Louvain School of Management

Analysis of the European electricity grid scenarios

Application to the Belgian renewable energies

Research Master's Thesis submitted by
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With a view of getting the degrees:
Master 120 credits in Economics and Business Administration, professional focus in Energy, Natural Resources and Environment
Master 120 credits in Management, professional focus in European Business

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Academic Year 2019-*2020*

Acknowledgements

I would like to thank my parents for their support and precious advice from the early beginning of this thesis to the end and more generally throughout all of my studies.

I am also grateful to my supervisor Mr Van Vyve and his colleague Mr Bjørndal from the NHH for their expertise and knowledge in the electricity sector, which helped me to deliver this work.

Finally, I would like to thank Mr Mauritzen who taught me the energy industry analytics course. It gave me the skills and the motivation to work on this specific topic.

Abstract

Elia analysed the renewable energy (RE) capacity required in each scenario (and for other variables such as other countries' production, etc) and then agreed on a transmission capacity for each border and each scenario. Based on these forecasts, I examined the influence of this new REs capacity (based on new transmission line capacity) on exports and on the price. The literature review highlighted the congestion problem due to the intermittent nature of REs. Therefore, in the Belgian case I focused on the situation where RE production was elevated.

After conducting the necessary transformations to ensure relevant results and analysing the relations between these variables when REs production was high, I forecasted the following:

- Exports based on a change in REs capacity installed
- Prices based on a change in REs capacity installed

Finally, I ran an autoregressive integrated moving average (ARIMA) model with the forecasted prices as the dependent variable and exports as the independent variable. The purpose was both to determine how the price is influenced by an augmentation of exports due to an increase in REs capacity installed and to identify the differences among scenarios.

The results revealed that in 2040, exports will influence prices negatively three times more than at present. Quantitatively, this development will result in the current decrease in price of 0.0039 €/MWh for each additional MWh of electricity exported becoming a decrease of 0.012 €/MWh by 2040.

Considering the best scenario for Belgium and knowing that its CO_2 emission targets are the same as the EU's, the global climate action (GCA) scenario outcome appears better than the two others. This projection allows for a substantial part of Belgium's electricity to be produced by renewable energies and limits the seasonality in the production presented in the distributed generation (DG) scenario. This result is due to a better mix in REs installed.

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List of Abbreviations

The following abbreviations are used in this thesis:

ACER	Agency for the Cooperation of Energy Regulators
ACF	AutoCorrelation Function
AIC	Akaike Information Criterion
ARIMA	AutoRegressive Integrated Moving Average
ATC	Available Transfer Capacity
BRE	Balance Responsible Entity
BRP	Balance Responsible Party
BSP	Balancing Service Provider
CACM	Capacity Allocation and Congestion Management
CAES	Compressed Air Energy Storage
COP	Conference Of the Parties
CWE	Central Western European
DG	Distributed Generation
DSO	Distribution System Operator
ENTSO-E	European Network of Transmission System Operators for Electricity
ENTSO-G	European Network of Transmission System Operators for Gas
ETS	Emissions Trading System
EU	European Union
FBMC	Flow-Based Market Coupling
FRM	Flow Reliability Margin
GCA	Global Climate Action
GDP	Gross Domestic Product
GHGs	Greenhouse Gases
HVDC	High-Voltage Direct Current
kV	Kilovolt
MOE	Merit Order Effect
MRC	Multi-Regional Coupling

MWh	Megawatt-hour
NEMO	Nominated Electricity Market Operator
NRA	National Energy Regulatory Authority
NTC	Net Transfer Capacity
PACF	Partial AutoCorrelation Function
PCI	Project of Common Interest
PX	Power Exchange
RE	Renewable Energy
ST	Sustainable Transition
TRM	Transmission Reliability Margin
TSO	Transmission System Operator
TTC	Total Transfer Capacity
TYNDP	Ten-Year Network Development Plan
UK	United Kingdom
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
XBID	Cross-Border Intraday Market

1. Introduction

1.1 Context

Electricity is becoming a global concern for both political and climate change-related reasons. Human societies cannot function properly without this resource. It is everywhere, from the fridge to store our food to the private or professional laptop to the water supply. And the era of this energy source is only just beginning. Many sectors are becoming electrified such as the transport sector. Such developments will lead to a growth in the global electricity demand in the coming years, and other important issues will need to be handled. Moreover, electricity is considered as both a polluting sector and a way to decrease human CO_2 emissions.

In Europe, the electricity market landscape is completely changing. There are successive plans to integrate this sector at the European level, although it is historically a national competency. This willingness has led to many issues and changes: whole actors are attempting to adapt and work in the same direction, but the lack of cohesion in the EU is slowing down the project.

1.2 Problem setting

Th research question is formulated as follows:

"How are the electricity prices/exports going to evolve during high renewable energies (REs) production periods given an increase in the cross-border transmission lines capacity based on the European development scenarios?"

The purpose of this thesis is to analyse the relation between exports, the production of renewable intermittent electricity sources and the electricity price in the context of EU electricity market integration. This integration can only progress if the capacity exchange between price zones rises.

To address this topic, the case of Belgium is considered. The relationships between three key variables and their impacts are analysed and forecasted. Finally, the results are compared to

Elia's forecasts (Elia is the Belgian TSO) for cross-border transmission lines and to the expected outcomes from the literature. To this end, the previous questions are divided in several sub-questions:

- What is the effect of REs on electricity exports?
- Is there a real difference between high and low REs production in terms of their effects on exports and prices?
- How do prices and exports interact?

1.3 Motivations

Studying "European Business" and "Energy and Natural Resources", I have naturally chosen a subject linked to both topics. In addition, this work was an opportunity for me to gather my observations on many topics I have studied in the past five years. From European integration and statistics to all aspects of the electricity sector (i.e. microeconomy for price formation, finance in the PXs, etc.).

Moreover, being Belgian, I am aware of the complexity of the electricity industry, since we have four energy ministers and plans for the country's electricity mix often change from one government to another. Therefore, my motivations are not only academic or scientific but also personal. I want to understand the situation in my country as well as to understand one sector that is currently undergoing expansion and related to many interesting twenty-first century issues.

1.4 Plan of the work

This thesis begins with a brief reminder of the main concern of this century: climate change (2). The electricity sector is quantitatively linked to this phenomenon to demonstrate the usefulness of REs such as solar panels and wind turbines.

The literature review is divided into two main parts. First, the political calendar of the previous and actual packages for the electricity industry are explained. Then, relevant political issues are described. Since Europe is composed of 27 countries with different rules, visions and political colours, policy or market changes are not always quickly and effectively integrated

(3). Second, the electricity sector is broadly explained to provide a thorough understanding of the actual challenges. The end of the section focuses on cross-border transmission lines (4).

Based on this literature review, the methodology utilised to answer the research question is described (5). Following this part, the case of Belgium is presented, including the country's actual situation, the future expansion plans, the integration of EU scenarios into the national plans and so on. An exploratory analysis is conducted to elucidate the data from Belgium (6).

Subsequently, the method used is explained in detail to facilitate understanding of what the result expectations could be. Attention is also given to other models that could be used in this situation and to the reasons they are not utilised in this thesis.

Finally, the results obtained are compared, analysed and criticised based on the hypothesis developed prior to the model. These results are then compared to the findings of other studies discussed earlier in the literature review (7).

2. Why discuss renewable energies (REs)?

2.1 Why is a better use of REs required?

Climate change is defined in the Oxford Dictionary as follows:

A change in global or regional climate patterns, in particular a change apparent from the mid to late 20th century onwards and attributed largely to the increased levels of atmospheric carbon dioxide produced by the use of fossil fuels.

This definition implicitly asserts that human beings are at the basis of the climate change issue since they are the only users of fossil fuels, a phenomenon known as anthropogenic effects. Scientists have already identified several climate changes since the origin of the world which have been caused by natural phenomena. In the last two decades, however, scientists noticed that some changes have not been caused by nature but are due to human activities (Eurostat, 2018).

2.2 Global Efforts on Climate Change

Since the early 1990s, climate change has been increasingly recognised by the political and scientific world. At the global level, the fight against it is led (or at least coordinated) by the UN. This intergovernmental organisation represents 193 states and enables countries to express their views through its different committees. Since the 1990s, the UN has organised several processes and meetings to generate agreement on targets to reach and the means to achieve them in several fields such as security and climate change (United Nations, n.d.).

One outcome of these processes was the signing of the United Nations Framework Convention on Climate Change (UNFCCC), which is intended to prevent any damaging effects from human activities on the ecosystem and to officially recognise climate change as caused by humans to compel nations to cooperate in fighting it. The UNFCCC can be considered a framework against climate change. It entered into force in 1994 (CDE, 2019).

The Conference of Parties (COP) has been held every year since 1995. The first treaty to cut greenhouse gas (GHG) emissions is the well-known Kyoto Protocol, proposed in 1997 during the third COP, when developed countries recognised their role in producing such emissions. This agreement bound these countries to decrease such GHGs. The principal outcome was the introduction of a cap-and-trade system on emissions. The protocol was renegotiated a second time through the Doha Amendment during COP 18 in 2012, with the new terms binding until 31 December 2020 (CDE, 2019; United Nations, n.d.).

The most recent key event is the signing of the Paris Agreement in 2015. This text indicates a willingness to address climate change in a stronger way than before, proposing the limiting of the global increase in temperatures to 2°C compared to the pre-industrial period. Another important point is the engagement of developed countries to assist poorer nations in reaching their climate goals (United Nations, n.d.).

The Paris Agreement set goals to be reached in the future. However, in this agreement (and in general in the types of agreement requiring a large consensus among nations), the words used to describe goals and actions are broad and imprecise. Policymakers are not consistent in their climate visions. In this context, climate researchers and scientific advisors have a crucial role: they have to be aware of who is going to use their work, how it will be interpreted and to serve which interests (Geden, 2016).

2.3 Electricity and Climate Change

To evaluate the proportion of GHGs emitted by the electricity sector, it is common to speak in terms of CO_2-equivalent. GHGs include gases such as methane or nitrous oxide that contribute to climate change. Depending on their properties, they are converted into CO_2-equivalent to assess their effects. In this section I examine the amount of CO_2-equivalent per year in Europe produced by the electricity sector (Eurostat, 2018).

At the global level, CO_2 emitted by the electricity and heat sector represented in 2014 49.04% of all CO_2 emitted by fuel consumption (The World Bank, 2014). In the EU in 2016, electricity generation represented 36.6% of the EU’s total fuel combustion, which is equal to 1,197.5

million metric tons of CO_2 emitted into the atmosphere (Statista, 2018). The total amount of GHGs emitted that year was 4,292.7 million metric tons (European Environment Agency, 2018).

