacity, in contrast with 4,4 GW of hydroelectric and 2,8 GW of solar PV installed (2013) [6].

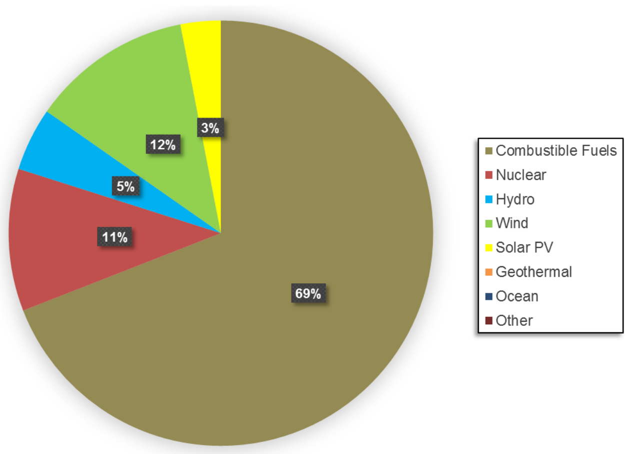

Figure 2.8: Shares of electricity sources by installed capacity in Great Britain

There are two electricity Spot markets operating in parallel in Great Britain – the APX UK Spot

Market, and the N2EX, operated by Nordpool Spot (which operates the Spot market primarily in the Nordic countries). Traders may use either market to take part in the auction, with the result being the same in order to facilitate linking to the rest of the european system. The N2EX has a higher share of volumes traded (about 35 % in June 2015), whereas the APX UK had a share of 17 % in the same month (the rest of the exchange happening Over the Counter (OTC)) [13].

Chapter 3

Analysis

3.0.1 Definition and Description of Flexibility

"Flexibility" on its own is a rather vague term as applied to electricity markets. It is important to clearly define what flexibility is, so that clear indicators can be defined. The report by von Roon et al. (2014) gives some pointers to what could be potentially considered as indicators of flexibility in electricity markets, and that definition has been largely used in this study [14].

In this study, the flexibility studied is as applied to traditional electricity markets in connection with European and national power systems. Other perspectives might include studying the grid parameters for indicators of flexibility, or studying the volatility in the markets in a purely economic study. For the scope of this study, flexibility, as defined by von Roon et al. (2014) could come under four broad categories:

- Flexibility in adjusting to variations in residual load
- Flexibility in recovering from price extremes
- Flexibility to adjust to load gradients
- Short Term availability of power

There could be various measurements done using available market data and power system data in order to measure each of these four 'types' of flexibility. These particular measurements were selected since they are deemed to be representative and give a clearer indication of flexibility as defined above.

- Analysing the variation of the residual load (*i.e.* the standard deviation of residual load)
- Analysing the extremeness of extreme prices and capability of recovery
- Analysing the frequency and steepness of residual load gradients
- Analysing the difference between the Day-Ahead and Intraday market prices

3.1 Methodology Used

Residual Load is defined as the total load on the electricity system that remains after discounting the electricity infeed from sources of energy that *must run* due to either feed-in regulations or very low sale price, or other compulsions. Hence these sources are deemed “uncontrollable” because their infeed is, in effect, mandatory (except in exceptional cases where the TSO can decline infeed). In most cases, these must-run sources are wind and solar PV installations. The residual load denotes the amount of power that is needed to be covered by “controllable” sources like conventional power plants whose grid infeed is not guaranteed and whose generation can be controlled, therefore being regulated by the market [15]. So, the residual load is defined as:

$$L_{res} = (L_{total} - I) \tag{3.1}$$

Where:

L_{res}: is the residual load (GW)

L_{total}: is the total load (GW)

I: is the “uncontrollable” infeed, *i.e.* infeed from wind and solar PV

as demonstrated in Figure 3.1.

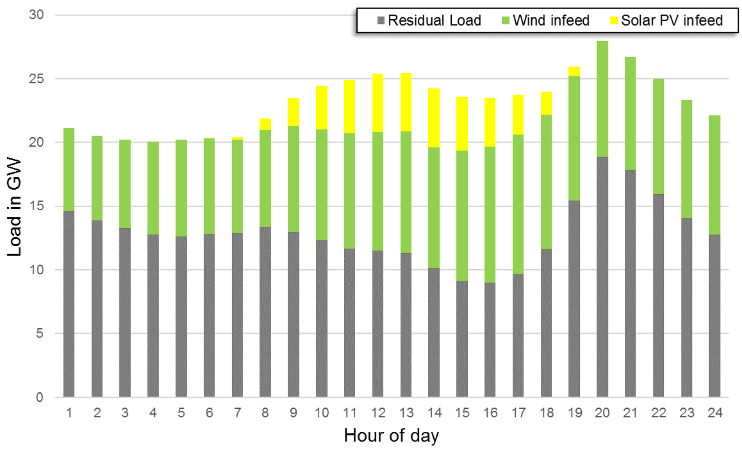

Figure 3.1: Load in Spain on 13 September 2015 showing the Residual Load

All the intermittency associated with solar PV and wind energy installations is now transferred to the value of the residual load. Since the power plants generating the residual load can, by definition, be controlled, the residual load is a meaningful measure to study the requirement and availability of flexibility.

3.1.1 Aspect 1: Flexibility in Adjusting to Variations in Residual Load

There is a requirement of flexibility to even out variations in residual load. A flexible power system would be better capable of evening out differences. As such, the degree of variation of the residual load can be seen as a measure of the flexibility *demanded*. The Standard Deviation of the residual load would give a good measure of the demand of this aspect of flexibility in the power system.

A higher value of standard deviation would denote a higher variation in residual load in the given time interval, and therefore an increased demand for flexibility to balance it out. The time interval selected will also be crucial here, since extended intervals of time may be influenced by seasonal variations.

When it comes to the *supply* of this aspect of flexibility, there could be many options that could be studied, including, but not limited to, analysing the amount of storage or storage potential that the country has, and also by analysing the cross-border interconnection capacities. However, data on storage in particular, was not reliably available publicly, and that analysis was not performed.

3.1.2 Aspect 2: Flexibility in Recovering from Price Extremes

When a merit order curve and the corresponding buy curve is considered (e.g. Figure 3.2), each curve is constructed by plotting the bid price and cumulative bid volume of each order. The bid price here is considered the marginal price of the bidder. The structure of the curves and also the extremeness of the price show a measure of the shortage of flexible power. So, by flexibility of price-dependent power, the capability available in the market to remain within a specified price range is denoted.

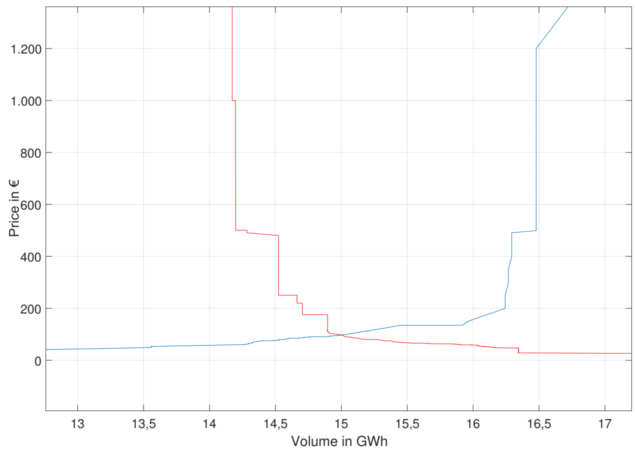

Figure 3.2: The Buy and Sell curves for France on 8 April 2015, 10:00 Hrs, showing an extreme price of 96,88 €

To determine the amount of flexible power *demanded*, the curves for each hour and each day are analysed. First, the price limits are to be defined, beyond which it is deemed an extreme price. For this analysis, to maintain uniformity, any price outside of $\pm 2\sigma$ (2 standard deviations) from the mean price of the reference year, is considered an extreme price. A compilation of the extreme prices defined for each country is as shown in Table 3.1. All the prices have been calculated for the year 2015, the year in consideration.

The hourly price is determined by the intersection point of these two curves. In case the price is outside of the defined limits, the buy curve is shifted accordingly to be at an acceptable price level. The volume (X-Axis) by which it needs to be shifted shows the measure of flexibility available. If the curve

Country	Mean Price (μ) (2015)	Standard Deviation (σ)	Lower Extreme Price ($\mu - 2\sigma$)	Higher Extreme Price ($\mu + 2\sigma$)
Germany	31,65 €	12,65 €	6,33 €	56,96 €
Austria	31,65 €	12,65 €	6,33 €	56,96 €
France	38,46 €	12,94 €	12,57 €	64,35 €
Switzerland	40,29 €	13,15 €	13,99 €	66,60 €
Spain	31,44 €	16,00 €	0,00 €	63,45 €
Portugal	31,44 €	16,00 €	0,00 €	63,45 €
Great Britain	39,41 GBP	10,73 GBP	17,93 GBP	60,88 GBP

Table 3.1: The extreme prices for the countries considered (GBP = British Pound Sterling)

at the region of intersection in the graph is too flat, then the system would be deemed to have a high demand for flexible power, since it takes a large volume shift in order to attain a non-extreme price. If it is not flat, then a lesser volume would be needed to shift to an acceptable price level and the system is deemed to have low demand for flexible power.

As demonstrated in Figure 3.3, when there is an extreme price detected, the buy curve is shifted along the X-axis to the nearest non-extreme price point. In this case, the price is above the extreme price limit, so it is shifted left. The amount by which the shifting occurs is taken to be representative of the amount of flexibility demanded.

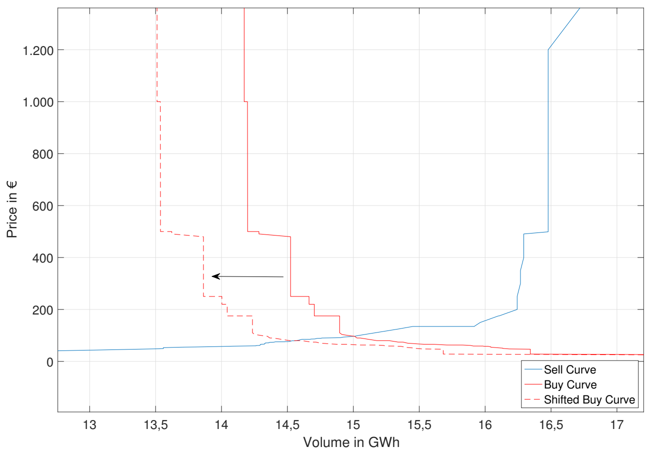

Figure 3.3: The Buy curve from Figure 3.2 shifted to the left to get a non-extreme price

To determine the *supply* of flexibility to avoid price extremes, once again the sell and buy curves are examined. All sell orders below the intersection point of the curves should be deployed as well as all buy orders above the intersection. So, the total available flexible power here is considered to be the amount by which the buy curve can be shifted (or conversely, the sell curve in the opposite direction) till there are no more available sell offers. This translates to the difference between the first point in the buy curve and the last point in the sell curve as seen in Figure 3.4.

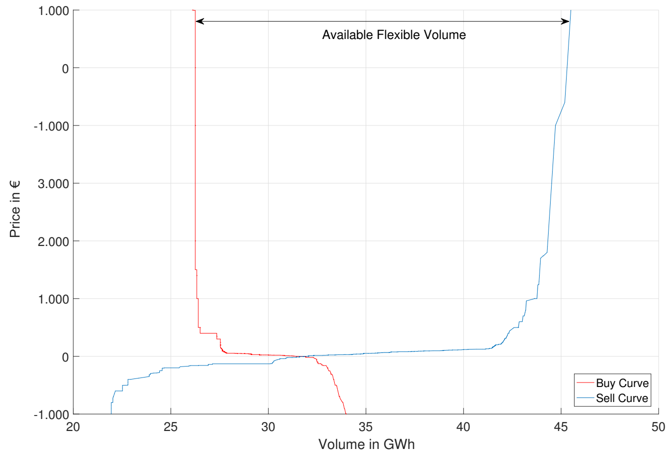

Figure 3.4: Determining the available flexible volume on the market, curve on the French market on 1 March 2015 at 03:00 Hrs

3.1.3 Aspect 3: Flexibility to Adjust to Load Gradients

The load on the system is a continually changing measurement; within a day there are variations according to to daily routines, among other factors. Intermittent power sources like solar PV installations contribute to another cycle of variations, whereas both solar and wind energy installations are subject to other general weather variations not necessarily related to the daily cycle.

This measure of flexibility measures the existence of high gradients in the residual load and correspondingly, the necessity of flexibility to handle the gradients. Gradients are defined here as the difference between the residual loads of each point in time:

$$\Delta = \frac{L_{res,t+1} - L_{res,t}}{t} \tag{3.2}$$

Where:

Δ: is the gradient in residual load (GW/h)

L_{res}: is the residual load at that hour (GW)

t: is the timestep (h)

The load and generation data available from most providers is in 1-hour intervals, and so as far as this study is concerned, gradients are measured with respect to 1 hour. If data in shorter intervals were encountered, they were converted to 1-hour intervals.

The *demand* of this aspect of flexibility can be seen by the frequency and the magnitude of the residual load gradients. The *supply* of this aspect of flexibility can be determined by the bid curves (e.g. shown in Figure 3.4). The amount of available flexible volume is the difference between the volume of the highest sell bid and the lowest buy bid. At any particular hour showing a high gradient, it is checked to see how much available flexible volume is present in the market.

3.1.4 Aspect 4: Short Term Availability of Power

This aspect of flexibility refers to the availability of tradeable volume of electricity on the markets after the day-ahead markets have closed i.e. on the Intraday market. The *demand* of this aspect of flexibility can be demonstrated when there is a change in the short term situation in availability of power on the market. The actual load and the load as forecasted can often be different. The forecasted load would have likely been used as a basis for the trade on the Day-Ahead market, and in cases of an inaccurate forecast, electricity on shorter-term markets would have been used.

The difference between the forecast and the actual load can be differentiated into the *known* and the *unknown* forecast error. The *known forecast error* would need to be compensated by the volume traded on the Intraday market. The volumes traded as well as the price levels on the Intraday market, and further, the differences in the price levels between the Day-Ahead and Intraday markets would give a measure of the demand of this aspect of flexibility. The unknown error would likely be supplied by the reserve markets.

For the analysis of the *supply* of this aspect of flexibility, further analysis into the Intraday market curves would be needed. Since this data was not available publicly for all the countries, the analysis was not performed.

3.2 Implementation of the Analysis

The analysis methods mentioned in the previous section are applied to the market data and generation data of the countries chosen, subject to availability of data. The data used is derived from various sources including ENTSO-E as well as the individual markets of each region. Specialised downloaders were developed using Python to download, format and store the data. The Powerbase tool developed at the FfE is used to store the data in a central database. The sources for the data are as mentioned in Table 3.2.

Data	Country(ies)	Source
Generation Data	All countries	ENTSO-E
Market Data	Germany, Austria, Switzerland, France	EPEX SPOT/EEX
Market Data	Portugal, Spain	OMIE
Market Data	Great Britain	APX UK
Load Data	Switzerland	Swissgrid

Table 3.2: Data used for the study and their sources

The analysis itself was performed using MATLAB and MS Excel, using code previously developed as well as newly written for this purpose.

Chapter 4

Country by Country Analysis

In this chapter, the four aspects of flexibility defined in chapter 3 are analysed for each country considered. In certain cases, the markets were combined, and in such cases, the analysis is done for the market zone instead.

4.1 Germany

4.1.1 Aspect 1: Flexibility in Adjusting to Variations in Residual Load

Over the year 2015, the residual load variation curve for Germany follows a certain trend (as seen in Figure 4.1), with the standard deviation curves showing a marked upward trend during the winter months as opposed to the summer months. The month where the highest variation (*i.e.* highest standard deviation) in residual load takes place is in December (noting that data is missing for January), and the lowest variation in residual load takes place in August. The greatest increase occurs from September to October, precisely when summer ends and the cooler months begin.

A possible explanation could be that Germany does not receive a lot of direct sunlight in the winter months due to its northerly latitude, as well as due to generally cloudy climate.

A look into the incidence and frequency of high variations in wind and solar PV infeed (combined) points to the observation that out of 9 days with extreme variations in wind and solar PV infeed, 7 of the days were also days with higher than average residual load variation. In addition, 7 out of the 9 days with extreme variations in wind and solar PV infeed were in the winter months, pointing to a possibility that variations in wind power infeed could have played an influencing role in the variations in residual load.

The general level of the standard deviation was between 8 GW and 14 GW, with Germany having a yearly mean residual load of 41,6 GW

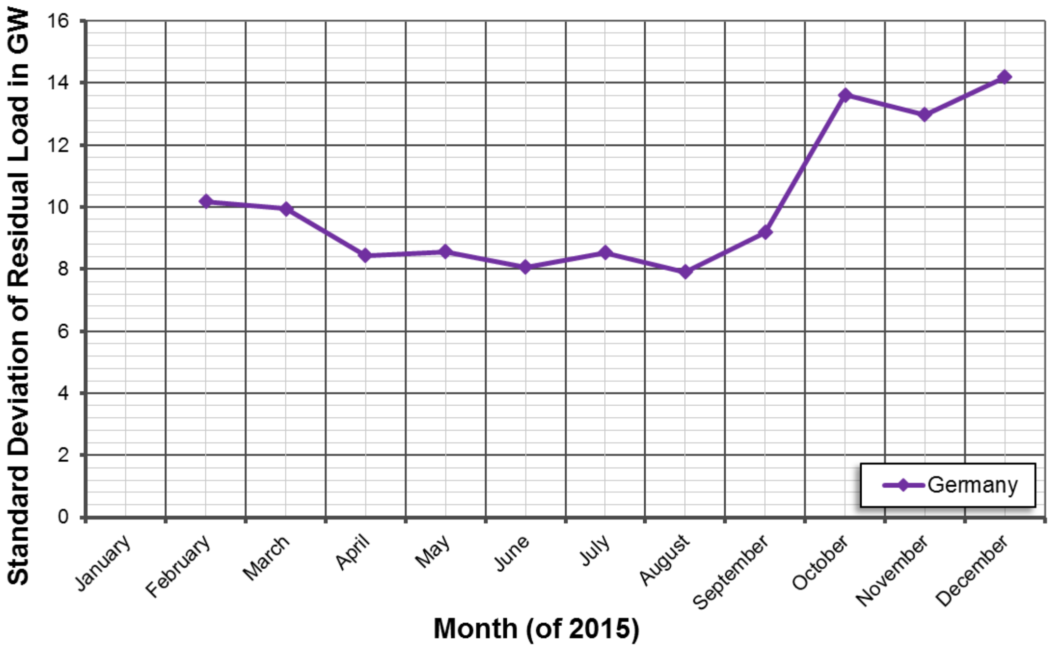

Figure 4.1: Graph of the Standard Deviation of residual load in Germany through the year 2015

4.1.2 Aspect 2: Flexibility in Recovering from Price Extremes

Since Germany and Austria form a single common bidding zone with a common Day-Ahead market operated by EPEX Spot. Therefore the analysis done in this section applies to both Germany and Austria.

In the Germany-Austria Day-Ahead market, the average price in 2015 was 31,65 €, and the extreme prices were defined as 6,33 € and 56,96 €. In 2015, there was clearly a greater amount of average "right shift" that was needed (1,487 GWh) than the amount of average "left shift" (0,417 GWh) that was needed. This does not necessarily point to a higher incidence of low price extremes as compared to high price extremes, but it points to the observation that whenever the low price extremes did occur, they would have required a much higher volume of electricity to bring them to a non-extreme price. The average volume of flexible electricity available was 13,16 GWh, and this represented about 33,9 % of the average total volume on sale on the market.

A potentially useful measure could be the ratio of the available flexible volume to the total volume on sale on the market. As seen from Figure 4.2, this ratio does not seem to indicate any seasonal variations. In addition, although the curve looks chaotic, it actually is in a very narrow band, between 0,32 and 0,36. When compared to other countries, this variation becomes almost insignificant.

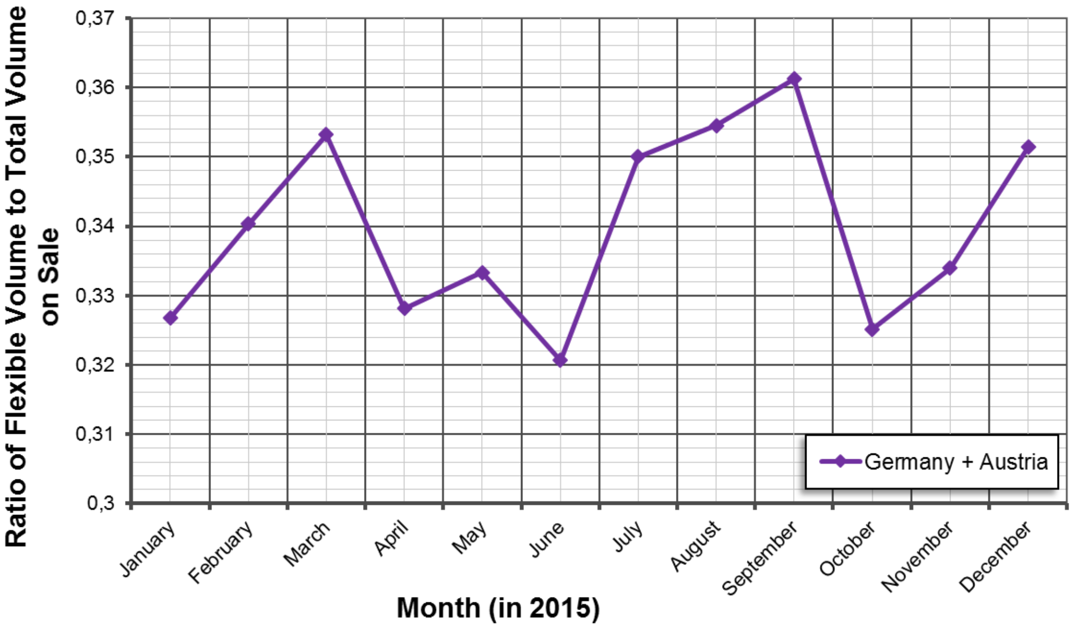

Figure 4.2: Monthly variations of the ratio of available flexible volume to the total volume on sale on the Day-Ahead Market for Germany and Austria

4.1.3 Aspect 3: Flexibility to Adjust to Load Gradients

When the frequency of hourly gradients and their severity are considered for Germany, it is immediately clear that the majority of the hourly gradients are within the range of -1 to $+1$, as seen from Figure 4.3. It is worth noting, however, that a high negative gradient (less than or equal to -2 GW/h) was observed on more than 2.000 occasions. Positive gradients were more spread out, with even very high positive gradients (greater than or equal to $+5$ GW/h) being observed on more than 200 times.

The hours on which very high gradients ($> +5$ GW/h or < -5 GW/h) were observed were filtered, and the availability of sufficient flexible load on those particular hours on the Day-Ahead Market was observed. It was found that on those particular hours, there was no significant change in activity on the market data observed. This could be due to the fact that if these changes were previously forecasted, then the market would have adjusted to the forecasted data accordingly. In addition, short term variations in power demand would have been dealt with in the Intraday market rather than the Day-Ahead market.

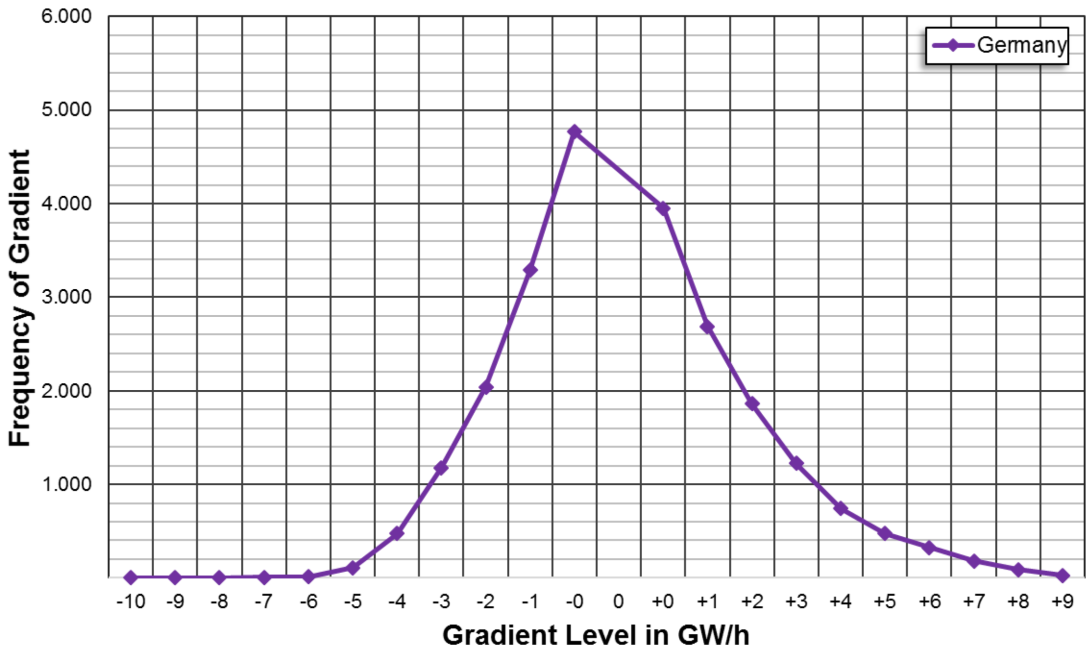

Figure 4.3: Frequency chart for Germany of hourly gradients of the residual load against the severity of the gradient (Note: the X-Axis coordinate of each point represents the frequency of gradients *lesser* than that value for negative values, and *greater* than that value for positive values)

4.1.4 Aspect 4: Short Term Availability of Power

The average absolute price difference between Intraday and Day-Ahead market prices for Germany and Austria were as shown in Figure 4.4. There was no significant seasonal variation observed through the months of the year, and the price difference largely remained within the range of 4 €/MWh and 6 €/MWh, suggesting that on the whole on a monthly scale, there was no significant change in the flexible power demanded on the Intraday market. In this case as well, Germany and Austria are treated as a single region due to the operation of a single market for both Day-Ahead and Intraday markets.

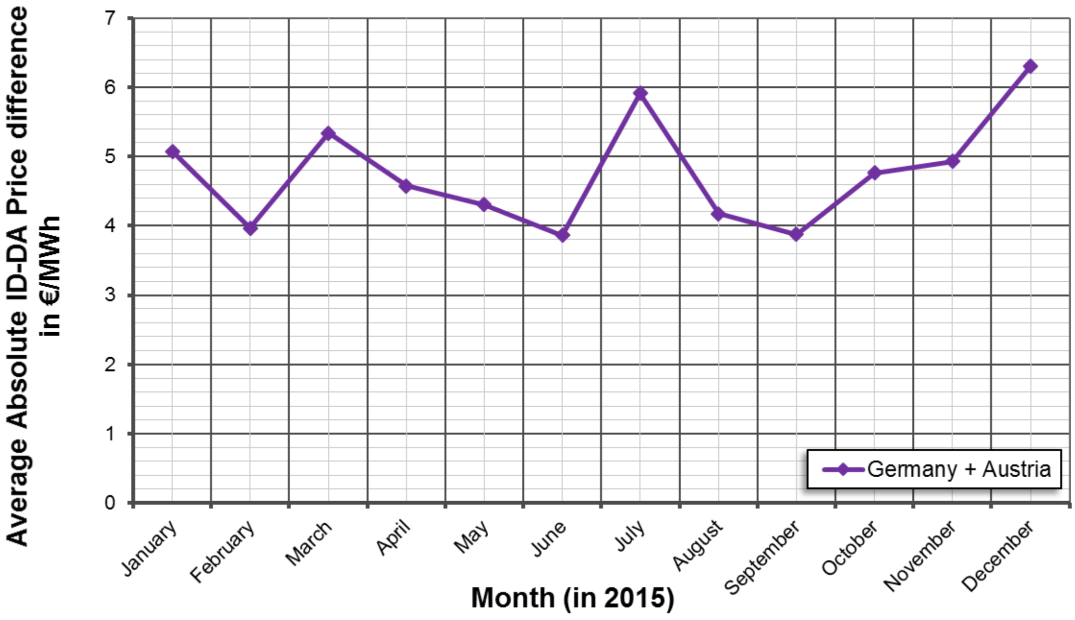

Figure 4.4: Graph showing the monthly variation of the average absolute price difference between the Intraday and Day-Ahead market prices in the German and Austrian (combined) market

4.1.5 Possible Impact of Policy on Flexibility

Germany has one of the more publicly visible and followed energy policies of the countries considered. The national target for 2020 is 18 % of gross final consumption by renewable sources. For electricity, the share of renewables targeted is 38,6 % [16].