The electricity sector is therefore a CO_2 emitter (28% of the EU's total emissions) contributing directly to climate change. Hence, it is mandatory to increase the share of RE in the electricity production to reach the targets set by the EU for GHGs reduction for 2030 and 2050. Achieving these targets requires many constraints such as redesigning the market, electrifying several sectors, managing the drawbacks of REs (intermittency, etc.), constructing new infrastructure and ensuring that the security of energy supply remains reliable. These subjects are discussed more deeply in subsequent sections (Miller et al., 2018).

3. Energy Union and European Green Deal

3.1 European market

The electricity market in the EU has been integrated little by little. The electricity market can be considered as involving not only the flow of electricity moving from one country to another but also the flow of money and the flow of service. These flows have been enabled year after year by the integration of the European market.

To understand why the Commission is building an Energy Union, we have to go back in time. After the Second World War, European countries no longer had substantial gold reserves and foreign currency. Thus, governments decided to implement strong national rules such as the interdiction of changing the national currency into another one. Economic exchanges between countries already existed before the Second World War but significantly diminished during the years following the war (Defraigne & Nouveau, 2017, p. 60).

To restart the European economy and with the impetus of the US, the European Steel and Coal Community was created in 1952 by France, Germany, Belgium, the Netherlands, Luxembourg and Italy. This process consisted in removing customs duties for steel and coal through the creation of supranational institutions and price regulations, which can be considered the roots of the present-day EU. Since 1952, many improvements have been made towards European integration with several major treaties (Rome, Lisbon, etc.), but this process is not yet finished (Defraigne & Nouveau, 2017, pp. 86–88). When seeking to integrate a sector into the European market, several barriers can slow down or even stop the process:

- Physical obstacles. Countries can, for example, be delimited by natural borders such as mountains. It is not always easy and cheap to connect electricity or water networks between two countries separated by such boundaries.
- Institutional barriers. Such barriers are encompassed by the four freedoms of the Schengen agreement: the free circulation of goods, money, services and persons.
- Cultural barriers. Differences over language, previous wars, religions and so forth can create huge reluctance for countries and people to conduct business in another state (Defraigne & Nouveau, 2017, pp. 16–19).

The energy industry and electricity supply in particular have always been highly nationalised to ensure the security of supply. From 1986 to 2002, there was a huge increase in mergers between companies due to the increase in competition on the European market. More and more national champions emerged in each country, which was a nationalist reflex in response to the borders opening. However, with the number of mergers increasing, the amount of international mergers overtook that of national ones (Defraigne & Nouveau, 2017, p. 19). The national policies adopted by governments slowed down the process of economic integration (Defraigne & Nouveau, 2017, p. 143). The next section focuses on the packages released by the EU to integrate the electricity market.

3.2 Liberalisation of the Electricity Market

Until the early 1990s, the electricity supply industry in Europe mostly took the form of publicly owned utilities. The EU's inhabitants and companies could not freely choose their electricity supplier because of the monopolistic position of public utilities. However, England and Wales were the first in Europe to restructure their electricity industry in 1989 through the Electricity Act. It aimed at restructuring the sector through privatisation. Other EU countries started to implement equivalent measures soon afterwards, but the method in England and Wales (i.e. through privatisation) was not always followed. This is the case for the Nordic countries where utility ownership remained within the public sector (Wangensteen, 2012).

The first element to be privatised is the distribution segment followed by the generation segment. The transmission segment has been less commonly privatised due to its national strategic importance. Following these steps, a set of regulations was established with a regulator, resulting in a principal (regulator)-agent (utility) relationship (Ajayi, 2017). The transmission and distribution sectors therefore remained monopolies. The reason on the distribution side is the economy of scale, while on the transmission side, the monopoly is motivated by the idea it is simpler when only one actor is responsible for the operation and planning functions (Wangensteen, 2012, p. 312). However, grid companies must keep access for any third party who wishes to use the grid, and this requirement must be achieved without any discrimination (Wangensteen, 2012, p. 81).

This restructuring led to the end of vertical integrated monopolies in the electricity industry and a horizontal split in the generation and retail sides. It enabled the entry of new actors, an increase in the competition among firms and a higher effectiveness. On the transmission side, regulations became incentive-based to foster investment (Jamasb & Pollitt, 2005).

3.3 Energy Packages

Liberalisation started at national level but has been followed by European directives. There have been three major packages released by the EU Commission to facilitate a more open and liberalised market and further integration of the European electricity market. These packages concentrated on gas and electricity, but I will focus only on electricity below (Gouardères, 2019; Wangensteen, 2012).

The first EU energy electricity package was voted through by the parliament in 1996 and then transposed at national level two years later. The package (like the three following packages) was structured as an EU Directive, implying that countries should transpose it into their national law. States had a maximum period of time to implement the required measures, risking sanctions from the EU if they failed to comply. The second directive is from 2003. The main purpose of both was to unbundle the gas and electricity industry step by step and to open national borders to all the EU companies aspiring to compete in another country. Through these initiatives, the EU Commission merged different national markets into a single gas and electricity market. To create such a market, many regulations had to be enforced at all levels in the sector (i.e. TSOs, DSOs, compliance, security of supply, etc.) (Jamasb & Pollitt, 2005).

The third energy package entered into force in 2009. Its aims were to maintain the continuity of the previous regulations in proceeding with the unbundling of the industry and to fix some difficulties identified in the two previous directives. To be closer to a perfect market, agencies were established to oversee the implementation of rules such as cross-border regulations. These agencies will be discussed later in this paper (European Commission, 2019b).

On the one hand, 80% of the electricity produced in major EU economies (Germany, France, Italy, Spain, Belgium and the Netherlands) is managed by the same companies as before the energy packages. Moreover, these companies lack any real competitors, and the gap in price between some zonal prices (more or less equal to the country) is highly significant (Defraigne, 2018, pp. 51–90). On the other hand, Jamasb and Politt asserted in 2005 that the centralised approach to electricity market liberalisation was a success due to the EU electricity directives. Most EU consumers witnessed a decrease in price or at least converging prices among nations. These directives were based on the minimum requirement principle, and it has been observed that improvements went far beyond what was expected. The researchers also noticed that some technical issues had to be solved and that the interconnection capacity is far too low to claim that the sector is now more European than national (Jamasb & Pollitt, 2005).

3.4 Energy Union

The next step after the third energy package was the willingness of the Juncker Commission to build a European Energy Union.

3.4.1 Ambitions

The Juncker Commission released a communication to the parliament in 2015. This statement aims to establish a strategic framework for building an Energy Union which will ensure energy security, sustainability and competitiveness in Europe. It is divided into five main topics including a fully integrated European market continuing the aims of the energy packages. One major proposal was to achieve improved interconnections within the market (i.e. improve the internal market’s hardware).

To this end, European institutions select infrastructure projects known as projects of common interest (PCIs).[1] The goal by 2030 is to achieve at least 15% of interconnection in terms of gas and electricity. In 2015, the estimated costs were around €200 billion a year for one decade. This investment was thought to be useful for diversifying European suppliers.

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[1] Projects of common interest “are key cross border infrastructure projects that link the energy systems of EU countries” (European Commission, 2019).

This communication was partly motivated by the fact that the EU members were collectively spending over €400 billion a year for non-EU produced energy. Fifty-three percent of the EU's total energy consumption was dependent on non-EU nations (European Commission, 2015b).

3.4.2 Results on the grid

For assessing the results four years later, the European Commission released a fourth report on the State of the Energy Union in April 2019.

A first improvement that has been made is to connect all regions in Europe such as the Baltic countries, which were previously isolated. To realise this aim, grid connections have been built with Sweden, Poland and Finland. Grid expansion is now proceeding with an increase in the interconnection capacity between France and the Iberian Peninsula.

These improvements have helped the EU get closer to its initial objectives. Dependency rates on non-European countries are declining, the competition on the electricity market is better than before, average prices have decreased for consumers and REs have been enabled to acquire an improved position in the grid. However, these improvements are only a start, and many further actions will be required to go forward (European Commission, 2019a).

Future plans for grid expansion are described in the next chapter, along with the long-term planning in the EU electricity sector.

3.5 Political reluctance

EU efforts to integrate REs into the electricity sector have met with reluctance from some countries. The Union is composed of 27 countries which do not all share the same viewpoints and priorities. There is a separation between the Western countries seeking to boost REs and the Eastern states more concerned about the security of supply and consequently unwilling to transition from fossil fuels to RE. It is important to be aware that while the first reason is doubtless related to political issues, non-political factors and concerns often play an important role. Some countries such as Hungary and Romania lack several key elements of infrastructure necessary for implementing REs (sufficient wind or solar capacity, technical knowledge, etc.) (de la Esperanza Mata Pérez et al., 2019).

3.5.1 Reasons

Since the choice of the energy mix is a national competence, each country can decide which kinds of resources will be used for its own electricity production. Figure 1 indicates the division between countries[2] (in green) which see REs as a business opportunity and a means to address climate change and countries (in blue) which prioritise security of supply and view REs as a win-loss instead of a win-win prospect. The latter countries are often dependent on Russia as their only gas supplier. They sometimes also have a substantial number of workers in the oil and gas industry. Moreover, given their lack of competence in the REs sector, such states see no economic and social benefits in altering their energy production system. Eastern countries have in general a smaller GDP per capita than Western countries, so such a change would have negative socio-economic consequences for the population. Thus, these states prefer to spend funds on diversifying gas suppliers instead of investing in REs (de la Esperanza Mata Pérez et al., 2019).

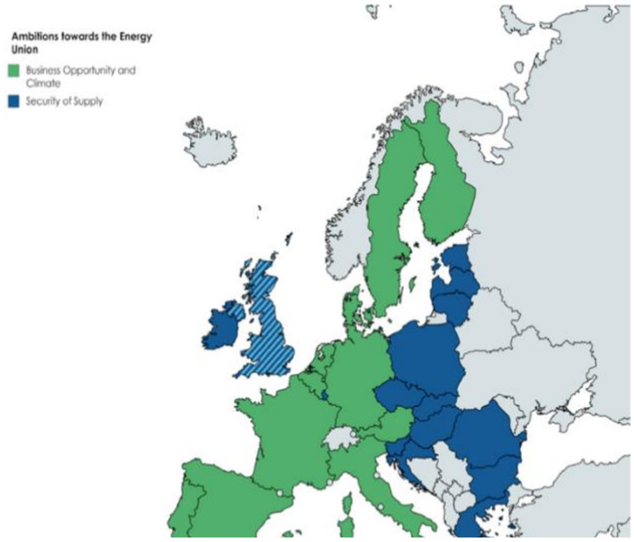

Figure 1: Member States clustered according to their Energy Union ambitions. (de la Esperanza Mata Pérez et al., 2019)

3.5.2 A Two-Speed EU for the Energy Sector

In discussions of European integration in recent years, a two-speed Europe has often been evluated. It consists of countries being able to choose whether to participate in a particular

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[2] As the authors of this diagram explain, "The two clusters of countries have been identified based on data from relevant European agencies and organizations, data collected by the EC, bibliographical analyses, and from consultations with and observed political discussions at the EC's Directorate-General for Energy (DG ENER). The two clusters have been defined following two main indicators: first, energy import dependency together with supplier concentration – with special attention to Russia – and second, macroeconomic benefits of increased renewable energy penetration – in terms of electricity prices, low-carbon technology patents, market shares and turnover" (de la Esperanza Mata Pérez et al., 2019).

integration process. Changes and new laws will thus only apply in the participant countries. In this subsection, I consider the effects of such a method of integration.