There have been several measures favouring renewable power production in Germany since 2010, one of the immediate ones being in 2011, the latest amendment of the nuclear power law that essentially stopped many of the country's nuclear plants, and with the government announcing a nuclear energy-free country by 2022 [18]. The changes in the nuclear power situation is important for renewables because they are seen as (at least partial) replacements for the lost capacity. The 2011 decision would likely continue to have its effects through 2016 as well as the coming years. In addition, there was a further impetus towards increasing funding for offshore wind power, a measure that would increase the volume of renewables influx.

The *Erneuerbare-Energien-Gesetz* (EEG), or the Renewable Energy Sources Act was first introduced in 2000 to increase support for renewable electricity, and it has undergone multiple amendments in 2004, 2009, 2012, 2014 and most recently in 2016. The feed-in tariffs for renewables were generally being cut, particularly for solar PV, and in 2012 and 2014 the policy was moved towards direct marketing of renewable electricity, working on a market premium based model instead [17]. In general it could be said that incentivising renewables through a high feed-in tariff would increase the volume influx of intermittent renewable energies in the market and in the system. These increases in intermittent renewables would certainly contribute to larger demand for flexibility.

The most recent amendment to the EEG in 2016 moved renewable energy capacity procurement to an auction-based system. The process was first tested for ground-mounted solar PV installations at a small scale. The main difference being that projects will be remunerated according to the bid price of the project (not a fixed remuneration) [19]. The general reaction was that it will hinder further renewable power development. These measures seem to demonstrate or move towards finalising a gradual opening of the renewable power market to the market.

With respect to battery storage, there was a scheme announced from 2012 to 2015 offering a 30 % rebate per energy storage project installed along with a PV system. In 2016 there was a new initiative announced, making 30 million € available to support investments in battery storage of electricity [20]. Storage options could serve to supply flexibility, particularly in the cases of aspects 1 and 2 of flexibility as defined in the report.

4.2 Austria

4.2.1 Aspect 1: Flexibility in Adjusting to Variations in Residual Load

Austria, in 2015, followed a similar trajectory to Germany as far as variations in residual load was concerned. The trend as shown in Figure 4.5 follows a seasonal variation, with the summer months having a relatively lesser standard deviation than the winter months. However, this seasonal variation is less pronounced than for Germany, and possibly has to do with the fact that although Austria has a broadly similar climate to Germany, Austria does not have the breadth of diverse climate conditions that Germany does. Since the country is land-locked and is mountainous for the large part, it is more conducive to hydroelectric installations as opposed to certain other renewable electricity sources, particularly wind power. Indeed, wind power in Austria is concentrated on a small strip on its eastern border on the plains. It could be probably due to this reason that there is not a large difference in the standard deviations in residual load for summer and winter months. Looking only at the days having highly varying infeed of solar PV and wind power, it was noticed that on 15 out of 18 days of extreme variations in intermittent renewable infeed, the residual load also was above average, pointing to the correlation between increased infeed of intermittent renewables and higher variations in residual load.

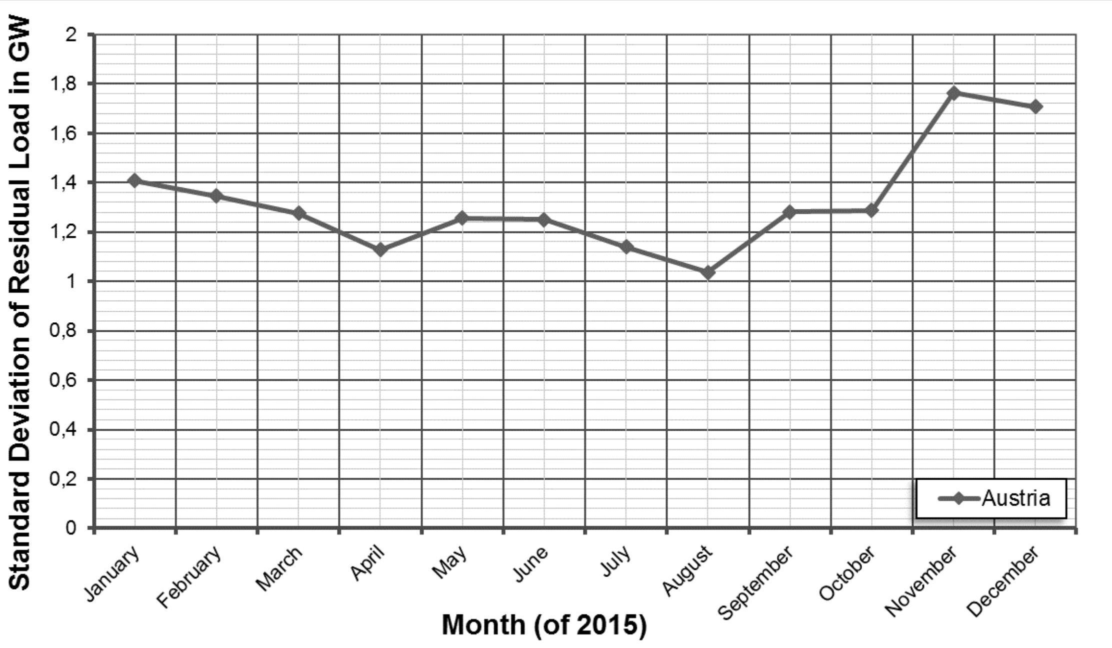

Figure 4.5: Graph of the Standard Deviation of residual load in Austria through the year 2015

Note: Analysis of aspect 2 involves market data, and owing to the common market shared between Austria and Germany, has been dealt with in section 4.1.2.

4.2.2 Aspect 3: Flexibility to Adjust to Load Gradients

Considering the variations of the hourly gradients of residual load with respect to their severity, it is apparent from Figure 4.6 that for Austria, the vast majority of the gradients were within -1 GW/h and $+1$ GW/h, without too many outlying points on the larger gradients. In those points of time where high gradients were observed, there were no significant changes in the ratio of available flexible volume to the total volume on sale in the market, possibly due to the fact that the Austrian market is part of the combined market with the much larger German market, which would have damped much of the market signals.

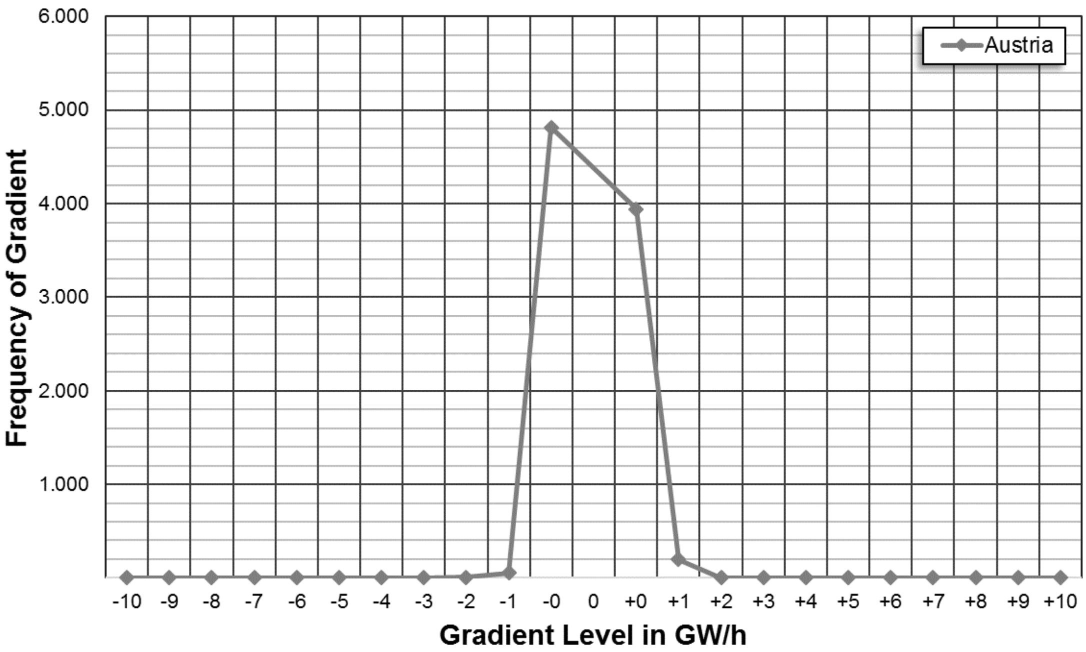

Figure 4.6: Frequency chart for Austria of hourly gradients of the residual load against the severity of the gradient (Note: the X-Axis coordinate of each point represents the frequency of gradients *lesser* than that value for negative values, and *greater* than that value for positive values)

4.2.3 Possible Impact of Policy on Flexibility

Austria, according to its 2020 renewable energy targets, should target to consume 34 % of its gross final energy from renewable sources. Nearly 70,6 % of its total electricity consumption is to be from renewables – a much higher share compared to most other EU countries, thanks to Austria's hydroelectric power potential. However, as seen in section 2.2.2, the share of wind and solar PV is low, and hydroelectric generation is clearly a more dominant source [21].

According to Austria's "Green Electricity Act" of 2002 (subsequently amended in 2006, 2007 and 2008), "Green" electricity sources including micro-hydro, solar PV and wind power are eligible for a feed-in tariff, along with a feed-in priority. The more recent Green Electricity Act of 2012 announces further investments in renewable energies, and the accompanying feed-in tariff decree in 2012 determined new feed-in tariffs for renewable electricity [22]. Smaller solar PV installations are covered instead by the funding provided by the *Photovoltaik Förderaktion* (Photovoltaics Support) from 2013 that offers different (and higher than the Green Electricity Act) feed-in tariffs [23]. Considering the limited potential Austria has for installing newer intermittent renewables, it might not show a higher demand for flexibility.

Austria has largely stayed on track to meet or even surpass its 2020 targets, with the absolute installed capacities of renewable energies, the chief ones here being hydroelectric and wind power [24]. The installed capacity of pumped hydroelectric storage has increased from 3094 MW to 3622 MW from 2014 to 2016 which could positively affect the supply of flexibility.

4.3 France

4.3.1 Aspect 1: Flexibility in Adjusting to Variations in Residual Load

The residual load variation curve for France is as seen in Figure 4.7. It is clear that during the winter months, there is an increase in the standard deviation of the residual load. It is also very apparent that the general level of the standard deviation (when normalised to account for the fact that the average residual load in France was 50,6 GW) is much lesser than that of other countries (except Switzerland).

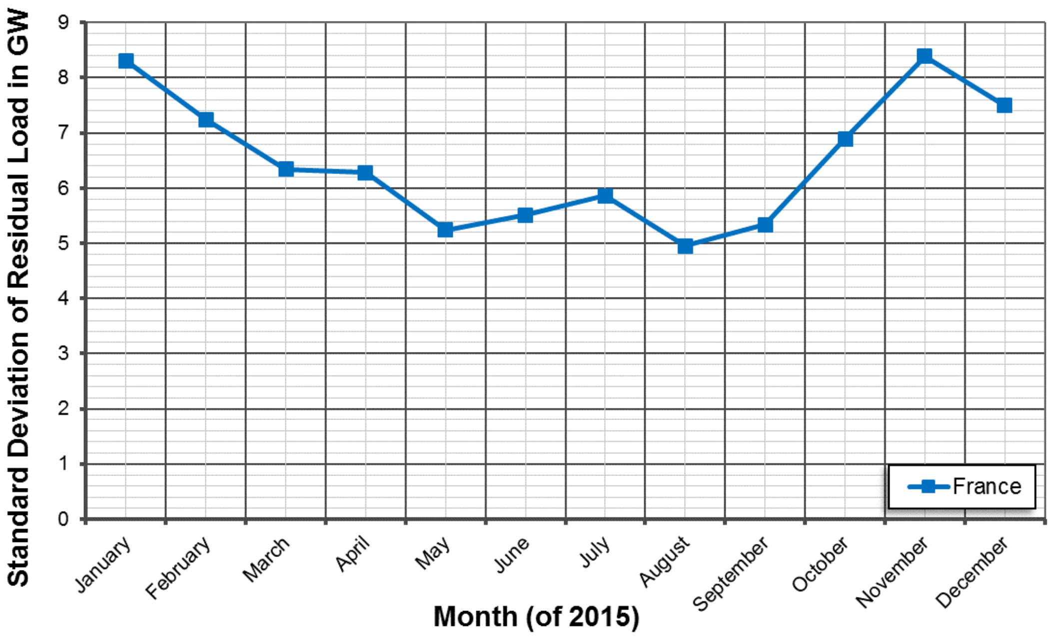

Figure 4.7: Graph of the Standard Deviation of residual load in France through the year 2015

In France, out of 8 days with extreme variations in wind and solar infeed, 6 of the days were also days with higher than average residual load variation, suggesting a mild correlation, if any, between high wind and solar PV infeed to variations in residual load. As with Germany, most of the days with higher wind power infeed were in the winter months.

The general level of the standard deviation was between 5 GW and 8 GW, with the country having a yearly mean residual load of 50,6 GW. This, when correlated with the share of intermittent renewables in France does show a pattern, discussed later in section 5.1.

4.3.2 Aspect 2: Flexibility in Recovering from Price Extremes

The average price in 2015 on the French Day-Ahead market was 38,46 €, and the extreme prices were defined as 12,57 € and 64,35 €. The average volume of flexible electricity available was 8,22 GWh, and this represented about 43,2 % of the average total volume on sale on the market. This value is similar to the one of the German-Austrian markets, although looking at the average "shifts" needed, there was, again, more total "right shift" needed than average "left shift". The average "shift" as a percentage of available flexible volume remained on the same levels as Germany, compared later in section 5.1.

Considering the ratio of the available flexible volume to the total volume on sale (as a normalising factor), the monthly trend, seen in Figure 4.8 is largely constant, hovering between 0,4 and 0,5 consistently.

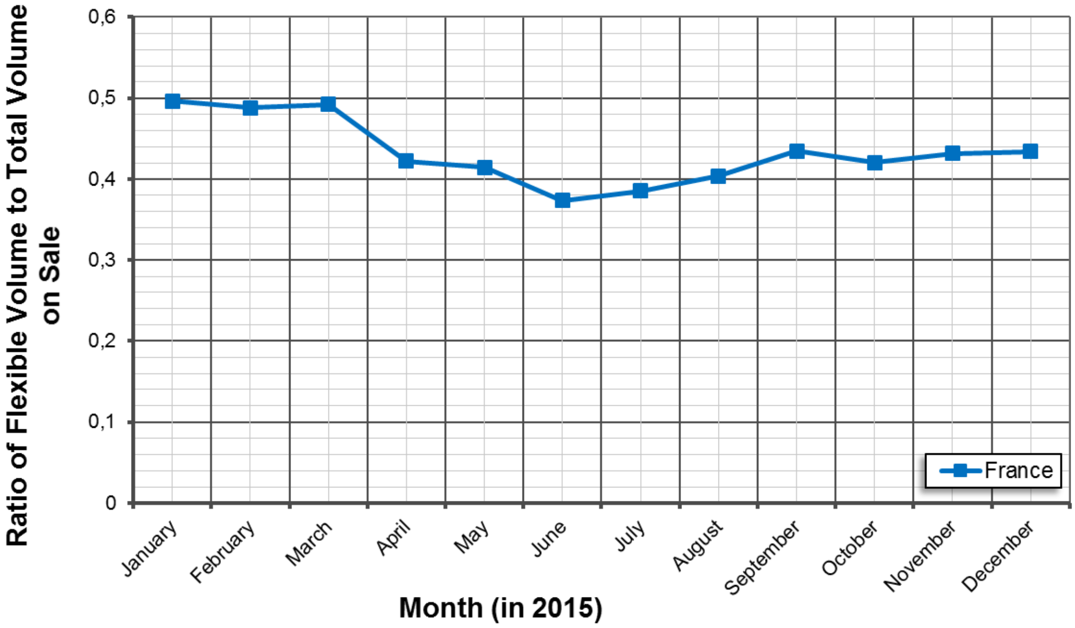

Figure 4.8: Monthly variations of the ratio of available flexible volume to the total volume on sale on the Day-Ahead Market for France

4.3.3 Aspect 3: Flexibility to Adjust to Load Gradients

Although the majority of the hourly gradients through the year 2015 for France were between -1 and $+1$ (as seen from Figure 4.9), a significant number of hours saw gradients higher than or equal to $+2$ GW/h (more than 1.500 times). This curve does tend to be more spread out for larger countries as opposed to smaller countries, plainly due to the fact that the total amount of residual load does tend to be larger for larger countries, and a direct comparison without normalisation of the values would not be very meaningful.

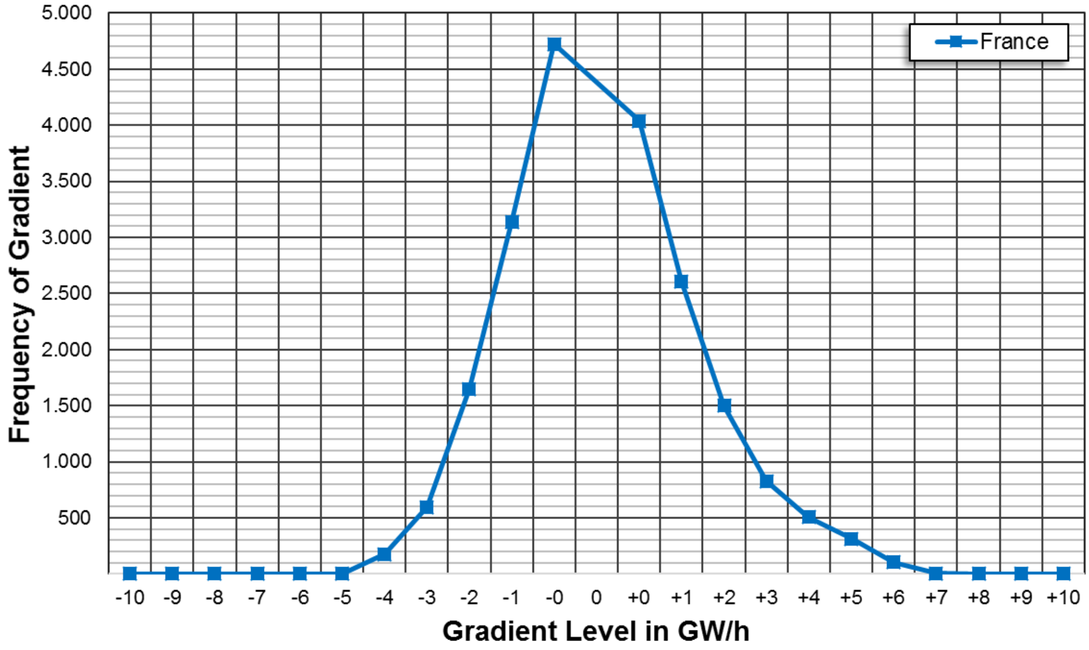

Figure 4.9: Frequency chart for France of hourly gradients of the residual load against the severity of the gradient (Note: the X-Axis coordinate of each point represents the frequency of gradients *lesser* than that value for negative values, and *greater* than that value for positive values)

4.3.4 Aspect 4: Short Term Availability of Power

The average absolute price difference between Intraday and Day-Ahead market prices for the French market were as shown in Figure 4.4. Once again, there were no significant seasonal variations to be seen and the price difference largely remained within the range of 4 €/MWh and 7 €/MWh.

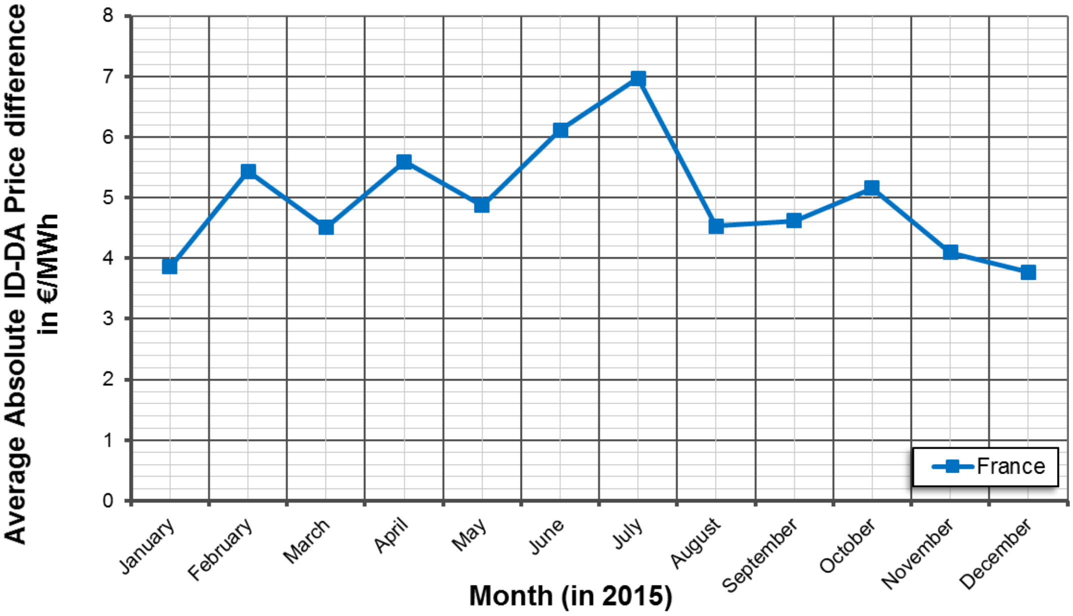

Figure 4.10: Graph showing the monthly variation of the average absolute price difference between the Intraday and Day-Ahead market prices in the French market

4.3.5 Possible Impact of Policy on Flexibility

France has historically been associated with a large share of nuclear power in its electricity mix with up to 74 % of total electricity production in 2013 coming from nuclear power [6]. Yet, there is a target of 27 % electricity from renewable sources by 2020, set by the country's National Renewable Energy Action Plan [25].

Although as of 2014, France stands behind its trajectory for renewable power, solar power in the country particularly stands out, since it has far outstripped the 2009 projections, possibly thanks to the contributions of the so called Mediterranean Solar Plan. On the other hand, with wind power, it lags behind a lot (about 2,46 GW behind projections in 2014), contributing to the total renewable power deficit (as compared to the projections) [26].

France is rather different from the other countries considered in that it does not have a feed-in priority for renewables. Its feed-in tariff schemes are at a slightly lesser but comparable price level to other countries like Germany, particularly for solar PV installations. There are newer support schemes, however, for offshore wind installations [27]. However, as seen from the analysis and the trajectory in which policy is generally heading in France, there might not be a high demand for flexibility expected.

4.4 Switzerland

4.4.1 Aspect 1: Flexibility in Adjusting to Variations in Residual Load

The analysis of the standard deviation of the residual load of Switzerland through the year 2015 shows primarily that there was very little to no seasonal variation in the variations of residual load (Figure 4.11). Yet there was a small increase observed in the winter months, quite possibly related to the consumption side rather than generation, and due to increases in the heating and lighting load in the winter months.

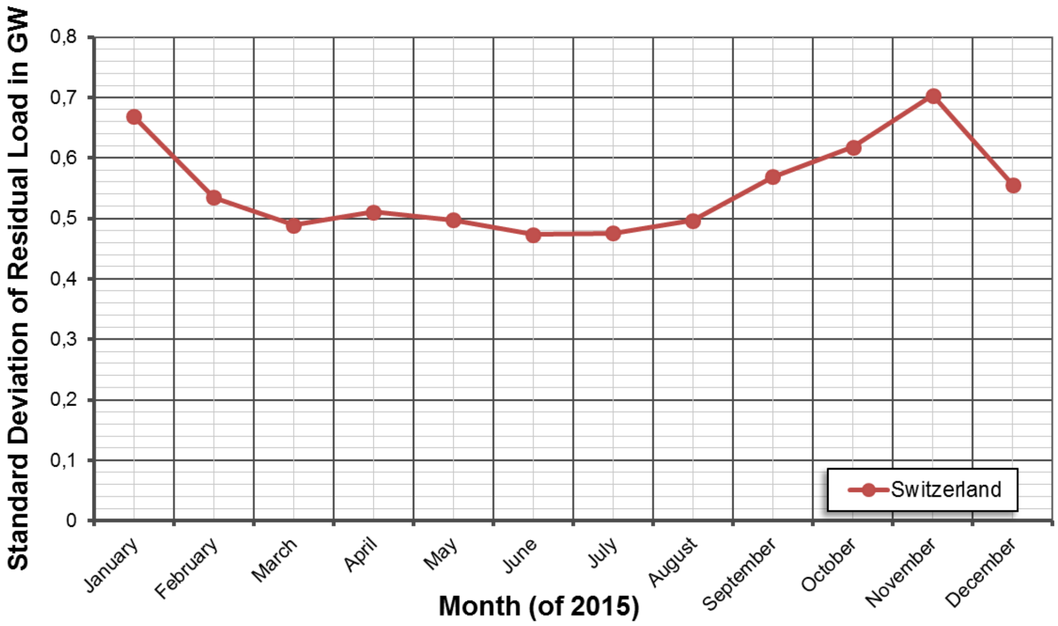

Figure 4.11: Graph of the Standard Deviation of residual load in Switzerland through the year 2015

Another interesting point of note for Switzerland is that the overall variation in residual load was much lower than in all the other countries studied (except France). A possible explanation for these outlying values would be that there was lesser penetration of intermittent renewable power in the country, which is largely dominated by hydroelectric and nuclear power plants, as previously discussed in section 2.2.4. There are very few significant installations of wind and solar PV power in Switzerland, which could possibly account for the reduced amount of variation in the residual load.

4.4.2 Aspect 2: Flexibility in Recovering from Price Extremes

Considering the price extremes for the Swiss Day-Ahead market, it was observed that in 2015, the average price was 40,29 €, with the lower extreme price was 13,99 € and the higher extreme price being 66,60 €. There was more average "right shift" of 1,826 GWh as compared to 1,080 GWh of average "left shift", denoting that more volume of electricity was needed to recover from low extreme prices as compared to high extreme prices. The average volume of flexible electricity available on the market was 6,78 GWh, and this represented about 83,35 % of the average total volume on sale on the market. This value is the highest among all the countries in consideration. Looking at the hourly curves, this could simply mean that there is a large volume of unsold or not bought electricity that is either on sale or to be bought. Looking at the Figure 4.12, the ratio of the average flexible volume to the total volume on sale does not seem to show seasonal variations, but stays in a relatively high band of 0,78 to 0,88 as compared to other countries (compared in section 5.1).

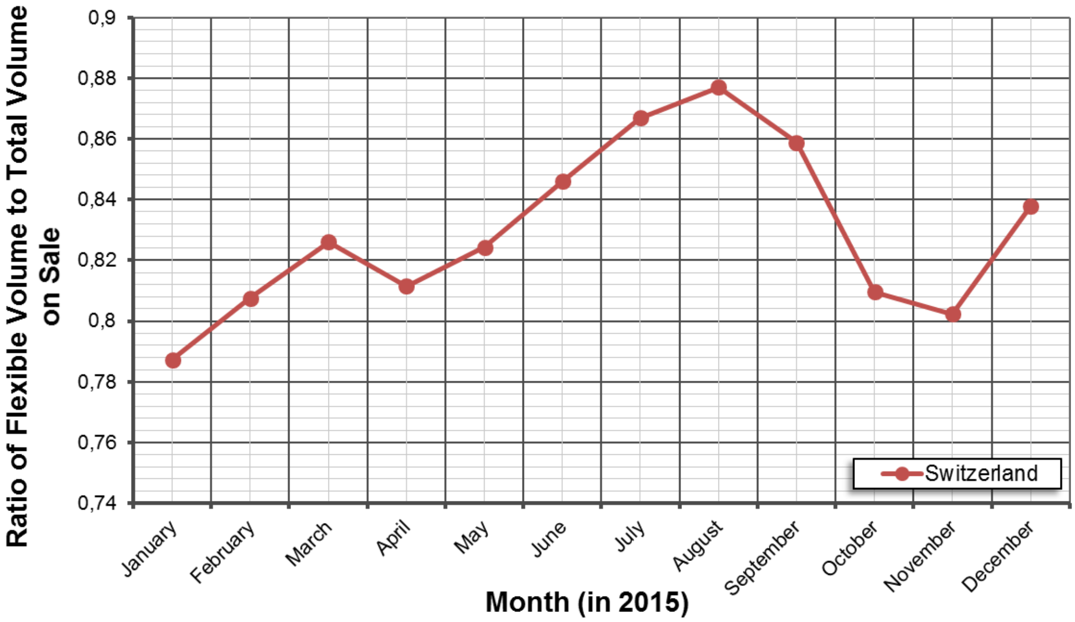

Figure 4.12: Monthly variations of the ratio of available flexible volume to the total volume on sale on the Day-Ahead Market for Switzerland