Since its establishment, the EU has grown from 6 countries to 28, and is now down to 27 after the UK decided to leave. To manage the Union, integration policies have been implemented in many sectors encompassing the energy sector. These integration measures for achieving a single market brought an increase in the GDP for member states. But after 60 years of growth, the first major troubles occurred when the 2008 crisis exposed Europe's weaknesses. Divergences between countries' economic, political and social concerns are rising. To address this challenge, the idea of a two-speed Europe was proposed (Kundera, 2019).

Policies to decrease the gap in incomes between EU countries

The Treaty of Rome of 1957 does not mention any method or policy for decreasing inequalities among the six founder members, but differences were not so important at that time. The belief was that the common market would solve the inequalities through competition. After the EU's enlargements, and especially those in 2004 and 2007 with Eastern countries, the gap between different countries became much more important. The most developed states have a mean income many times higher than the least developed states. This difference is one of the reasons why nationalism is resurgent in contemporary Europe.

Solutions to face the problem started in the 1970s with a regional policy. European Investment Funds in conjunction with other funds began to lend money to the poorest countries to improve their infrastructure and fight unemployment. This regional policy has been criticized because these amounts were not significant and also for the way the policy was managed and applied. Since 2000, the priorities of this policy are to reach the target set in the Lisbon Treaty.
(Defraigne & Nouveau, 2017, pp. 476, 556–558)

The selection of this kind of integration can lead to high cooperation and an improvement in political and socio-economic sectors between participating member states (green in figure 1). Potential outcomes of this process can include a feeling of being left behind experienced by the blue countries. It can divide the Union and foster stronger links between Eastern countries and Russia, which would be a disaster for the health of the EU. The economic gap between these two groups will increase and could have negative effects on other polities. However, the interests and sovereignty of each state will be respected, and it will enable the green group to progress more rapidly without being hindered by the reluctance of the blue countries. The integration process will be improved by countries willing to take a step forward in recognising that some common policies are not appropriate for all members (de la Esperanza Mata Pérez et al., 2019; Kundera, 2019).

To forecast what will occur and determine the possibilities for improving the integration of the common energy market, a White Paper[3] was released in 2017 to present the following five possible scenarios for the improvement of integration by 2025: carrying on, nothing but the single market, those who want more do more, doing less more efficiently and doing much more together (Kundera, 2019).

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[3] "European Commission White Papers" are defined as "documents containing proposals for European Union (EU) action in a specific area. In some cases, they follow on from a Green Paper published to launch a consultation process at EU level. The purpose of a White Paper is to launch a debate with the public, stakeholders, the European Parliament and the Council in order to arrive at a political consensus." From https://eur-lex.europa.eu/summary/glossary/white_paper.html.

4. Electricity market

As stated in Chapter 3, energy and thus electricity is a national responsibility. Currently, the purpose of the Commission is to create a European electricity market. This goal requires the implementation of standards and regulations respected by every actor. In this section the electricity market is presented alongside an explanation of new cross-border operations. The main features of the network are then described. Finally, current and future solutions for improving the grid efficiency and penetration of REs are discussed.

4.1 Shape of the Electricity Sector in Europe

Electricity is transmitted through cables from the point where it is produced to the point it is consumed. While this process may seem simple, it is more complex than might be expected. Many market participants work at each step. The electricity sector can be roughly divided into two parts: the physical infrastructure whereby the electricity is transported from the producer to the final consumer, and the electricity market where money and data are exchanged. Each player has its own responsibilities and duties.

There are many ways to trade electricity. It can be traded bilaterally, which involves a direct agreement between a producer and either a trader, a supplier or a final consumer, often with one or several intermediaries included. A common intermediary is the power exchange (PX), a place of meeting between buyers and sellers. In this case, the generator sells their energy produced and it is bought by either a final consumer, a supplier or even a trader. The electricity market wants to provide the best price, namely the price where the supply and demand curves cross each other. This price is variable because electricity produced and weather conditions can change within a single day.

Figure 2 helps one to understand the sector. Money flows from the right to the middle, while the electricity flows from the middle to the left.

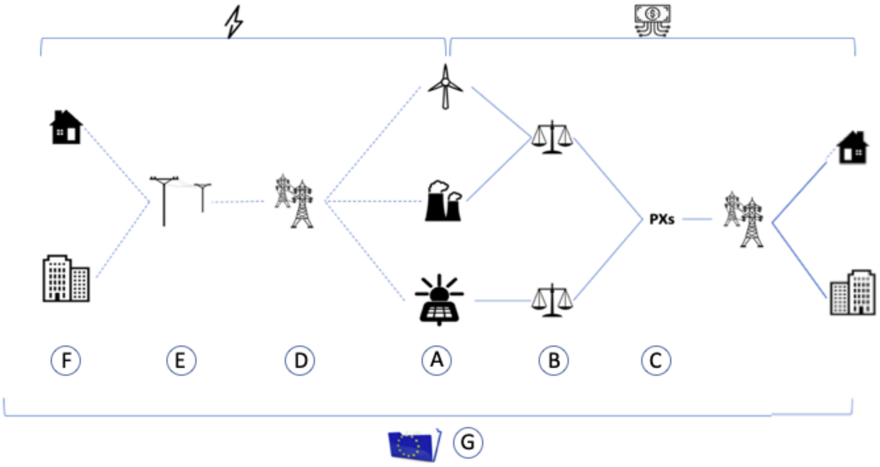

Figure 2: the two parts of the electricity's market

A. Producers

Producers are in charge of producing the electricity which is sent through the grid. Since the deregulation introduced by the EU, there are no more monopolies on the production side. This category of actor also includes big power plants and inhabitants owning solar panels installed on their roof (Wangensteen, 2012, p. 81). They are paid by energy suppliers to produce (Erbach, 2016).

B. Balance Responsibility Entities (BREs)

This actor carries the amount of electricity generated and consumed by its clients (producers and final consumers). A producer or a company can be its own BRE, but this role is sometimes delegated, for instance fore prosumers.[4] BREs provide a balanced schedule to the system operator. This schedule contains the forecast for the next day, which calculates as precisely as possible the hourly consumption of their consumers. If they fail to provide the forecasted amount, penalties are imposed depending on the gap between the reality and their forecast.

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[4] "Prosumers" are final consumers who also own small power plant such as solar panels or a storage device.

C. Power exchanges (PXs)

PXs are in charge of trading the electricity, which can be done in two ways. On the one hand, there is auction-based trading. The producers send their bids to the PX before a certain deadline. Retailers willing to buy electricity do the same with their offers. These bids and offers are then ranked following the merit order principle (see Section 4.3), which means that the lower/higher bid/offer is primarily chosen. Based on that, the equilibrium price is determined when the addition of bids equals the addition of offers (i.e. chosen based on their price)[5]. This system allows maximising the economic value of transactions. On the other hand, there is continuous bilateral trading. Offers and bids are submitted within a trading session and then directly matched with what has been submitted earlier. If it is not possible to find a counterpart for a particular bid or offer, it remains on the trading book of the trading session waiting for another offer. This maximisation of the economic value is less efficient in such a direct agreement between a generator and a consumer. The major PXs in the EU operate following the auction-based system (Pototschnig, 2013).

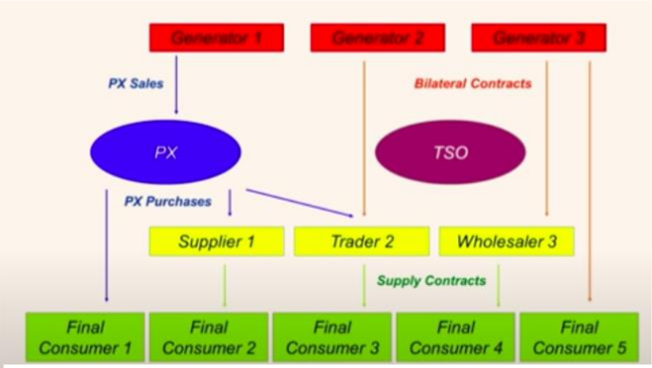

Figure 3 Commercial relationships in Liberalized Electricity Market. (Source: EUI, 2013)

PXs can be owned by a system operator, by another market participant or can even operate independently. These arrangements vary from one country to another.

D. Transmission System Operator (TSO)

In most European countries, the grid operator and the system operator are managed by the same entity, the TSO. On the one hand, as grid responsible, the company has the responsibility for the physical grid. Therefore, they must be concerned with the maintenance and make the necessary investments to enlarge the network when required. While the TSO manages the transmission function, the distribution is managed by the distribution system operator (DSO).

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[5] Prices might differ due to transmission constraints. In case of constraints when delivering electricity, a supplier from a high demand zone will have to pay less transmission costs than a supplier from a low-demand zone who is not able to sell all his electricity produced in his zone. It is a consequence of the congestion problem. An increase in transmission lines could decrease this supplier's cost. (de Paz, 2015)

On the other hand, as a system operator, TSOs are responsible for the security of supply. To guarantee security, they must ensure the frequency in the grid remains constant. The TSOs have many functions and are therefore in contact with all the actors of the electricity sector. Their functions will be examined throughout this work (Wangensteen, 2012).

E. Distribution System Operator (DSO)

The DSO is in charge of transporting electricity from the TSO to the end users. The distances of these distribution lines are shorter than transmission lines, and the lines carry electricity at a smaller voltage, which can be used directly for consumption.

F. Consumers

Consumers are households or companies paying for consuming electricity coming from the market. They can also be a producer if they own any electricity device (solar panels, storage systems, etc.) able to send electricity through the grid. In this case, they are prosumers.