4.4.3 Aspect 3: Flexibility to Adjust to Load Gradients

While looking at the frequency of the hourly gradients of residual load with respect to their severity in Switzerland in 2015, it was seen that all the gradients were between -1 GW/h and $+1$ GW/h, indicating that almost at no point was there a sharp increase or decrease in residual load, as seen from Figure 4.13

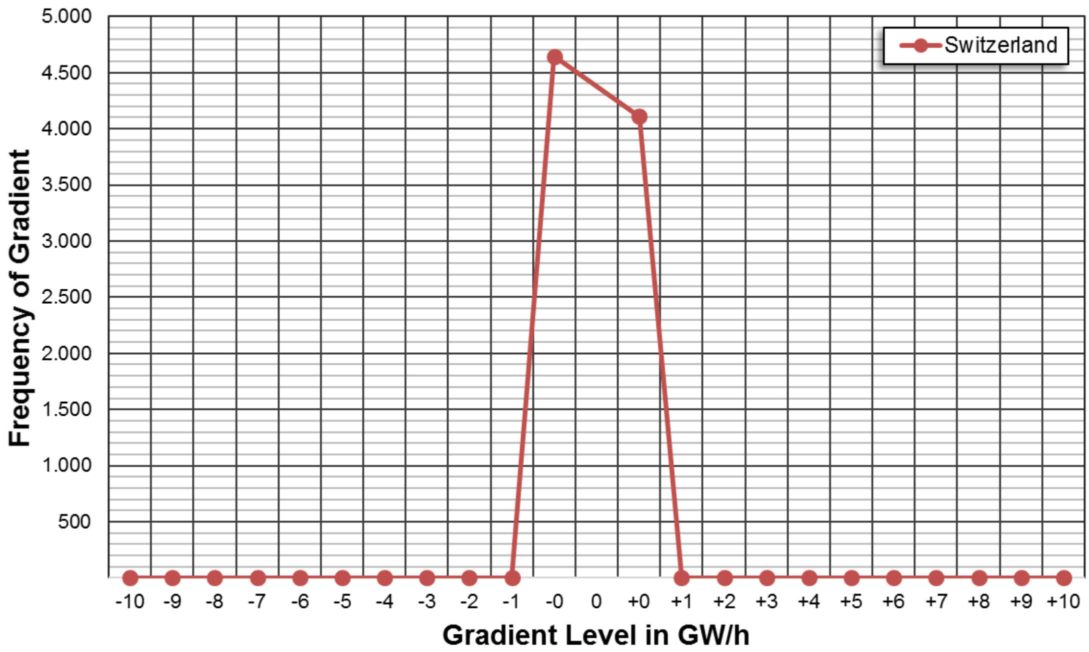

Figure 4.13: Frequency chart for Switzerland of hourly gradients of the residual load against the severity of the gradient (Note: the X-Axis coordinate of each point represents the frequency of gradients *lesser* than that value for negative values, and *greater* than that value for positive values)

4.4.4 Aspect 4: Short Term Availability of Power

The average absolute price difference between Intraday and Day-Ahead market prices for the Swiss market in 2015 were as shown in Figure 4.14. The data shows no significant seasonal variation, and the price difference largely remained within the range of 4 €/MWh and 6 €/MWh, suggesting that on the whole on a monthly scale, there was no significant change in the flexible power demanded on the Intraday market.

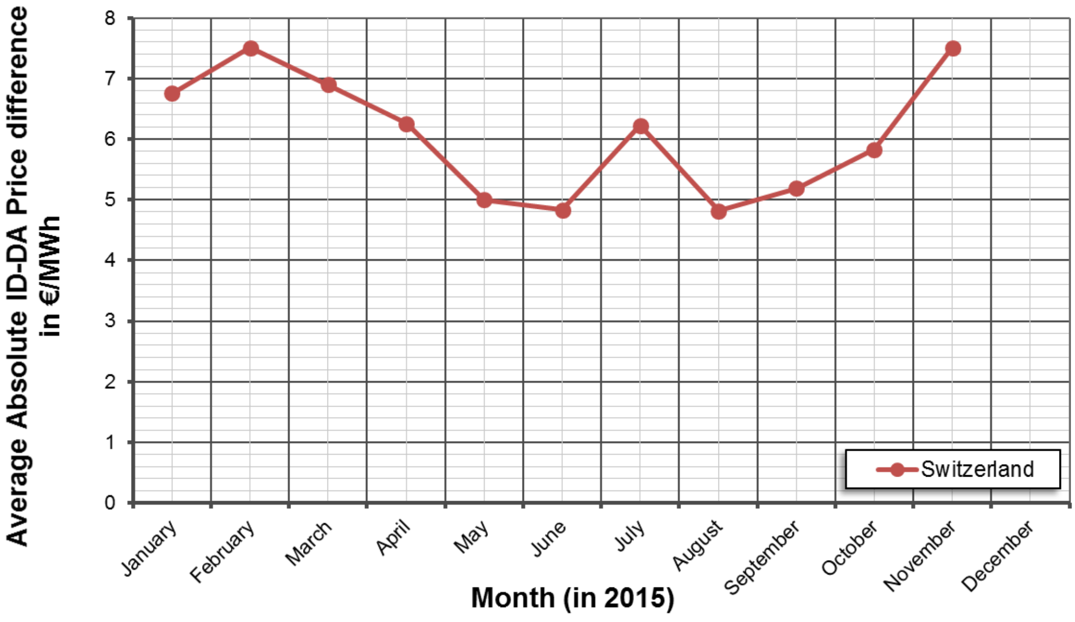

Figure 4.14: Graph showing the monthly variation of the average absolute price difference between the Intraday and Day-Ahead market prices in the Swiss market

4.4.5 Possible Impact of Policy on Flexibility

Switzerland, not being in the EU, was not obliged to form a 2020 target for renewables and prepare a national plan. In 2008, the government did publish a plan to achieve 24 % of the country's final energy consumption by 2020 from renewable sources [28].

The country however, has had a stable and largely non-disruptive energy policy. Some of the major incentives for renewables started in 2005 with the "Additional Cost Financing"" (*Mehrkostenfinanzierung*) (MKF) which worked similar to a market premium for infed electricity [29].

In 2009, a feed-in tariff system was introduced with the "Cost-covering Feed-in compensation" (*Kostendeckende Einspeisevergütung*) (KEV). The KEV works with a quota for each renewable technology so as to not over-spend on individual technologies. In this case, the fed-in electricity is acquired by the grid operator, Swissgrid, and a levy on the final consumer is charged to compensate for the extra cost [30]. The KEV scheme has been criticised for capping the market demand and the total available amount being lesser than the market demand. In 2013 though, the government increased the cap on the levy, enabling further investments to take place under the scheme. Renewable energies are not given feed-in priority.

The demand for new renewable installations came particularly after 2011 when Switzerland's version of the "nuclear phase-out" was announced. Unlike Germany which places a timeline on the phase-out, Switzerland places no definite, binding timeline or deadline for the phase-out. It is estimated (unofficially), however, that the last reactor could go offline in 2034 [31]. The announcement did lead to an increased demand for investments in renewable energies, which could lead to an increased demand for flexibility. Due to high capacities of pumped hydroelectric storage, there is a good supply of flexibility. In general, it would be interesting to note how nuclear power is planned to be replaced in the long term, and demand for flexibility would largely be based on those future plans.

4.5 Spain

4.5.1 Aspect 1: Flexibility in Adjusting to Variations in Residual Load

For the Spanish power system, Figure 4.15 shows the variation of the residual load seen in the months of 2015. As with Germany, Austria and Switzerland, an increase in the standard deviation values during winter is seen for Spain. 26,2 % of the country's installed electricity capacity is wind and solar PV, comparable with that of Germany, Austria and Portugal, and this probably accounts for the higher levels of standard deviation when normalised and compared with other countries like France and Switzerland.

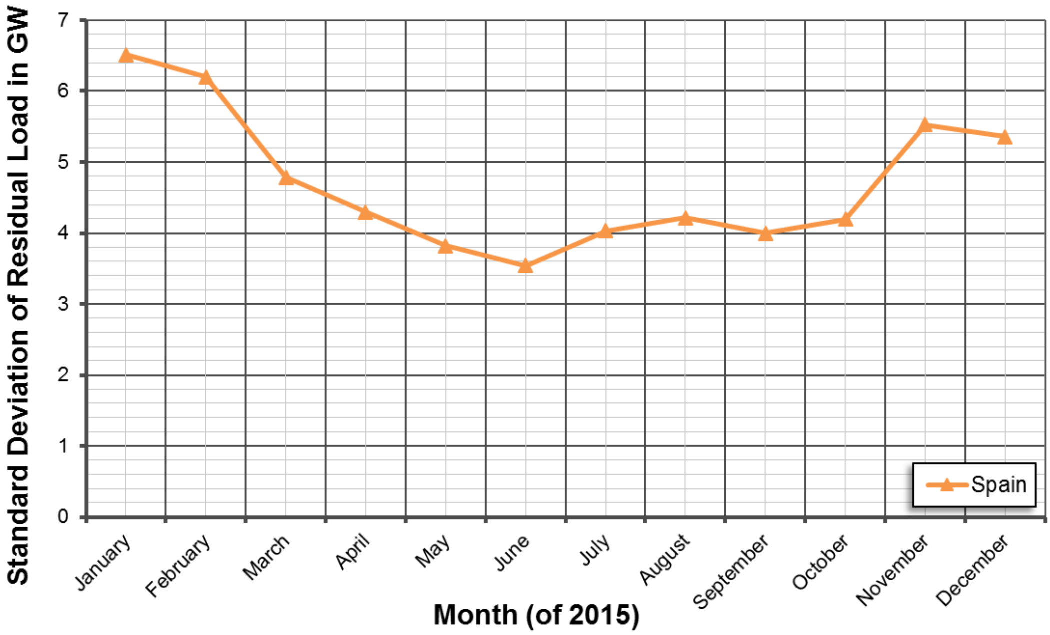

Figure 4.15: Graph of the Standard Deviation of residual load in Spain through the year 2015

To further investigate the correlation between wind and solar PV and high variations in residual load, a cluster analysis was done to filter out those days with high wind and solar infeed and compare the variations in wind and PV infeed variations and residual load variations. Out of the 15 days with extreme wind and solar PV infeed, 11 days also showed high variations in residual load, showing a mild correlation between these factors.

The general level of the standard deviation was between 3,5 GW and 6,5 GW, with the country having a yearly mean residual load of 21,4 GW.

4.5.2 Aspect 2: Flexibility in Recovering from Price Extremes

The average price in 2015 on the Day-Ahead market of MIBEL (Spain and Portugal) was 31,44 €, and the extreme prices were defined as 0 € and 63,45 €. The average volume of flexible electricity available was 41,46 GWh, and this represented about 68,3 % of the average total volume on sale on the market. This is the highest among the three major market considered in this study, and as seen in the comparison, the highest after Switzerland. The lower extreme price for the market was less than 0 €, and since the market rules do not allow sub-zero prices, for this analysis, 0 € was considered the lower extreme price, and no analysis was made for the "right shift". There were occasional "left shifts" needed in case of extreme high prices, but it is worth mentioning that these were few, and

Looking at the ratio of the available flexible volume to the total volume on sale, the monthly trend as seen in Figure 4.16 is shows variations with big dips in winter and summer, with highs in spring and autumn. This seasonal variation was not observed in other countries.

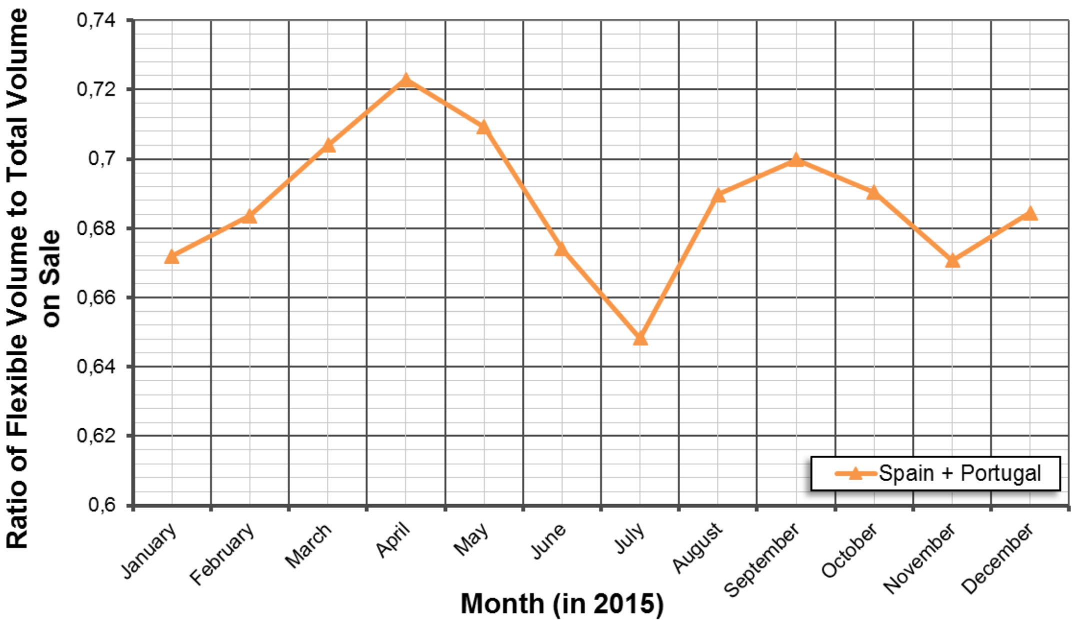

Figure 4.16: Monthly variations of the ratio of available flexible volume to the total volume on sale on the Day-Ahead Market for Spain and Portugal

4.5.3 Aspect 3: Flexibility to Adjust to Load Gradients

As with France, the hourly gradients through the year 2015 for France were largely between -1 and $+1$ (as seen from Figure 4.17). Although the curve is not as steep as compared to Austria or Switzerland, it still has a large number of occasions when the gradients were higher than or equal to $+2$ GW/h. Interestingly there are not as many high positive gradients as compared to Germany and France.