G. The Regulator

The regulator sets the rules that everyone must follow. At the European level, the Commission developed the energy packages that entered into force in each member state. However, since the rules are understandably not identical in every country, the EU created the Agency for the Cooperation of Energy Regulators (ACER). This agency emerged in 2011 in the course of the implementation of the third energy package and is in charge of verifying if all National Energy Regulatory Authorities (NRAs) are in line with EU requirements. From the perspective of the integration of the European electricity market, ACER is also responsible for promoting further cooperation among NRAs (ACER, n.d.).

4.2 Balancing

To ensure the security of supply, the production of electricity must equalise the electricity consumption at each moment. This equilibrium can be measured by the frequency in the grid which has to be equal to 50 Hz or very close to this value. The balancing market was created to manage this task and, therefore, to avoid any system blackouts. Because the BREs also known as balance responsible parties or BRPs) are not able to perfectly balance the amount of electricity sold and bought instantaneously, the TSO is in charge of such balancing in real time. For this purpose, balancing service providers (BSPs) keep in contact with the TSOs to provide reserves (Doorman et al., 2011, p.9). Figure 3 provides an overview of the process in the balancing market.

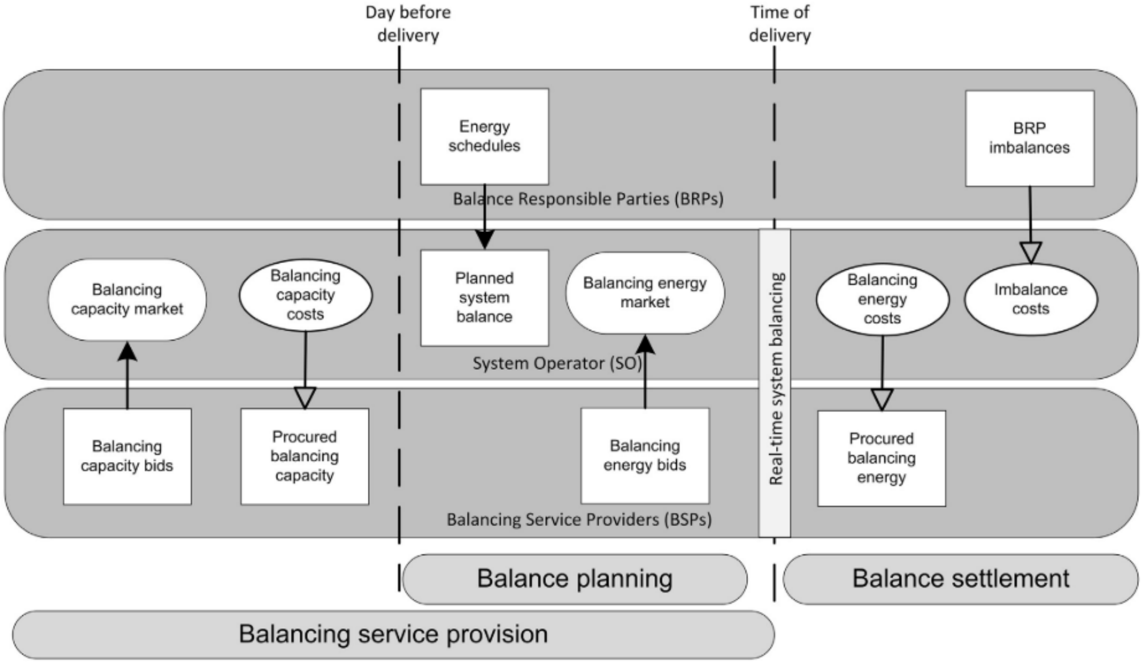

Figure 4: Basic structure of the balancing market. (van der Veen and Hakvoort, 2016)

As the diagram indicates, there are two markets for balancing: the balancing capacity market and the balancing energy market. The first operates before the day-ahead market and gathers balancing capacity bids from BSPs. The second runs in the day-ahead market and collects chosen bids from the balancing capacity market. These bids will enable the TSO to compensate the gap in energy demand forecast by BREs. The TSO will pay for the service and will impose fines on BREs for any gaps between actual electricity production and their forecasts (van der Veen & Hakvoort, 2016).

These reserve bids are classified in multiple categories based on their ability to start producing quickly and the type of regulations required. The European names for these reserves are the frequency containment reserve (primary reserve), which is able to start producing automatically within a few seconds, the frequency restoration reserve (secondary reserve), which can be activated in a maximum of 7.5 min and is managed by the TSO, and finally, the replacement reserve, which can be activated within a few minutes to an hour and is activated manually to replace the secondary reserve. Reserves are not only useful in the case of a lack of electricity but also when too much electricity is produced, as in the several options explored in Section 3.5 (Next-kraftwerke, n.d.-a; van der Veen & Hakvoort, 2016).

4.3 Merit Order Effect (MOE)

The merit order effect (MOE) defines both the types of energy which will be produced for national consumption and the price. To develop this definition, the marginal cost of each energy is compared and the lowest cost type will be the first chosen. Without taking into account binding constraints, it continues until the energy amount forecasted is reached. The market price will be equal to the marginal cost of the last source of energy chosen.

REs have two main advantages here. First, their marginal cost is close to zero, and second, they are helped by the European legislation which forces suppliers to first purchase all the REs available. Therefore, the MOE can be seen as the correlation between the spot price and the energy mix composition. It means that the lower the price, the higher the amount of REs in the mix. Figure 2 shows clearly how this process works:

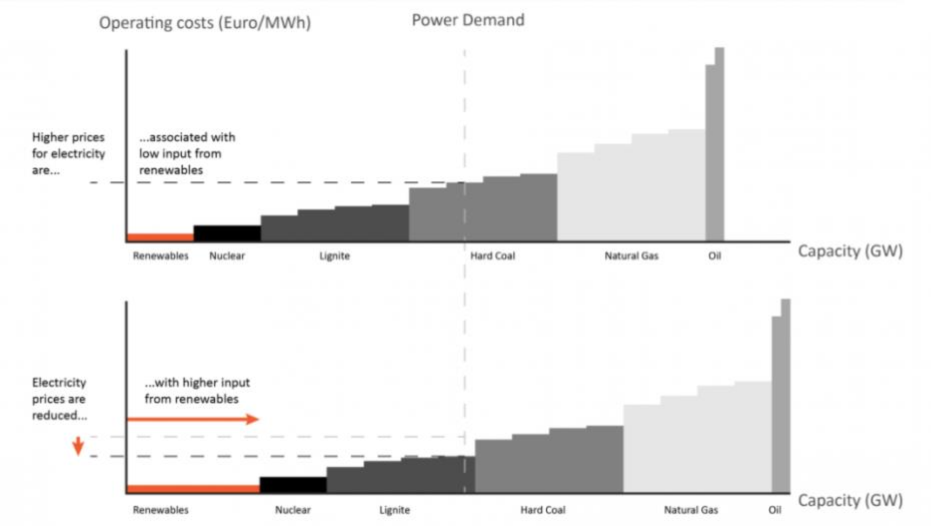

Figure 5: Merit order effect (Kerstine, 2015)

The impacts of REs on the MOE are multiple. With solar energy, the spot price during the day becomes flatter. At lunchtime electricity demand increases, and this need used to be fulfilled by conventional power plants. Since the implementation of solar panels, however, prices have remained stable instead of increasing with the demand due to the higher amount of sunlight available during this period (Janda, 2018)(Kerstine, 2015). The introduction of a carbon tax at the European level (ETS) has also had an effect on the merit order position of some resources because the tax is linked to the amount of CO_2 emitted (NERA, 2005).

However, the effects of REs on the electricity price have to be mitigated. The literature is divided between a slight decrease in the price (Janda, 2018) and an economic efficiency due to the impossibility for the MOE to fit with cost-efficiency and price-consistency concepts (Morales & Pineda, 2017).

4.4 Congestion management and the market coupling in Europe

4.4.1 European electricity market coupling

European market coupling began in 2006 when Belgium, France and the Netherlands decided to pair their day-ahead electricity market. Germany and Luxembourg joined them in 2010 to form the Central Western Europe (CWE) region. Austria entered in the group in 2013. During the same period of time, other countries started to fuse their electricity markets such as Spain and Portugal and the Scandinavian states. At present, this market coupling encompasses 19 countries, which represents the majority of European electricity consumption and is known as the Multi-Regional Coupling (MRC) (Next-kraftwerke, n.d.-b).

In 2010, the PXs of the MRC area went a step further by creating the Price Coupling Region (PCR). These actors decided on a common way to determine the best method for computing electricity prices by using cross-border line capacity as efficiently as possible. Afterwards, the CWE region switched from the Available Transfer Capacity (ATC) to the Flow-Based Market Coupling (FBMC) model to facilitate better use of the cross-border capacity, which resulted in a more integrated electricity market (as detailed in the next subsections) (Next-kraftwerke, n.d.-b).

To simplify, the former electricity market was separated into several markets. Each market had its purpose, such as cross-border allocation or electricity trading. Now, all these activities are grouped into a single European decentralised integrated market. It is considered decentralised because each region still has its own prices and data are not centrally managed (Next-kraftwerke, n.d.-b).

The coupling arrangement has also been implemented on the intraday market since 2018. It is called XBID (cross-border intraday market) and enables participant countries to send bids within the working day on the European market. A major advantage of this improvement is that it makes it easier for countries to manage their balancing market (Next-kraftwerke, n.d.-b).

4.4.2 European Regulation on Congestion

The EU regulation 1222/2015 entered into force to set a guideline on Capacity Allocation and Congestion Management (CACM). It has several goals, namely stimulating competition among the generators, trading and supply industries, guaranteeing a much better use of transmission lines across Europe, allowing the information to be transparent and available for all the market participants and providing a higher share of REs for integration into the network (European Commission, 2015a; Emissions-EUETS, 2020).

Through the regulation, the Commission wants to implement both XBID and day-ahead market. Accordingly, requirements and tasks have been assigned to nominated electricity market operators (NEMOs). Each country has had to ensure that at least one NEMO is in charge of market coupling operations. These operators can be linked to the PXs, but not completely due to PXs playing many more roles beyond the market coupling function (ACER, 2019; Weiss, n.d.).

4.4.3 Physical Capacity

The transmission grid is composed of physical lines capable of transporting high-voltage electricity from one point to another. Each line has an upper limit on the amount of electricity it can handle. This limit is set by the material used. When electricity goes through transmission lines, it creates heat that can melt the line if the amount of electricity exceeds the capacity of the cable. This is known as the thermal constraint, and it sets the transfer capacity which can be declined in several concepts (explained in the next subsections) (Wangensteen, 2012).