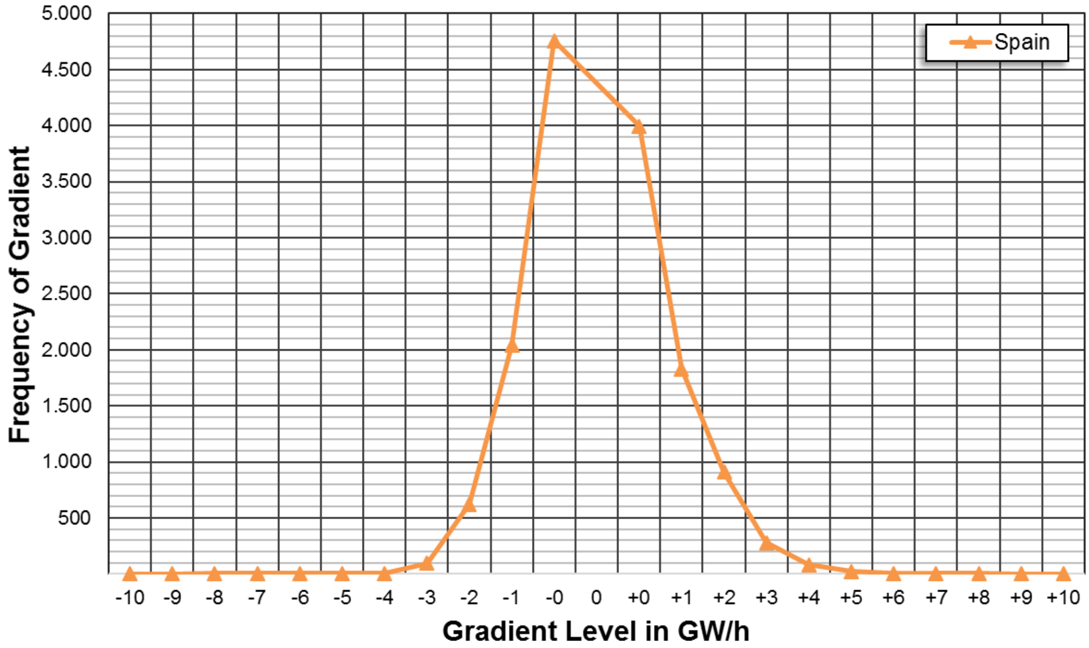

Figure 4.17: Frequency chart for Spain of hourly gradients of the residual load against the severity of the gradient (Note: the X-Axis coordinate of each point represents the frequency of gradients *lesser* than that value for negative values, and *greater* than that value for positive values)

On the hours with high gradients, there was no exceptional activity observed on the Day-Ahead markets.

Note: Due to unavailability of data, analyses for aspect 4 could not be performed.

4.5.4 Possible Impact of Policy on Flexibility

Spain has a target of 20 % of gross final energy consumption from renewable sources by 2020, and the share of it in electricity was projected to be up to 40 %, according to its National Renewable Energy Action plan published in 2010 [32]. Renewables are covered under the “special regime” of production of electricity, which in effect enjoy feed-in priority.

Going by the share of renewables in the energy mix in Spain, the original Action Plan document predicted a 31,9 % share of renewables in electricity generation in 2013, and 32,9 % in 2014. Going purely by share in the mix, the country has exceeded its targets by a large margin – the actual share being 36,7 % and 37,8 % in 2013 and 2014 respectively [33]. However, the initial projections were done in 2009-10, before the european sovereign debt crisis affected Europe and Spain. Indeed, the GDP forecasts used in the document assume a 1,8 % growth in GDP for 2011, with “*subsequent annual* *increases of 2,7 % up to 2020*" [34]. The actual growth of GDP for Spain in 2011 was -1 %, and indeed, the GDP growth crossed 2 % only in 2015 [35].

Looking at the plans and forecasts more closely, it is seen that the gross electricity generation is significantly below forecasts, particularly for wind and solar installations. Between 2013 and 2014, there was a net addition of 2 MW to solar installations, and 17 MW wind installations [33].

In 2010, months after the publication of the National Renewable Energy Action Plan (NREAP), the Spanish government introduced a levy through Royal Decree-Law 14/2010 on electricity fed in to the grid, by producers from the normal and "special regime" (renewables) alike [36]. The levy introduced was a flat 0,50 € levy, which clearly has a disproportionately larger effect on smaller producers of power. Through Royal Decree 1565/2010, Spain started cutting support for renewable energy projects, particularly solar PV, by reducing the feed-in tariffs [37]. Then, support for wind and solar thermal power was reduced by reducing the tariffs through Royal Decree 1614/2010 [38], that could possibly contribute to lesser electricity traded on the market. Certain measures were taken with Royal Decree 1699/2011 to simplify the procedure for smaller producers to connect to the grid [39]. The Ministerial Order ITC/2914/2011 and Royal Decree-Law 13/2012 further incorporate Directive 2009/28/EC, establishing Guarantees of Origin for renewable energy sources.

The Royal Decree 647/2011 addressed the management of load, particularly as affecting non-peak hours and electric vehicle charging [40]. This would have the potential of reducing gradients and peaks in load curves, as well as eventually being seen as a source of storage, hence increasing supply of flexibility.

With Spain on track to meet its 2020 renewables share targets, the most widely publicised measure against renewable generation was in 2013, with Statute 15/2012, known colloquially as the "solar tax", which imposed a 7 % tax on electricity generation. This was seen to have hit solar PV power producers particularly hard [41]. Spain formally moved away from the feed-in tariff regime in 2013 through Royal Decree-Law 9/2013 by announcing a fixed tariff to replace the feed-in tariffs (also retroactively) [42]. In 2015, there was an attempt at enforcing the rules regarding self-consumption, with Royal Decree 900/2015 establishing a penalty between 6.000.001 € and 60.000.000 € for those who fail to report their self-consumption status [43]. The NREAP document published in early 2010 makes no mention of these measures.

The so-called "solar tax" particularly would lower the demand of flexibility available in the system that is discussed in this study. This is because the tax targets producers of electricity who choose to store it, for e.g. in batteries [44]. In early 2016 though, there was general political talk about the tax being repealed, although given the uncertain political situation in Spain, concrete action seems unlikely. The unfavourable policy climate in Spain for further investments in renewable power could mean that there will be reduced demand for flexibility.

4.6 Portugal

4.6.1 Aspect 1: Flexibility in Adjusting to Variations in Residual Load

Portugal in 2015 showed a much higher standard deviation in residual load through the year than all the other countries. The trend as shown in Figure 4.18 shows a clear seasonal variation, with the summer showing a relatively lesser standard deviation than winter. Filtering out the days having extreme variations in infeed of solar PV and wind power, it was noticed that 17 days out of 19 days of extreme variations in intermittent renewable infeed also had high variations in residual load.

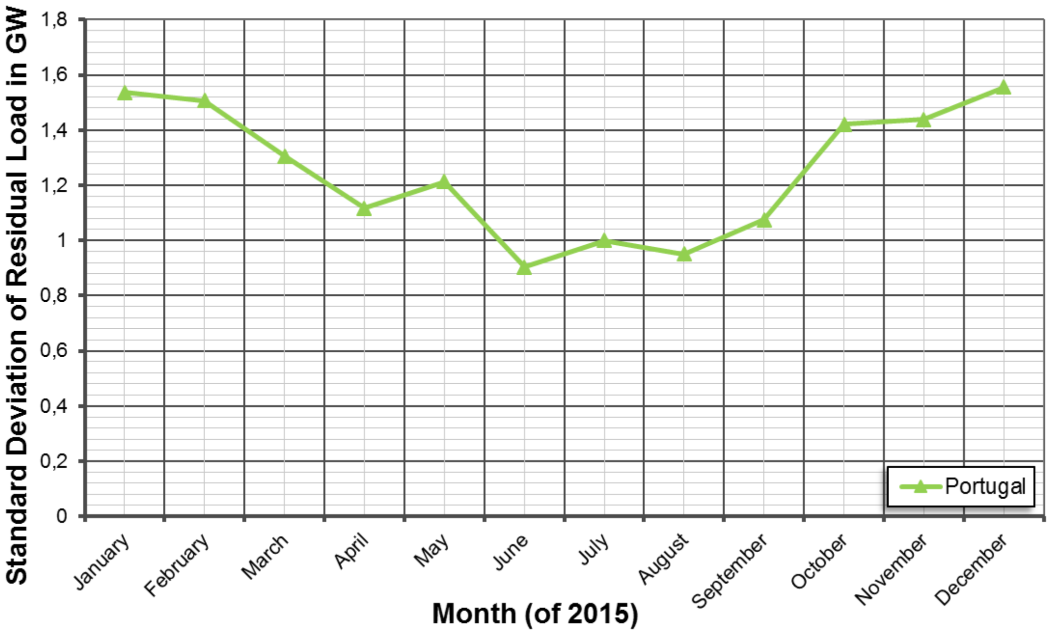

Figure 4.18: Graph of the Standard Deviation of residual load in Portugal through the year 2015

Note: Aspect 2 involves market data, and owing to the common market shared between Portugal and Spain, has been dealt with in section 4.5.2

4.6.2 Aspect 3: Flexibility to Adjust to Load Gradients

It is apparent from Figure 4.19 that for Portugal, all the hourly gradients of residual load were within -1 GW/h and $+1$ GW/h. Naturally, gradients would be more discernable if the scale was reduced or normalised, but in this case it is not very useful since most countries follow very similar patterns.

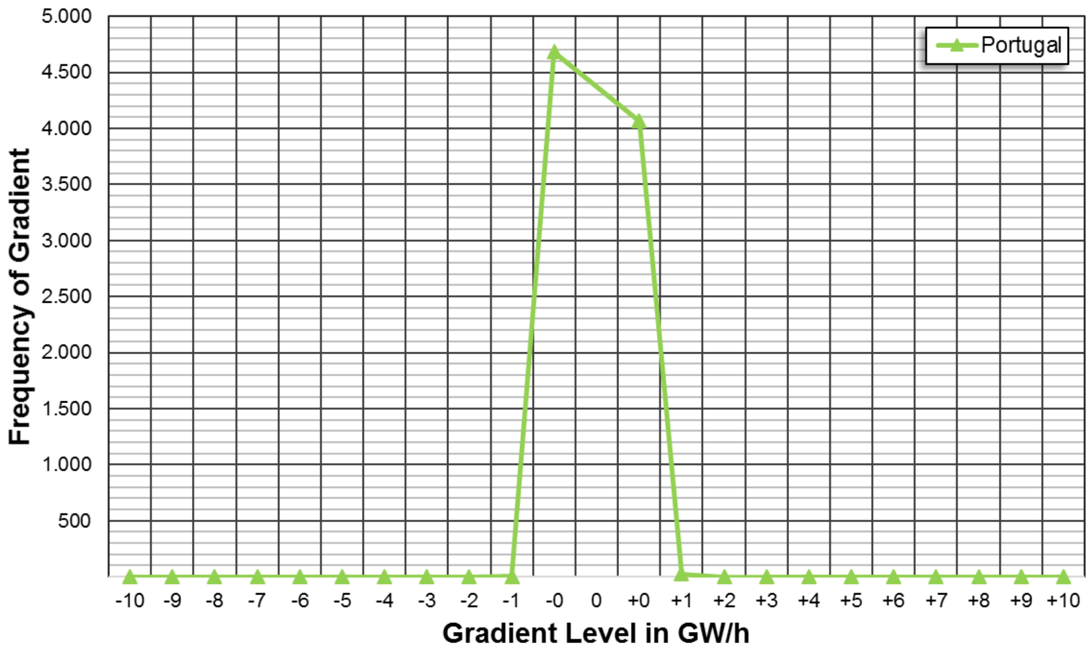

Figure 4.19: Frequency chart for Portugal of hourly gradients of the residual load against the severity of the gradient (Note: the X-Axis coordinate of each point represents the frequency of gradients *lesser* than that value for negative values, and *greater* than that value for positive values)

4.6.3 Possible Impact of Policy on Flexibility

According to the National Renewable Action Plan published by Portugal, 31 % of the gross final energy consumption of the country in 2020 needs to be from renewable sources. In the electricity sector, 55,3 % of the electricity produced needs to be from renewable sources (including pumped hydroelectric production) [45].

Since 2010, the share of renewable energy in electricity has steadily increased, with 52,08 % of electricity coming from renewable sources in 2014. Portugal is ahead of its predicted RES trajectory as far as 2014 is concerned. Barring extraordinary circumstances, it looks to well overshoot the predicted trajectory in the coming years. The initial predictions were made just before the european sovereign debt crisis, and may have predicted reduced investments in renewable energy during the years after the crisis. Part of the reason why the renewable shares are high is also due to decreased overall growth. The current share of renewables, however, is close to meeting the target [46].

Electricity generated from renewable sources is supposed to be acquired from the generators by the supplier of last resort, with a feed-in tariff being paid according to the so called “special regime” (*regime especial*) of electricity production. Most types of small scale renewable energies are included in this regime, as are most large scale renewable production except hydroelectric production. Wind energy is bearing most of the share of intermittent renewable production, with 4,6 GW out of 4,9 GW of installed capacity being of wind energy installations [6].

In 2009, the expected amount of hydropower that would be built by 2020 was estimated at 7.000 MW [47], and as of 2013, 5.700 MW was already built. A major measure of energy storage in Portugal is the pumped hydroelectric installations. This directly affects the supply of flexibility as defined in section 3.1.

As of 2016, the installed capacity of pumped hydroelectric storage is 1.623 MW, which is an increase from 1.245 MW in 2015.

The high level of solar PV and wind power production can be expected to increase the demand for flexibility. In 2013, according to the Ordinances 430/2012 and 431/2012, the feed-in tariffs were lowered by about 30 % from the 2012 rates. In 2014, the rates for solar PV in particular were lowered again, ostensibly because the country on the whole was on track to meet the 2020 targets [48]. The reduced impetus for renewables can also imply lessening demand for flexibility.

4.7 Great Britain

4.7.1 Aspect 1: Flexibility in Adjusting to Variations in Residual Load

The standard deviation of the residual load in 2015 in Great Britain can be seen in Figure 4.20. While there is a clear seasonal component to the curve discernible, there is a curious uptick in the variations in early summer, although the UK Meteorological Office reported that there were no significant anomalies in that season. Overall, the pattern is very similar to those of countries that have high infeed of intermittent renewables. There was about 15,6 % of intermittent renewable electricity in the installed capacity that could account for the higher variations as compared to countries like France [6].