4.4.4 The Best Approach for Congestion

The electricity market has evolved at a national level, which helps to explain why Europe has a zonal approach (or bidding zone) and not a nodal approach as in the US. However, due to the willingness of the European Commission, links between European markets are made, which is known as market coupling. Electricity is traded in each bidding zone without constraint. With market coupling, cross-border electricity trade is required to take the NTC into account. When electricity moves through the grid, it is not transmitted directly from the producer to the consumer but follows the physical Kirchoff's law. To manage the congestion and maximise the allocation of electricity through transmission lines, one of several methods or algorithms (and also a set price) must be chosen (KUL Energy Institute, 2015).

The Nodal Market Clearing Method is based on the nodal approach and is not used in the EU where each node is seen as a market. The second is the ATC method, which considers all the nodes within a zone (approximately equal to a country) as a unique market. This approach implies that only cross-border transmission lines are considered. ATC defines the maximum commercial exchange between two zones. Finally, the FBMC method is also run with zones. The main improvement compared to the ATC method is that all transmission lines are taken into account when there is an exchange between two zones and not only the direct transmission line (Van den Bergh et al., 2016; Bjørndal & Bjørndal, 2017).

In Europe, both ATC and FBMC approaches are utilised. First, only the ATC method was used, but since 21 May 2015, the CWE region decided to switch to the FBMC model for the day-ahead market. The FBMC method was evaluated for three years with the Euphemia algorithm and started to manage the network after receiving validation. This algorithm (FBMC is a part of it) facilitates more competitive pricing, increases socio-economic welfare and leads to a more efficient capacity allocation (Bjørndal & Bjørndal, 2017). It also results in higher cross-border flows, provides better data for congestion management and, so far, corresponds to results from tests conducted between 2012 and 2014 (Kristiansen, 2020).

This model has introduced many changes into the CWE operating market compared to those described in the previous section. At present, PXs operate not only in their bidding zones but also in the other zones participating in the CWE electricity market. Schedules are the same in all bidding zones, but prices remain different among them. REs lead to less congestion than with the ATC model. However, the main drawback compared to the old model is the transparency. In regulatory terms, the FBMC is more transparent but not when one wants to establish which transmission capacity is accessible to the market (Bjørndal & Bjørndal, 2017; Van den Bergh et al., 2016).

The NTC is computed through the flow-based method which replaced the ATC method in 2015 in the CWE. Both methods are presented below.

In the **ATC system**, the Total Transfer Capacity (TTC) is the maximum flow of electricity the line is able to carry. This limitation is due to physical constraints such as the heat produced by the electron flows. If the heat level is too high, the line can melt. There are also voltage and stability limits. Similarly, if these limits are not respected, some undesirable events can occur (voltage collapses, blackouts, etc.). TTC focuses on the security of the line. Second, the Transmission Reliability Margin (TRM) is defined as a certain amount that will not be used on the line. It is a measure implemented in case one country in the network experiences an unexpected event. At that moment, countries sharing interconnections with this first country can use this "space" to help it avoid issues with its electricity network. Finally, the NTC is equal to the difference between the TTC and TRM. It is the maximal capacity that can normally be used for exchanges.

These numbers are set based on some assumptions that are less than optimal. Indeed, several circumstances might influence the NTC such as the external temperature (difference from one season to another) or when there is maintenance work on a line (Elia, 2009; ETSO, 2000).

In the **Flow-Based system**, there are some differences when computing the maximum flow on the line. There is also a maximum capacity and a security margin, referred to here as the Flow Reliability Margin (FRM), and the rest is composed by the flow of reference already known due to long-term contracts and the remaining available margin, which together represent the quantity available for the day-ahead market (KUL Energy Institute, 2015).

The flow-based method allows the market to trade a higher amount of electricity and increase the price convergence between areas. This method's outcomes are a set of critical branches with their corresponding capacities, whereas in the ATC method the whole region is not taken into account, but each border is calculated separately, and the outcome is the NTC.

In the remainder of this work, I will use the term NTC to refer to all the critical branches with their capacity. The ATC method is still utilised in some regions such as Nordic countries. FBMC is used for all international connections in Belgium except some places where international trade has no significant effect. Finally, some countries deal with both NTC and FBMC (KUL Energy Institute, 2015; CWE TSOs, 2015).

4.5 Issues and Beginning of Solutions for REs

REs also involve new challenges. This section first considers some issues related to particular categories of REs. In then addresses the integration of renewable energy generators (REGs) in the market, and it concludes by examining intermittency, which is the greatest obstacle to the integration of REs into the network.

4.5.1 Issues

4.5.1.1 Several common issues

REs produce electricity by harnessing the wind, the sun or other (infinite) natural resources, a feature which implies that the place chosen to build a wind turbine power plant is important. To maximise the output of this power plant, the location with the best wind conditions is required. However, the spot chosen might be far from the grid, and a cost for grid expansion therefore has to be handled (Mararakanye & Bekker, 2019; Sen & Ganguly, 2017).

Need in Grid Expansion: The German Case

Energy transition in Germany started with the phase out of nuclear power plants which will be followed in the long run by the coal phase-out. At the same time, many wind power plants are built the Baltic sea as well as in the northern part of the country where the wind is favourable. Many of the nuclear and coal power plants are located in the south of the country and provide energy for the inhabitants living there. If Germany wants to replace these energy sources with wind turbines, an expansion of the national transmission lines is necessary. This expansion is evaluated at €9.7 billion for the 3,600 km required. (Murray, 2019)

Another issue related to geography is the impact of these REs on the land and for the local communities. The best example is the implementation of a dam which will reduce the land suitable for urbanisation and change the amount of water available. In terms of technologies, it requires skills and knowledge to build and maintain such power plants. As explained in the section 3.5, this process can be very expensive for developing countries. Finally, policies can often be a barrier to the implementation of REs (Sen & Ganguly, 2017).

4.5.1.2 Renewable Energy Generators (REGs) Integration

More and more companies or individuals produce their own electricity through solar panels and other RE sources. These micro-power plants are linked to the network and must therefore be taken into account when forecasting and planning is conducted. More RE means a greater need to increase the flexibility of the network. That is to say, while the variable part in the energy mix is increased, the security of supply has to remain equal. This element of the energy mix leads to some issues in operational management.

4.5.1.3 Intermittency

The consumption of electricity is forecast based on available data (i.e. previous consumption, weather forecast, etc.). These forecasts can be divided into three parts: short-term, medium-term and long-term power system planning. Their scope is respectively the management of day-to-day system operation, the care of system assets and the analysis of new capacity addition. The problem with REs is their variability. It is simple to forecast the production of a nuclear power plant with high precision but very complicated for REs such as wind and solar. This variability generates problems in the balance of the network and difficulties for use in the baseload[6] (Das et al., 2018; Rahimi et al., 2013).

4.5.2 Solution: flexibility

To handle the intermittency issue, the power system has to be as flexible as possible in managing these variations in production while maintaining the same reliability in the security of supply. Such flexibility enables the management of any differences between the energy production forecast and the real production, to avoid outages or other problems. It is a feature

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[6] The baseload is “the minimum level of electricity demand required over a period of 24 hours. It is needed to provide power to components that keep running at all times (also referred as continuous load).” This definition is taken from https://sinovoltaics.com/learning-center/basics/base-load-peak-load/.

of the network that is mandatory for a higher penetration of REs (Ulbig & Andersson, 2015). This flexibility can be achieved through different means, as described below.

A. Storage

Solar panels provide electricity only when it is sunny and windmills only when there is wind. However, energy consumption does not always occur simultaneously to power production. These types of RE sources are going to have a larger share in the total electricity produced in Europe, so electricity storage is a major contemporary concern. Better storage would enable the difference between demand and supply in the sector to be balanced.

REs also poses problems for the grid. Even if the demand is equal to the electricity produced through renewable sources, the grid has to be able to transport this amount of energy from where it is produced to the point of consumption. Electricity storage enables the storing of renewable electricity surplus when the grid is congested and sends this surplus to the network when current production ceases or is insufficient (Miller et al., 2018).

Several types of storage technologies already exist. For instance, there are mechanical storage methods such as compressed air energy storage (CAES), pumped hydropower, flywheels and hydro storage systems (dams), which are particularly important since they provide renewable energy when other renewable resources cannot produce. Even if the hydropower technology is available, however, there is a need for mountains (the Alps, Scandinavia, etc.) which are not present in all regions worldwide. Other options include electrical and chemical storage, which continue to be developed further (Droste-Franke et al., 2012).

To increase the storage capacity, the vehicle-to-grid concept emerged. Increasing numbers of vehicles are either hybrid or electric and therefore include a powerful battery that can be used to store excess electricity produced by REs. For instance, when the wind electricity production is too high to integrate the total amount produced into the grid, it can be stored in multiple car batteries. This surplus energy will either be used to operate the vehicle or be sent back to the grid when there is a need. This system will lead to a better use of REs and will also have a positive impact on the electricity invoice of participating car owners. This technology requires some improvements in the electricity market and grid such as two-way communication (Lund et al., 2015).

Storage capacity is closely connected to the grid issue since it enables the balancing of both the electricity supply and the demand. Storage technologies are consequently highly useful and currently undergoing expansion. Given the uncertainty surrounding the current ability to store enough energy to be in charge of the balancing, the storage' solution will not be addressed further in this study. Accordingly, I will continue to consider electricity as produced and consumed instantaneously.

B. Demand side management (DSM)

This approach consists in adjusting the demand to acquire a favourable load curve, thereby enabling higher network flexibility. Many DSM methods have already been implemented. For example, decreasing the price at nighttime, smart metering which is the connection between devices and the network (the consumption of the device is automatically decreased when needed), the demand bidding with the predetermination of a decrease in consumption related to a predetermined price and so on. This system could decrease EU transmission congestion by 17% with a higher penetration of REs (Lund et al., 2015; Das et al., 2018; Strbac, 2008).

C. Grid Improvements

Flexibility can be improved through international connections. When a country has a lack of flexibility, interconnections play a major role in equilibrating the residual load fluctuations. This indicates that a good international network with a high transfer capacity would definitely increase the penetration of REs. Moreover, to realise the EU's 2050 objectives for RE, a grid expansion capable of handling from twice to seven times the current capacity (depending on the scenario) must be achieved. This expanded grid will also include connections with North African countries (Boie et al., 2016; Das et al., 2018).

The grid can be also improved in other ways. Due to recent technological developments, the idea of a smart grid has emerged. Here, all market participants are connected to each other, allowing direct sharing of information to everybody, and all technologies are connected, such as the storage capacities and smart metering. Another means of improvement is the micro-grid, which consists of a grid inside a neighbourhood where the production, capacity storage and consumption of every household is known by the system. It also requires further technological upgrades and can even utilise blockchain to improve transactions between system users (Lund et al., 2015; Z. Li et al., 2019).

Finally, all these grid improvements can be combined to attain considerably higher flexibility in the network and thereby improve the penetration of REs.

4.6 Focus on grid expansion

One solution proposed to the intermittency issue of REs is to better interconnect European countries by increasing the transmission lines capacity. This section sums up the main findings on the topic and will be used in the subsequent discussion comparing my own results to these discoveries. Some studies are already based on the EU scenarios presented later in this thesis.

Bahar and Sauvage (2013) stated that international electricity trade will facilitate developing a higher level of flexibility for European countries, enabling the grid to better manage a short-term load variability. Moreover, this gain in flexibility will enable the grid to manage a higher amount of REs such as solar or wind. It is explained that renewable power plants are located all across Europe. If the network capacity is high enough, this green electricity could be consumed far from the point of production, in locations where there is less wind or solar energy available. This grid expansion will also lead to a smoothing of demand across European countries.

The authors also discuss prices. When analysing the European exchanges, it is mandatory to consider the price. When two countries are trading, electricity moves from where it is cheapest to where it is more expensive to produce. The outcomes are an increase in price in the producing country and a decrease in the consuming country with high prices. Their findings indicate that trade flows are strongly influenced by both the price and the NTC. A change in price therefore has a positive impact on cross-border trade.

Finally, the researchers cite several studies supporting the conclusion that prices vary strongly during high production of intermittent RE, which leads to a lower price during these periods (Bahar & Sauvage, 2013).

Fürsch et al. (2013) develop two different scenarios which optimise the grid expansion and fulfil the 2050 EU targets. Their results assert that most renewable power plants are cost efficient even if a huge link has to be built between the production and consumption points (i.e. offshore wind turbines). For the most remote areas, it is still economically interesting but not optimal (i.e. solar power from North Africa). On the other hand, costs related to the grid expansion for remote power plants influence the country of destination. The problem of too much renewable electricity being produced is solved by storing the exceeding amount.

The authors conclude that the grid expansion is a mandatory requirement to fulfil European targets on CO_2 reduction (Fürsch et al., 2013).

Burgholzer and Hans (2016) studied the case of the Austrian grid expansion. They built several scenarios for 2050. In all these scenarios, savings from switching out of fossil fuels are positive. The Austrian 380 kV circuit will allow a better integration of REs through connections with wind farms and remote pumped hydro storage. Regarding the costs, a substantial share of future revenues will be allocated to reimburse money spent on cross-border connections. (Burgholzer & Auer, 2016)

These three articles were the most interesting I found. All focus on Europe, but only one was written after 2015. Hence, I supposed that these researchers did not take the FBMC method into account. Their study results may therefore underestimate the capacity exchange and overestimate the costs. Although many more papers analysed this issue, the most significant results are presented in the articles chosen.

Outside Europe, ***Li et al. (2016)*** focused on the inter-regional electricity grid expansion. Their results indicate an increase of 2% of CO_2 emissions by 2030 and economic benefits. However, because the environment is different in China (and in other regions of the world such as the US), I do not compare my results with Li et al.'s findings. Indeed, among other differences, the increase in CO_2 is due to that electricity produced from coal which will be cheaper to transport, and China does not have the same objectives as Europe (Y. Li et al., 2016).

It is also interesting to cite ***Ritter et al. (2019)*** who warn about consequences of any delay on the expected outcomes. The outcomes of such a delay might be increases in price and in CO_2 emissions. This assessment is partially explained by the future impossibility for Northern countries to send/sell their REs production to Southern European countries due to a lack of interconnection capacity (Ritter et al., 2019).

Finally, the expected outcomes of an increase in transmission lines are assessed by Elia in its report “Plan de développement fédéral du réseau de transport 2020–2030”, which I examine further in Section 6.2.1, after discussing the relevant scenarios.

5. Methodology

The previous section demonstrated the importance of cross-border transmission lines in the electricity sector, especially for the integration of REs. The next part of this study is dedicated to the Belgian case.

To solve the research question for this specific case, I modelled the case in R with data found on Elia and European Network of Transmission System Operators for Electricity (ENTSO-E)'s website. To obtain my results, I followed steps proposed by Hyndman and Athanasopoulos in their book *Forecasting: principles and practices*:

1. *Problem definition*: Based on the previous sections, I decided to focus on the transmission lines needs. Indeed, it is a mandatory requirement of the EU 2050 plan to reach a zero carbon emissions target, and I discovered that even if several cost-benefit analyses were conducted to assess the capacity in additional lines required to reach the European targets, the need for this increase in lines capacity and the effect on the price when REs production is high has not previously been analysed. To address this research gap, I investigated the relations between the REs produced, the export and the price.
2. *Gathering information*: this step required me to collect data about prices, capacity, production and other factors over a lengthy period of time to ensure relevant results. This task demanded additional effort that enabled me to deepen my understanding of this industry. Thanks to this knowledge, I was able to start the next step efficiently.
3. *Exploratory analysis*: To understand my data well, I needed to analyse it and find some explanation for each strange observation. Hence, I did not re-transcribe all my findings for each small event.

   The purpose here was to understand my data, which required plotting the different variables and trying to identify any trends, finding an explanation when some aspect of the data seemed puzzling and attempting to establish relations between variables. The knowledge derived from the second step helped me to avoid taking any shortcuts in the observations made in this third stage of the research.

4. *Choosing and fitting the model*: based on the third step, I had to choose an appropriate model for the problem. I examined the data analysis I had already conducted and assessed it in terms of the theory of diverse forecasting models and methods to determine the most appropriate choice. Indeed, when the forecast outcomes are odd or unexpected, this does not necessarily mean that the model or method is ineffective, since its success mainly depends on the type of data one is dealing with.
5. *Evaluating the forecast*: I criticised the results, assessed the accuracy of the work I had done and evaluated whether the model was reliable. To do so, I brought together the results, the hypothesis proposed and the relevant findings by other researchers (which are summarised in the literature review above). In combining these elements, I started writing the discussion section to correctly present my results.

6. Belgian Case

It has been highlighted in the previous sections that the electricity sector is responsible for a significant proportion of the CO_2 emitted in Europe. Moreover, more and more sectors will be electrified in the coming years. To face these problems, the EU agreed on a plan to cope with these issues and to solve them through integrating the European electricity market, increasing the security of supply and various other measures.

In this thesis I focus on the EU's decision to invest in cross-border transmission lines. It was proposed in Section 4.6.2. that an increase in cross-border transmission lines will lead to an increase in the network flexibility and increase the penetration of REs. The research question applied for the Belgian case can be formulated as follows: what are the effects on the Belgian price and net exports when an increase in the country's cross-border transmission lines capacities occurs?

These effects can be multiple, ranging from the prices at which the electricity is sold to the amount of electricity exported/imported. I attempted to analyse these factors while taking into account all aspects discussed in the literature review. These aspects are transcribed in the hypothesis of the model.

This section first presents the Belgian electricity situation and the scenarios published by the EU. Based on this information, the future requirements for the Belgian electricity sector are highlighted. Afterwards, the data utilised and the model chosen are presented along with the hypothesis to run the model and provide commentary on the outcomes.

6.1 Current State of Affairs

All Belgian transmission lines are managed by Elia. They build and administer lines from 70 to 380 kV and high-voltage direct current (HVDC) cables in both aerial and underground installations. While the main transmission lines are national, Belgium also has several interconnections (in 2019) with neighbouring countries:

- France: three 380 kV transmission lines and three 220 kV (some are located in the same area)
- The Netherlands: four 380 kV transmission lines
- Luxembourg: two 220 kV transmission lines
- UK: one HVDC cable

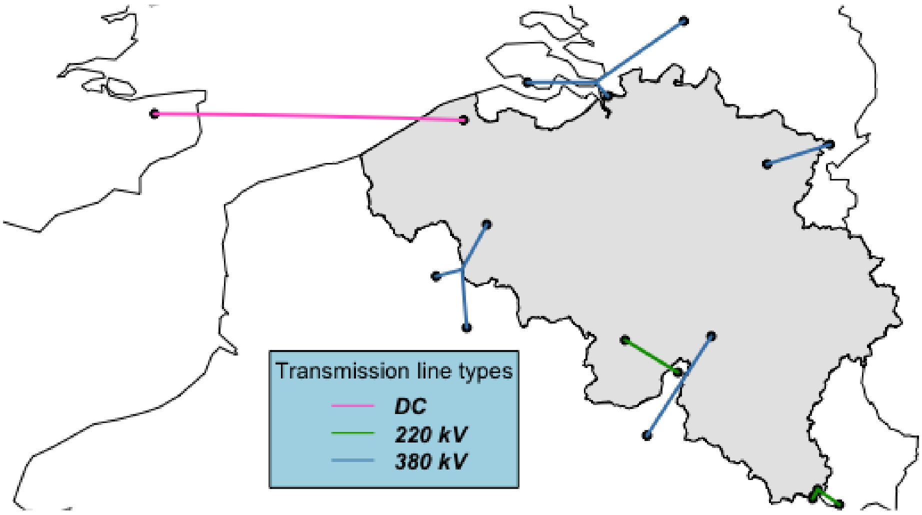


Figure 6 Belgian cross-border transmission lines in 2020

There is no direct connection with Germany, but an HVDC line is currently under construction. Lines connected with the Netherlands and France have been operating for many years, while the one linked to the UK started to work at the beginning of 2019.

6.2 Future of the European electricity landscape

This section first examines the respective EU and Belgian RE plans. Based on these details, needs are identified to fulfil objectives regarding each scenario.

6.2.1 Scenarios for 2040

The composition of the electricity mix and indirectly the future of transmission lines expansion is determined by both the federal and the European plan. The federal plan is developed in line with the international goals and objectives.

At the European level, the Ten-Year Network Development Plan (TYNDP) is led by ENTSOs. This plan is adjusted every two years to incorporate new variables and to update the model. The purposes are to fulfil Paris agreements through the integration of REs, ensure the security of supply and push the integration of the European electricity market further. This plan was devised with the assistance of many actors at the European and local levels, including NGOs. To realise its aims, three scenarios for 2030 and 2040 have been proposed: the Sustainable Transition (ST), Distributed Generation (DG) and global Climate Action (GCA) plans. These plans are based on hypotheses such as the demand growth, the increase in REs and the needs of specific countries. The motivation for proposing three plans rather than only one is to better encompass long-term uncertainties. Economic results are calculated for the 2030 horizon. For 2040, only the future needs for the electrical system have been identified.