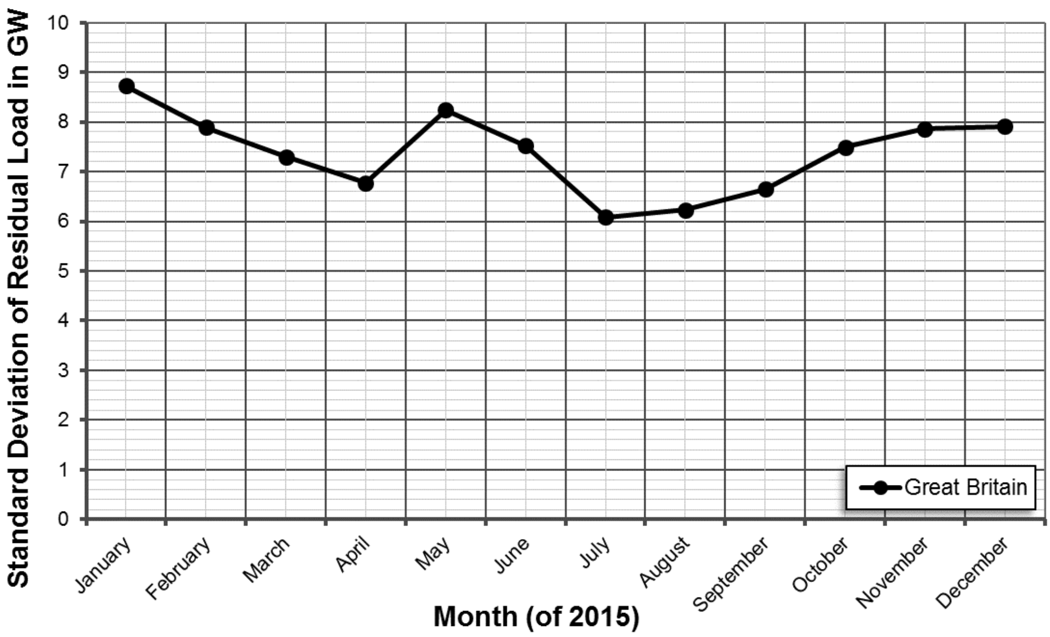

Figure 4.20: Graph of the Standard Deviation of residual load in Great Britain through the year 2015

A cluster analysis that filtered the days with high wind and solar PV infeed did indeed reveal that the days with high variations in residual load were in winter, and that on most of the days with high variation in intermittent renewable infeed, the residual load variations were also high.

The general level of the standard deviation was between 6 GW and 9 GW, with the country having a yearly mean residual load of 33,4 GW.

4.7.2 Aspect 2: Flexibility in Recovering from Price Extremes

The average price in 2015 on the Day-Ahead market of Great Britain (operated by APX) was 39,41 GBP (GBP = British Pound Sterling) and the extreme prices were defined as 17,93 GBP and 60,88 GBP. The average volume of flexible electricity available was 1,5 GWh, and this represented about 29,1 % of the average total volume on sale on the market. This is the lowest among all the countries studied, with the most likely reason being that this data is only for one of the markets (APX UK) and does not involve the data from the other market. In addition, data for the last three months of the year was not available for analysis. From Figure 4.21, it can be seen that flexible volume on the APX UK market was indeed comparatively very low, and is more apparent when compared to other countries.

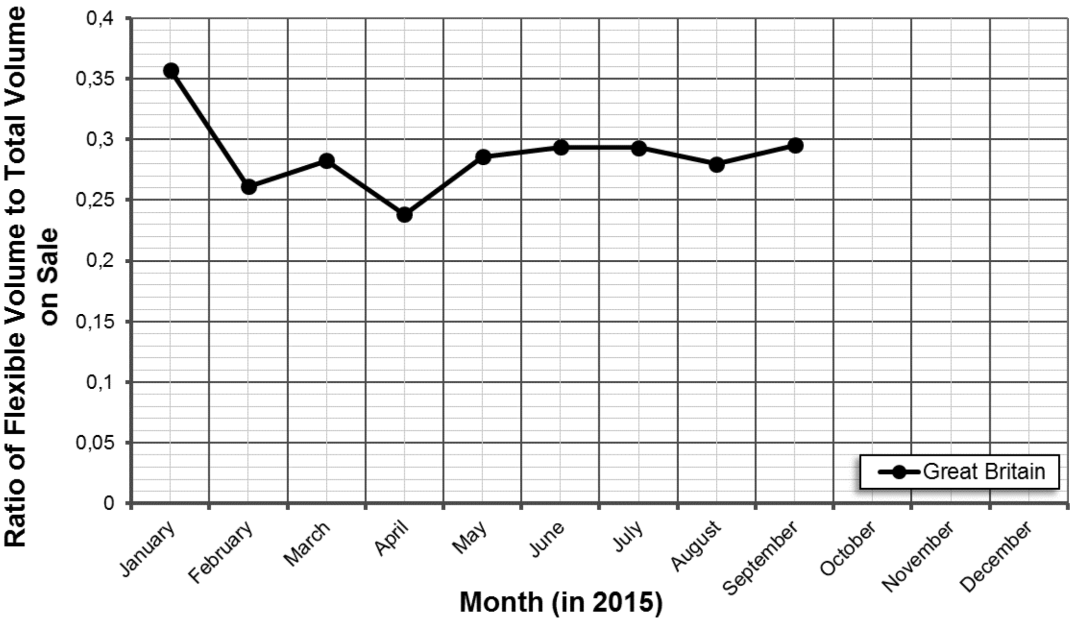

Figure 4.21: Monthly variations of the ratio of available flexible volume to the total volume on sale on the APX UK Day-Ahead Market for Great Britain

Note: Sufficient data to perform analyses for aspects 3 and 4 were not publicly available, and hence the analyses were not performed.

4.7.3 Possible Impact of Policy on Flexibility

The United Kingdom's renewables target for 2020 is a 15 % share of renewable energy in total final energy consumption, and for electricity, that amounts to a 31 % share of renewable electricity. The UK, at the time of writing of its National Renewable Energy Action Plan, was producing about 9 % of its electricity from renewable sources, hence requiring a steep increase in its renewable electricity deployments [49].

Although some commentators believe that the UK will likely miss its overall 2020 targets, in the area of electricity, the sub-target is likely to be met – it is at least exceeding expectations at present. This is more remarkable because this increase in the share of renewables is despite the fact that there has been no continued slowdown of economic activity in the country (as in the case of certain countries such as Spain) [50].

The increase in the share of renewables can be primarily attributed to a sharp increase in solar PV installations, as well as an increase in wind power installations, both of which are above the initial forecasts that were made in 2010. In particular, the rise in solar PV installations is very telling – an increase from 2,851 GW of installed solar PV capacity in 2013, leading to 5,377 GW in 2014, a yearly increase of nearly 88,6 %. In contrast, the forecast (in 2010) solar PV deployment for 2014 was 0,730 GW. The solar farms already built are concentrated all along the southern coast of England, but also in southern Wales and in the Oxfordshire and Gloucestershire counties of England. Wind power (both onshore and offshore) have also been exceeding their initial 2010 forecasts, with 12,988 GW of total wind power capacity as of 2014, whereas the forecasted (in 2010) capacity was 11,990 GW [49] [51]. This large overshoot in the renewable energy targets could possibly slow down further incentives for renewables, possibly stabilising demand in flexibility.

Until 2014, the primary method of support for renewable power sources was the "Renewables Obligation" (RO) scheme, which legally obligated utilities to buy a minimum percentage of their electricity from renewable generators, through Renewable Obligation Certificates (ROC). The generator earns income both by selling the electricity on the market, as well as by selling ROCs (which utilities are required to buy). Therefore, there is no feed-in priority offered to renewables, since they, by design, compete on the free market [52].

In 2010, the government started offering feed-in tariffs for small scale producers of electricity ($<$ 5 MW) [53]. However, the primary method of support was still the Renewable Obligations. Further incentives for small scale installations followed in 2013 with the "Green Deal" that offered soft loans for renewable power installations. The Green Deal incentives were criticised as being too low, however. In addition, they were more directed towards energy efficiency rather than specifically favouring renewable electricity [54].

The next big change in support scheme policies were in April 2013, where the "Contracts-for-Difference" (CfD)s were first introduced as an eventual replacement for the RO scheme. The CfDs are 15-year contracts agreed between each renewable power generator and the government (through the Low Carbon Contracts Company Ltd. (LCCC), a government-owned company). A price (strike-price) is agreed between each generator and the LCCC for each unit of electricity sold. The generator sells the electricity as usual at the market. If the market price is lesser than the strike price, the LCCC pays the difference to the generator. If the market price is higher than the strike price, the generator pays the difference to the LCCC. The CfD scheme co-exists with the RO scheme till April 2017, after which generators can choose only the CfD scheme [55]. In effect, the CfDs operate (in theory) to feed-in tariffs, and feed-in tariff rates would be directly comparable to the strike prices under CfDs. In practice, however, the generator does not automatically earn the strike price for each unit of electricity sold. Instead, the generator has to be able to sell their electricity on the market at the so-called "reference price". Only then will the generator benefit from the whole strike price. If the generator is unable to sell at the reference price, then the government pays the difference between the strike and reference prices irrespective of the actual sale price. It is unclear how this will affect the broader flexibility of the electricity system.

Although energy is legislated and governed largely at the central government level, some powers are devolved to the regional government in Scotland. Many of the above mentioned schemes are not applicable (or differently applicable) in Northern Ireland, and Northern Ireland is not considered in this study. Further, it is not very clear if and how the 'leave' vote of the 2016 referendum in the United Kingdom to leave the European Union will affect EU-wide targets, policies and plans.

Chapter 5

Comparisons and Conclusions

5.1 Comparisons

A comparison of how these seven countries stand with respect to the aspects of flexibility studied above was done. Wherever necessary, data was made comparable by normalisation with a suitable base.

5.1.1 Aspect 1: Flexibility in Adjusting to Variations in Residual Load

When the different countries are compared on the variations in residual load they exhibit through the year, there are two points of discussion that are very clearly visible, as seen from Figure 5.1. The graph has been normalised to account for each country's relative size (in terms of residual load).

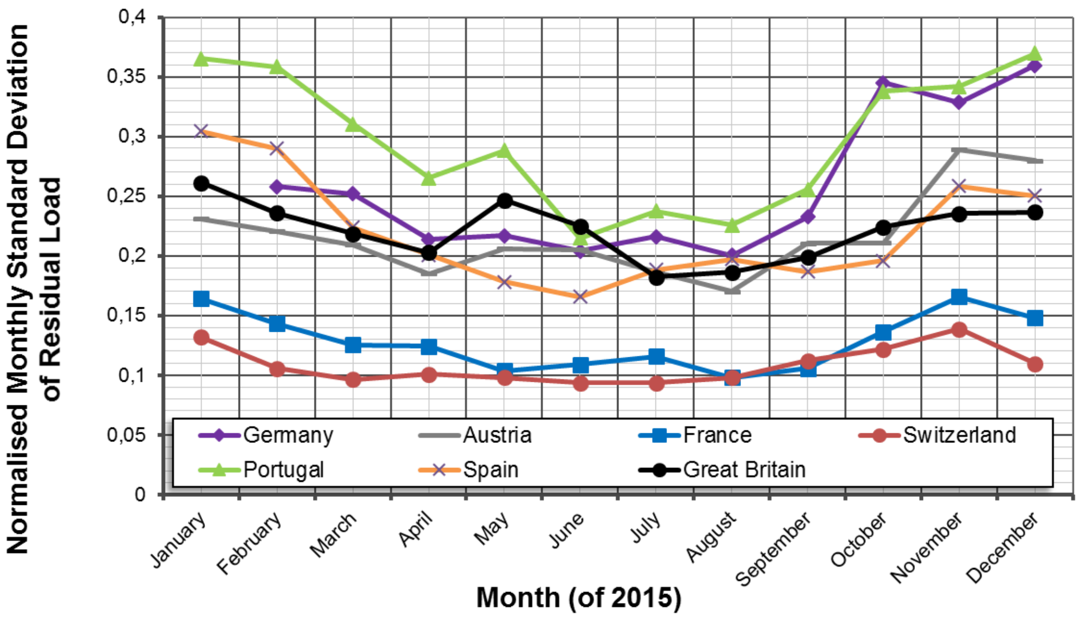

Figure 5.1: Comparison of the normalised standard deviation of residual load in 2015 for the countries studied

As previously noted, there is a seasonal variation that is readily apparent through the months of the year. Winter months tend to have a higher standard deviation of residual load as compared to summer months, and this is valid for almost all countries. Switzerland is an outlier in this in that it only shows mild increases in its winter months before reverting back to a near constant level.

The chief point notable in this comparison is the striking difference between two groups of countries: France and Switzerland are clearly well apart from the rest of the countries. France, particularly, is famously nuclear-intensive in its electricity mix, with significant shares of hydroelectric and combustible fuel-based power generation (as seen in section 2.2.3). Switzerland, too, has almost its entire electricity generation based on nuclear or hydroelectric power.

When the shares of intermittent renewables (wind and solar PV) in each country is seen alongside the average standard deviation in residual load as in Figure 5.2, there is a correlation that can be observed.

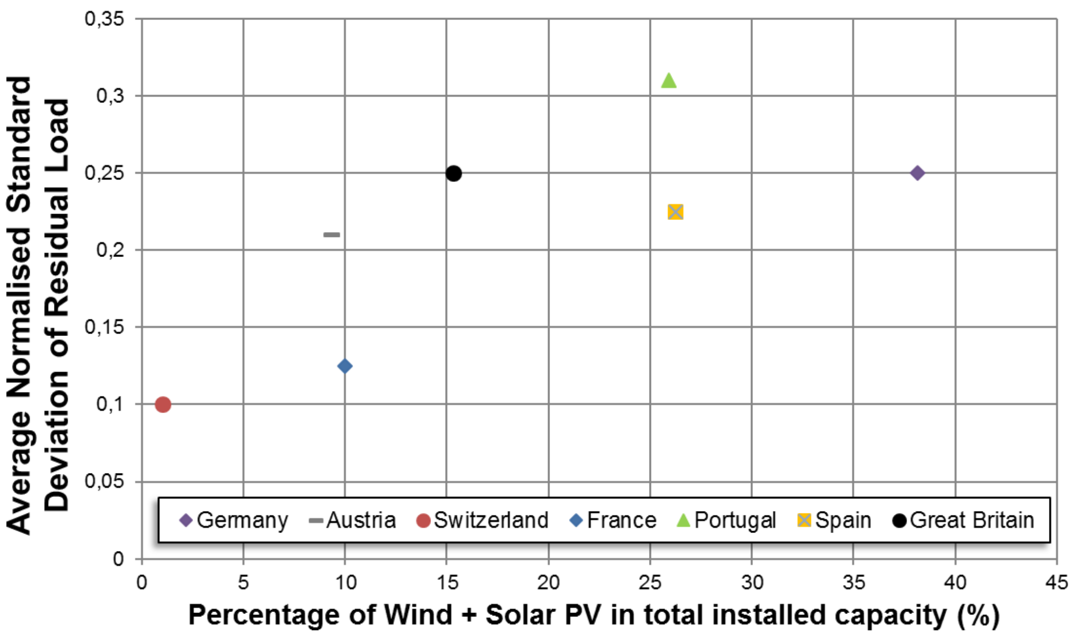

Figure 5.2: The average normalised standard deviation of residual load in 2015 versus the percentage of wind and solar PV in the share of installed capacity in each country

Countries that have higher shares of intermittent renewables do tend to have a higher standard deviation in residual load, indicating a mild correlation between the two factors. In previously presented cluster analyses, it was also shown that wind power was responsible for a large part of the increase in standard deviation.

However, it must be noted that the infeed of intermittent renewables is only one of the influencing factors, and there are other factors that could be taken into account in order to give a more comprehensive picture of the flexibility required in each of these countries.

5.1.2 Aspect 2: Flexibility in Recovering from Price Extremes

The central point in the analysis of this aspect of flexibility was the definition of extreme prices and defining the methods used to determine how flexible the market is in recovering from these extremes, by the concept of shifting or offsetting the Day-Ahead market curves. In the development of this aspect of flexibility, the concept of a "flexible volume" of electricity on the market was mentioned.

Due to the varying situations of different markets, a direct normalisation and comparison is not very meaningful. Yet, tables 5.1 and 5.2 show the amounts of "left shift" and "right shift" that was needed in each market to overcome the respective price extremes.

Table 5.1: Table showing the "left shifts" needed to overcome high price extremes

Country/ Market	**Average "Left Shift" needed (GWh)**	**Maximum shift needed (GWh)**	**Average as a percent of flexible volume available (%)**	**Maximum as a percent of flexible volume available (%)**
Germany + Austria	0,417	4,184	3,17	76,00
France	0,556	2,532	6,77	42,01
Switzerland	1,080	4,750	15,92	70,02
Portugal + Spain (MIBEL)	11,904	12,979	28,71	38,52
Great Britain (APX)	2,140	3,914	-	-

Table 5.2: Table showing the "right shifts" needed to overcome low price extremes

Country/ Market	**Average "Right Shift" needed (GWh)**	**Maximum shift needed (GWh)**	**Average as a percent of flexible volume available (%)**	**Maximum as a percent of flexible volume available (%)**
Germany + Austria	1,487	7,003	11,29	32,39
France	1,53	7,685	18,61	42,30
Switzerland	1,826	3,387	26,93	37,99
Portugal + Spain (MIBEL)	-	-	-	-
Great Britain (APX)	2,179	3,155	-	-

As previously explained, in the case of the MIBEL market, the lower extreme price was below the market allowed price of 0 €, so an analysis in that case was not possible.

From the tables shown below, it can be made clear that the Germany + Austria market had the lowest demand for this aspect of flexibility when compared to the other countries. The French and the Swiss markets demanded more flexibility.

The MIBEL market was unique in that the market did not have too many price peaks to report, due to the fact that whenever there were price peaks, they were very high.

In the interesting case of Great Britain's APX market, in the many cases there was a demand for flexible electricity on the market, it could not be supplied on this market. Great Britain's two markets share a common price, and the required flexible volume might have been supplied by the other market. Nevertheless, the dynamics of two markets working in parallel would be interesting to study further.

Concerning the demand of this aspect of flexibility, a useful measure to compare is the available flexible volume on each market. In Figure 5.3

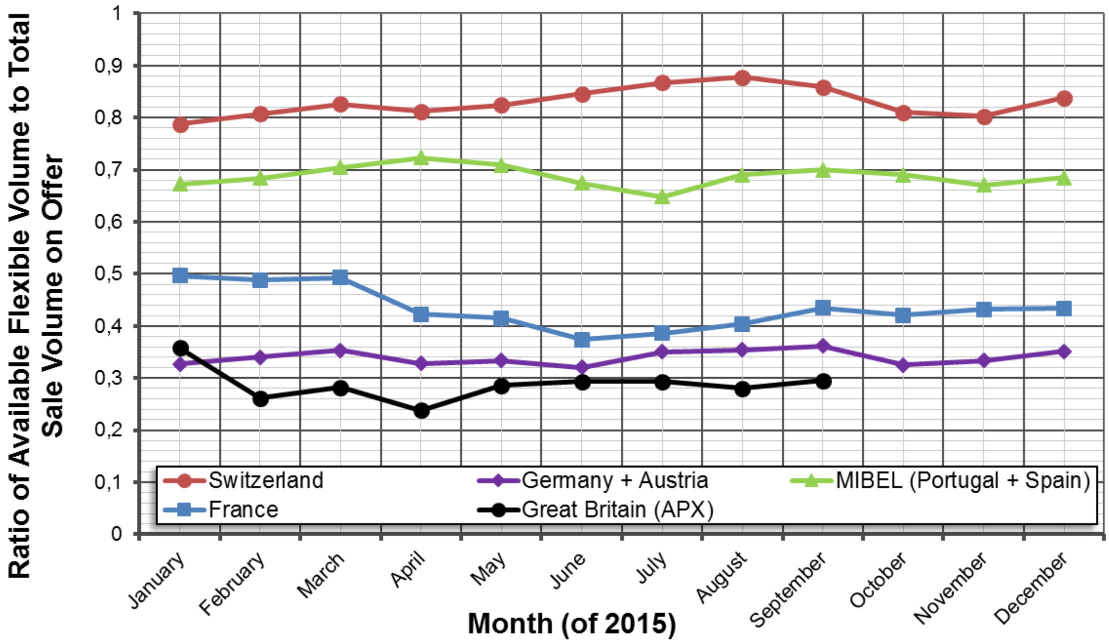

Figure 5.3: Comparison of monthly averages of the ratio of available flexible volume to total sale volume on offer for each market in 2015

The individually normalised values themselves might not be very useful for comparison, but what is interesting here are the relative positions of the countries. The observation here would be that the Swiss market and the MIBEL market do have a lot more flexible volume of electricity available on average as compared to the Germany + Austria, Great Britain's APX and French markets.

5.1.3 Aspect 3: Flexibility to Adjust to Load Gradients

Hourly gradients of residual load were calculated for each hour of 2015 for each of the studied countries, in order to determine if large gradients had any effect on the market and available flexible volume.

From Figure 5.4, it can be seen that most countries have residual load gradients that are relatively gradual.

However, this graph is not a normalised graph, and when normalised, the graphs look highly similar and overlapping. An interesting aspect to note is that for most countries, there are many more extreme positive gradients than negative gradients. This could possibly be due to the observed fact that gradients in the morning (at about 0500 Hrs - 0600 Hrs) are higher than the gradients in the night, when the loads go down gradually, possibly a characteristic of household loads.

With regard to the availability of this aspect of flexibility, on each of the hours with extreme gradients, there was no significant change in the available flexible volume on the markets of any country, possibly due to reliable forecasting or due to the fact that short term changes are not dealt with on the Day-Ahead markets.

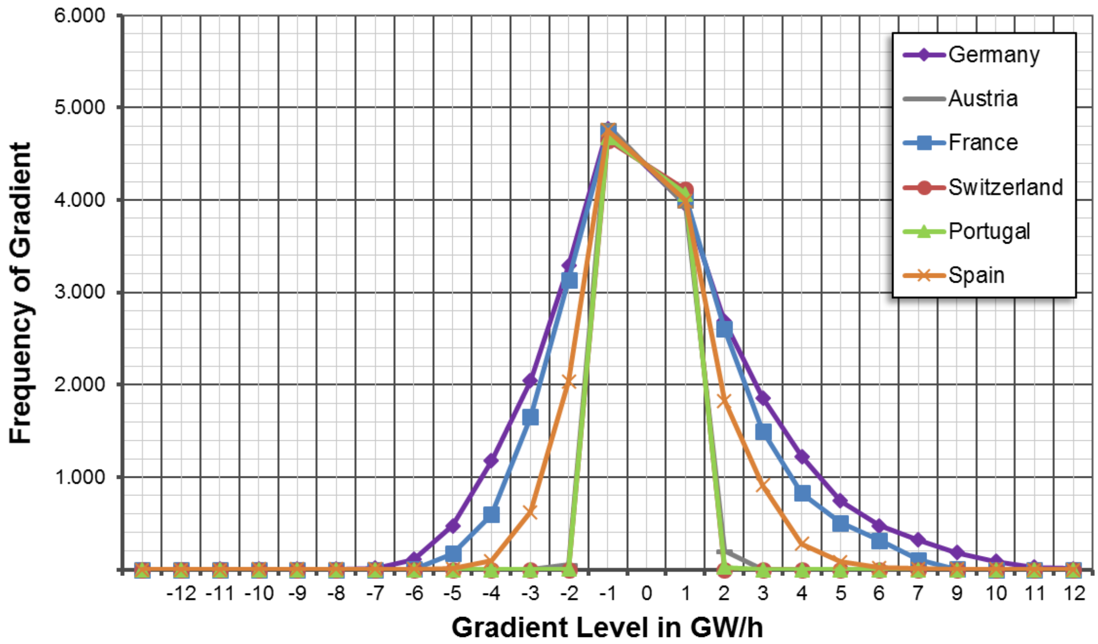

Figure 5.4: Graph superimposing the residual load gradient frequency curves of the studied countries in 2015

5.1.4 Aspect 4: Short Term Availability of Power

When the absolute difference in Day-Ahead and Intraday market prices were analysed and compared between countries, the results were as presented in Figure 5.5.

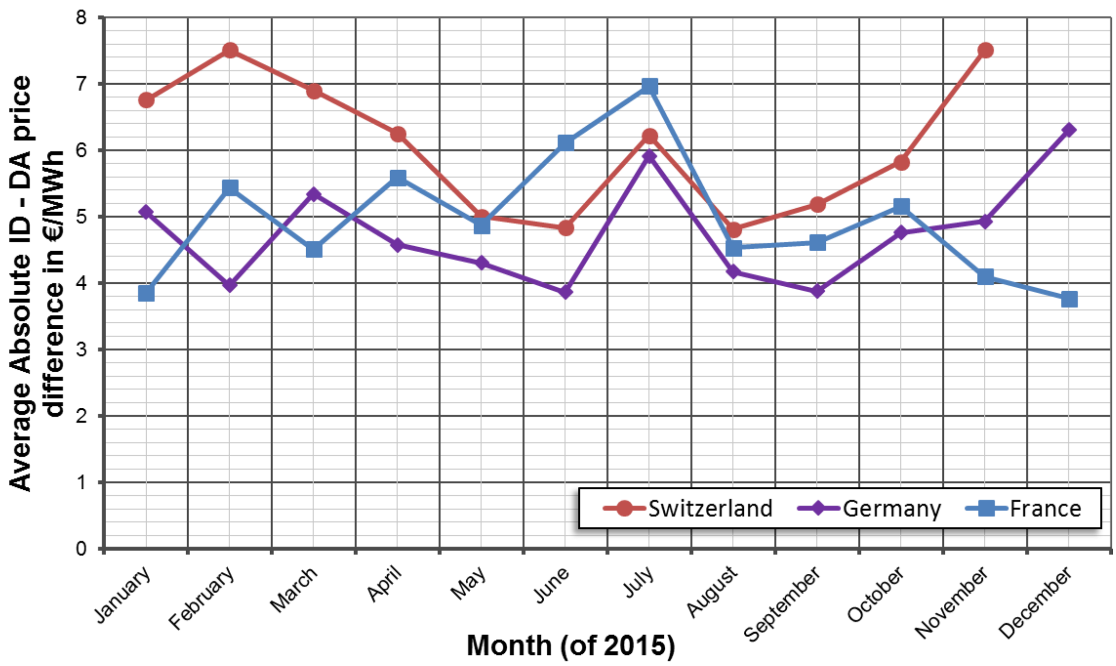

Figure 5.5: Comparison of monthly averages of the ratio of available flexible volume to total sale volume on offer for each market in 2015

Although all of these curves exhibit a curious upward trend in July, there seems to be little comparison possible, since the curves are very close to each other, without much to differentiate between them. More insight into the interplay between Day-Ahead and Intraday markets would probably be needed to investigate this aspect of flexibility further.

5.2 Conclusions

From the studies into the first aspect of flexibility presented in this study, *i.e.* the flexibility to adjust to variations in residual load, a chief conclusion was that there is a mild correlation between the share of intermittent renewable electricity in a country and the standard deviation of residual load. Investigating further, it was found that variations during winter months, possibly due to wind power infeed, was one of the major causes of increased variations in residual load. France and Switzerland in particular, show much lower variations in residual load, and therefore demand lesser flexibility from the system.

In the second aspect studied, *i.e.* the flexibility of the Day-Ahead markets to recover from price peaks, there were some differences in the demand of flexibility from different markets. The Germany + Austria market and the French market demanded the least flexibility, whereas the Swiss market demanded more flexibility. When comparing the supply of flexibility, however, the Swiss and the MIBEL market had the most supply of flexibility on offer. These comparisons did not clearly point to the reason behind this difference, and more information on influencing factors might be necessary.

The third and the fourth aspects, namely the analysis of hourly gradients in residual load and the analysis of the differences in Intraday and Day-Ahead prices yielded many similarities between the studied countries, with little to separate them, and as such, a study into more particular factors might be useful.

The electricity policies of the countries studied does show that there were various ways in which renewable electricity was encouraged by governments. This was dependent not only on the individual geographical positions and geographical or topographical benefits that each country has, but also on the individual histories and political attitudes of policymakers.

Most of the countries considered did make significant progress towards meeting their 2020 renewable electricity targets, but each in different ways. Some of the countries which promoted wind power heavily, for instance, did show increased demand for flexibility. It was seen that the greater impetus given to intermittent renewable energies particularly in countries like Germany, Spain and Great Britain was clearly demonstrated in the increased demand for flexibility, whereas the lesser aggressive promotion of them in countries like France, as well as other historical factors reflected in them having lesser demand for that aspect of flexibility.

While it is not possible to pinpoint specific impacts of specific policies on a macro level, it is useful to differentiate between countries to gain a perspective of the differences between countries on a comparative basis. An alternative or a supplementary approach would be to perform a historical analysis, provided that enough data is made available.

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