There are also estimates for before 2040. The 2025 best estimate is a single plan based on TSO outlooks. That year it might have a merit order switch. Based on the CO_2 prices, it will be “coal before gas” in the case of a CO_2 price low. In the other case, it will be “gas before coal”.
The ST plan wants the CO_2 reduction to be in line with economic interests. Gas replaces coal, and most of the effort to reach the 2050 goals are conducted during the last decade of the scenario. Here, there is a slower electrification of sectors such as heat compared to the two other scenarios. The DG plan focuses on prosumers. All attention is on a decentralised system with a development of smart technologies to connect end users. The electrification of vehicles is important and implies an increase in the total load. Finally, the GCA scenario promotes rapid decarbonisation. Nuclear power plants are still key energy market players, and the focus is on the installation of large-scale renewable power plants. The electrification of the heat sector leads to a small decrease in gas demand. Here, improvements target every sector of the economy and power-to-gas technologies are more widely used than in the two previous scenarios.

To compare the efficiency of these scenarios, the following table indicates the best scenario based on a specific purpose (Elia, 2019; ENTSO-E & ENTSOG, 2018):

	ST	DG	GCA
Electricity annual demand	+	+++	++
Gas annual demand	+++	++	+
Electricity installed generation capacity	+	+++	++
Electricity net generation	+	+++	++
Percentage share of electricity demand covered by renewable generation	+	++	+++
EU28 CO2 emissions	+++	++	+
Marginal cost of electricity	+	+++	++

Note:
+++ = highest number, ++ = in between, + = lowest number

Table 1: scenarios' outcomes (Elia, 2018)

The GCA scenario is clearly the most ambitious in terms of CO_2 reduction and increases in renewable capacity. The drawback is a higher electricity marginal cost than in the ST scenario (the least ambitious).

At the national level, Elia analysed the TYNDP plan and improved it with new data to fulfil national objectives and needs. Elia use TYNDP+ to name the new plan in which they renamed the three scenarios. The national plan is in line with the TYNDP and with domestic need (Elia, 2019). I use the objectives of the TYNDP and the federal plan to build forecasts.

To build its development plan, Elia pointed out several potential issues due to the three scenarios described above. First, the actual capacity is far below the capacity required for an optimal economic exchange at the European level. Second, all scenarios encompass an important growth in the future REs production, which will make forecasting the production more difficult. Finally, congestion will be more frequent in Belgium due to its position in the North Sea market (Elia, 2019). To face these issues, needs are analysed with Elia's forecasts and completed by the model in Section 6.6.

Elia also analysed the difference in price between the Belgian price zone and its neighbours. Depending on the scenario and with REs capacity increasing at different speed across various European countries, the difference in price growth forecast ranges from 1 €/MWh in 2025 to a maximum of 14 €/MWh in 2040. The EU does not want a difference in price of more than 2 €/MWh between two time zones. This objective could be achieved through the increase in transmission lines assessed by Elia in table 2 following the scenario chosen.

		Future needs depending on the scenario		
Border-Direction	**NTC 2020**	**NTC Sustainable Transition 2040**	**NTC Distributed Generation 2040**	**NTC Global Climate Action 2040**
BE-FR // FR-BE	1800 // 3300	4300 // 5800	3800 // 5300	4300 // 5800
BE-NL // NL-BE	2400 // 1400	4900 // 4900	4400 // 4400	4900 // 4900
BE-GB // GB-BE	1000 // 1000	2500 // 2500	2000 // 2000	2000 // 2000
BE-DE // DE-BE	1000 // 1000	1000 // 1000	2000 // 2000	2000 // 2000
BE-LU // LU-BE	300 // 180	300 // 180	300 // 180	800 // 680

Table 2 Future NTC depending on scenarios (Elia, 2019)

To install these new capacities, Elia wants first to optimise and modernise the capacity of the actual line before building new ones.

6.2.2 Needs analysis

These scenarios each involve hypotheses on needs, means of production and other factors that are different for each storyline. Therefore, the anticipated needs for 2040 regarding NTC and renewable capacity, among other factors, vary depending on the scenario. The table below displays the future Belgian renewable capacity for the three scenarios. Note that table 3 has been constructed by taking into account the details in table 2 (and many other variables such as the load, the storage capacity, etc.).

		Capacity 2040		
Renewable energy sources	**Capacity 2020**	**ST**	**DG**	**GCA**
Wind Onshore	2248	4200	5900	8400
Wind Offshore	1548	4000	5000	8000
Solar	3369	6000	18000	10000

Table 3 Belgian REs capacity (Elia, 2019)

This table forecasts the REs installed in 2040 depending on the scenario chosen. In the ST scenario, the capacity grossly doubles for each source. Because the DG scenario relies on a strong increase in solar panels owned by prosumers, the solar energy capacity is nearly six times higher than at present, and both onshore and offshore wind capacity strongly increase as well, although not as much as the solar. Finally, the GCA scenario has the highest growth in all REs installed on average.

The model encompasses table 2 to build forecasts on exports based on the relation between exports, the production of REs and the price.

6.3 Data Presentation and Exploratory Analysis

Data for the model are taken from Elia and the ENTSO-E website (Elia has to send Belgian data to ENTSO so the two data sets are the same, but each is differently aggregated). I downloaded, cleaned and gathered data from 1 January 2017 to 31 December 2020. During this process, I downloaded data, but sometimes Excel files contained data for only one variable and for one month. Thus, after uploading them in R, I had to bind them, remove empty rows, ensure that the data were hourly aggregated and so on. After completing this heavy task, I built one Excel file including all the variables hourly aggregated.

In this section, the data used are explained (in MW at 1H) and all data are "day ahead" (except NTC which is set weeks ahead).

The **renewable electricity production** has increased in recent years. This outcome is explained by an increase in solar panels and wind turbines installed. What is interesting in plotting this data is to see that solar produces large quantities of electricity in summer, whereas the wind turbines are most active in winter. This variable is important for the model. It is both logical and necessary to keep in mind that the RE produced depends only on the capacity installed and the weather, not on the price or export.

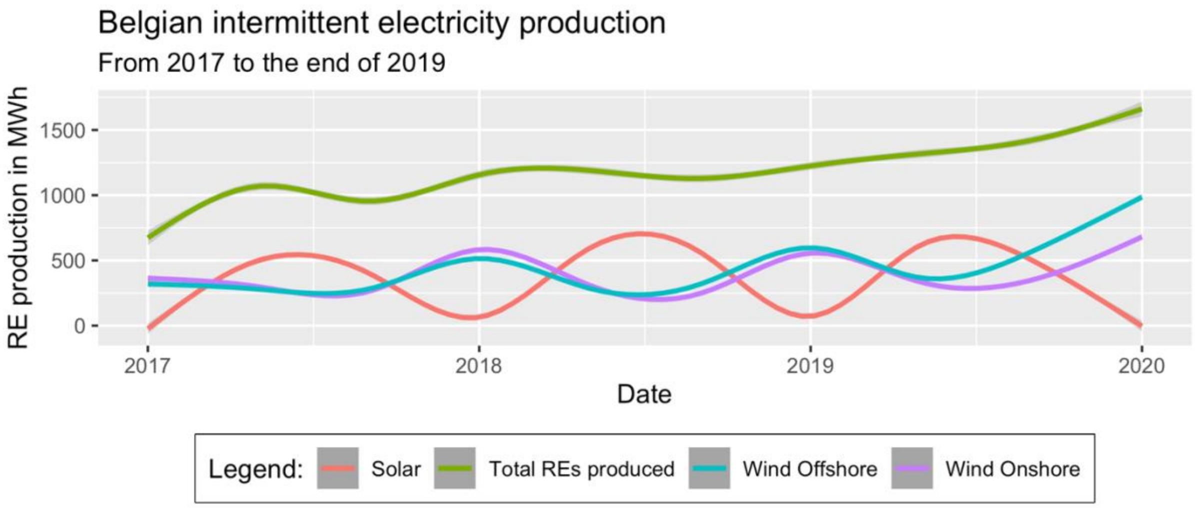


Figure 7 Belgian intermittent electricity production from 2017 to 2019

For the **total export/import**, I summed the export/import of all borders at time *t* to obtain the net export. I did the same with the NTC on each border (NTC import is different to NTC export). This procedure resulted in the following graph:

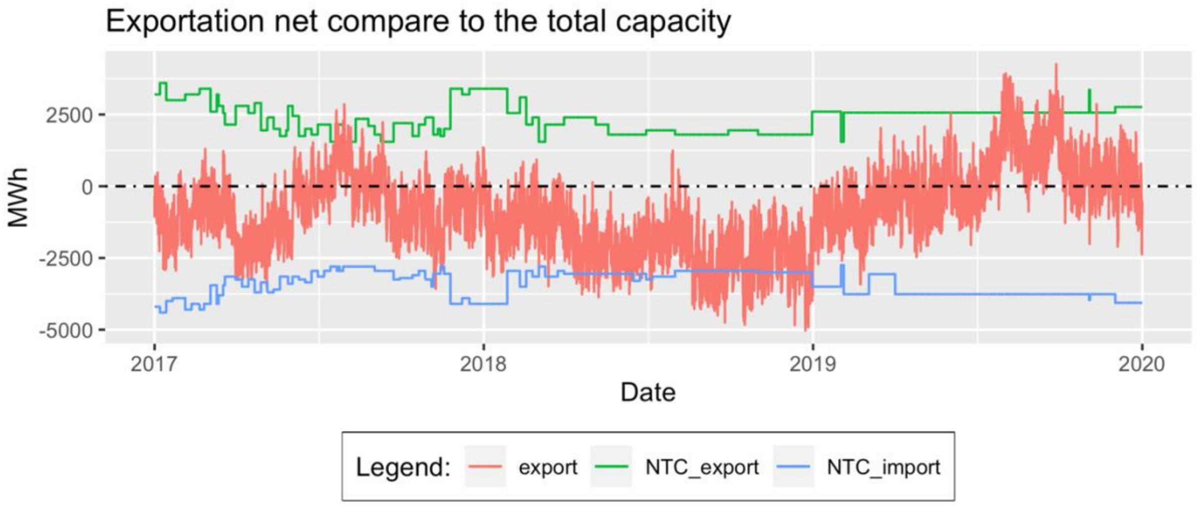


Figure 8 Net Export Compared to the Total Capacity

When the export line is above the dotted line, it means that Belgium is an overall exporter of electricity (both renewable and non-renewable) to neighbouring countries, while when it is below the line, Belgium is an overall importer. While 2018 can be classified as a year when Belgium was a major importer, 2017 and 2019 are in between. The explanation for the 2018 figures is that the country has seven nuclear power plants, many of which were out of service or in maintenance during this year. Belgium strongly relies on this source of electricity: in 2019, all nuclear power plants were operating and generated 46.1% of the total electricity produced.

The total NTC was not particularly stable in 2017 and did not increase notably over the period analysed. There was an increase in 2019 due to the HVDC line constructed between the UK and Belgium. The quantity exported was never constant. While the exportation might be high one day, it is possible to have completely opposite figures the next day or even a few hours later. Without doing any regression, it may be supposed that exportation depends not only on the production but also on the load at different times of day, the price and other factors.

Finally, the net import/export sometimes exceeds the total NTC. As explained in the NTC section, the TTC is composed by the NTC and a part of it is reserved in case of problems. The periods in late 2018 and mid 2019 could be characterised by several problems/congestion in the grid.

Note that the NTC with Luxembourg is not taken into account for several reasons. Electricity exchanges between both countries only occurred in 2018 with a small maximal capacity. Moreover, many data are missing for this country such as the NTC. Accordingly, the electricity exchange and the NTC with Luxembourg were removed from the database.

The **price** is analysed in the next section with the explanation of the autoregressive integrated moving average (ARIMA) model.

However, before running the model, it was important to consider if there was at least a correlation between the variables I intended to analyse. For this purpose, I ran several simple dynamic linear regressions between variables.

	Intercept	**Coefficient**	**R-Squared**
Exports ~ REs production	-1608	0.62	0.14
Price ~ REs production	52.61	-0.005	0.04
Price ~ Exports	40.29	-0.007	0.19

Table 4: Dynamic linear regressions between variables

I displayed relevant parameters in table 4. Note that the *p*-value is very small in each regression. To read this table correctly, the first relation should be considered. The intercept is the value when there is no production of RE. When the REs production increase by 1 MWh, exports increase by 0.62 MWh. The *R*-squared parameters provide information regarding the percentage of exports variation explained by the production of REs.

The first and third relations explained a significant amount of the dependent variable, while the production of REs explained only 4%. It is still relevant for the model to encompass this relation. Finally, the dynamic regression model is mandatory because the previous table is computed with a non-stationary time series. This outcome might lead to minimising the *p*-value and therefore, encompassing an irrelevant variable in our model. This element is explained further in the next section.

6.4 Dynamic regression model

To build a reliable forecast with my data I decided to use the dynamic regression model. It is based on the ARIMA model but allows for the addition of other variables different from lag values. The following subsections first elucidate the ARIMA/dynamic regression model and then explain why this model is useful in this work.

6.4.1 Autoregressive Integrated Moving Average (ARIMA) Explanation

The ARIMA model stands for autoregressive integrated moving average. It is a useful tool to forecast time series. Compared to other models such exponential smoothing, it focuses on lag values to analyse autocorrelations.

Before explaining how the model works, it is necessary to understand what stationarity is. The stationarity is defined by a constant variance, no trend and no seasonality in the data. Many models such as ARIMA are based on this concept. Employing these models without first ensuring that data are stationary could lead to an underestimation in the error terms, and thus one might use variables which are actually irrelevant due to the wrong *p*-value (Hyndman & Athanasopoulos, 2018; Mauritzen, 2020).

When looking at the electricity price in the data, I obtained the following graph after removing some outliers, allowing for a better visual understanding:

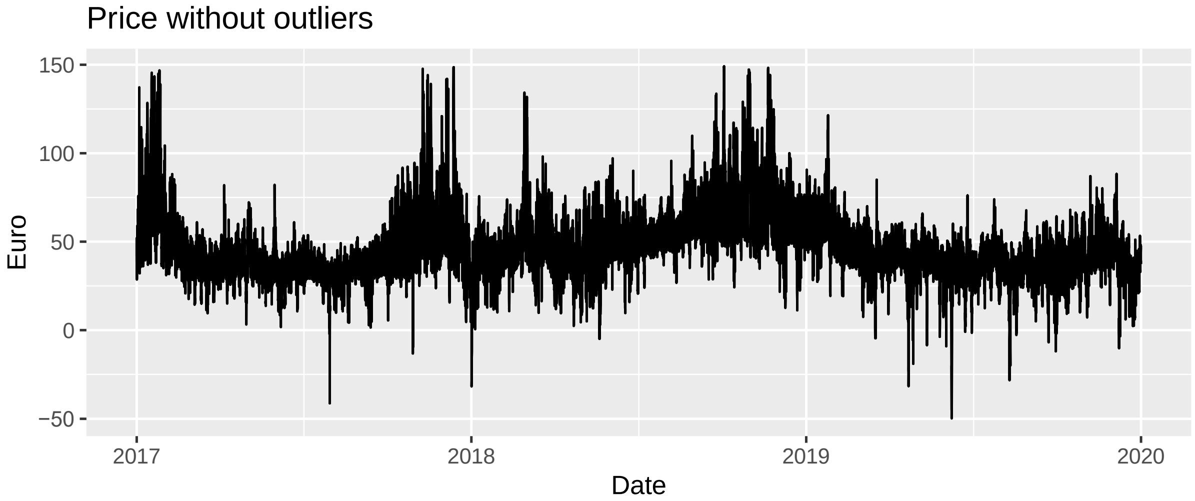


Figure 9: Time Series - Electricity price without outliers

It is clear here that the price is higher in winter than in summer, which indicates seasonality. Looking at a small part of the graph, weekly and hourly seasonality are also evident. Another important point is the high variance between observations, although there is no obvious trend in these three years. Therefore, we can assume that these data are not stationary.

To overcome this issue, it is common to use the differencing method. In this method, instead of taking the observations, one analyses the difference between consecutive observations. The graph of the price that results in depicted in figure 10 below.

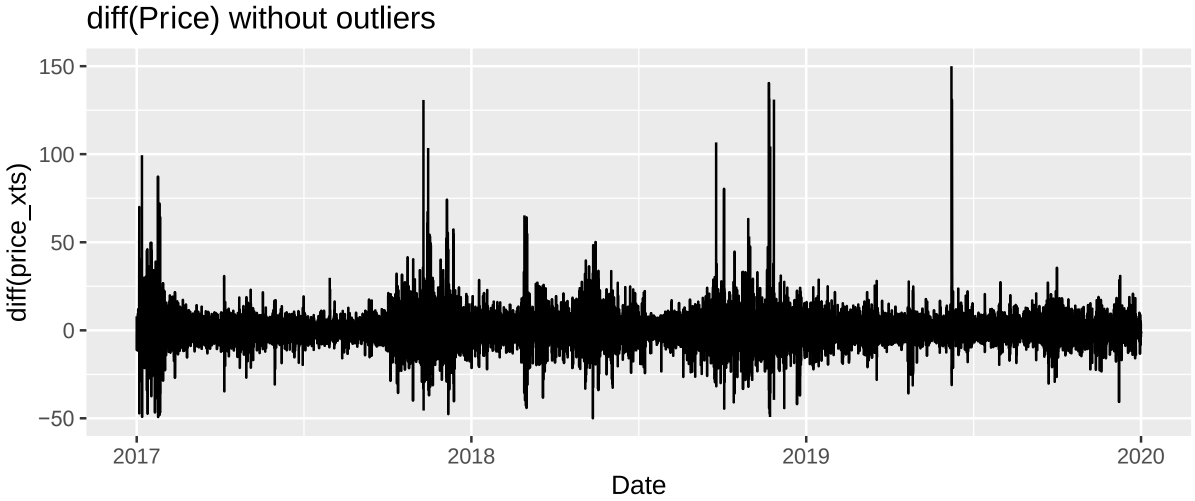


Figure 10 Time Series: Electricity Price Differencing Without Outliers

It is clear that the seasonality has disappeared, while the variance is more constant than in the previous graph, even if the variance is still less constant in winter than in summer. To check numerically if it is stationary, one can use the Dickey-Fuller's test. If the results obtained are still somewhat unconvincing, one can take the second difference and so on. This difference is represented in the ARIMA model by the "**I**".

AR: autoregression means that it is a regression not explained by another variable but by the previous value of the dependent variable. It is commonly called "lag value". For the prices in this study, this entails forecasting the price at time *t*+1 based on the value of *t*, *t*-1 and so on. The purpose is to capture the pattern to obtain a good prediction (Ritvikmath, 2019).

MA: the purpose of the moving average is to guess the next value based on the previous error compared to the average. For example, say that the average price per MWh is 55. If we decide to predict the next value with an MA(1), the next value is calculated by the sum of the average and the multiplication of the previous error by a constant: $\hat{f}_t = M + \varphi_1 * \varepsilon_{t-1}$.

To find MA and AR, one has to look at the autocorrelation function (ACF) graph and the partial autocorrelation function (PACF) graph, which are explained in the next section. An ARIMA (1,1,0) means that one examines the first previous value, then takes the first difference and does not take into account any moving average for lag value. To determine if the parameters are the right ones, it is common to run several ARIMAs and to consider the Akaike information criteria (AIC). The model with the smallest AIC is the best. Note that looking whether the AIC value is quite high or not is useless. This value can only be used to compare several ARIMAs among themselves. For example, the ETS model also gives an AIC, but there is no point in comparing an AIC from of an ARIMA model to one from an ETS model.

6.4.2 Why does this model suit this situation?

The model and the underlying method that I have chosen strongly depend on the type of data. There are three main methods to consider when forecasting: qualitative techniques, time series analysis and projection (Chambers et al., 1971). This work deals with many quantitative variables which are evolving through time. Thus, among the three basic types of forecasting methods, the obvious choice is time series analysis.

The next step is to select the best models to utilise with time series. Considering the data and the research question, I decided to work with the dynamic regression model. It encompasses the ARIMA model and is able to take into account variables other than lag values.

6.5 Hypothesis

The electricity sector depends on so many variables that it is always required to adopt some hypothesis to restrict the study area. In doing so, it is also necessary to examine one’s results while being aware of these hypotheses.

- The model is trained with data from three years. Special situations such as the Covid-19 crisis are beyond this scope.
- Because variables such as interconnection capacity and renewable production were chosen, others such as the load are not included in this thesis. The reason is evident: the study’s purpose is to examine the relation between three variables, so if the load

variable is added, the effects of these key variables might be hidden. Indeed, the price is strongly determined by the load. Therefore, the load is considered constant, which means that it has the same numbers as the three reference years and also that nuclear production will continue.

- Exchanges with neighbouring countries are taken into account except for Luxembourg due to the small amount exchanged and the unavailability of some data such as the NTC.
- Potential technological improvements that might arise in the coming years are not taken into account (i.e. batteries).
- Interconnection capacities are taken into account in the model as the sum of all capacities. Borders are not analysed case by case.
- The EU's vision for 2040 has been chosen. The RE capacities for 2040 forecasted by Elia are used to model other variables for 2040, 2041 and 2042.
- The future RE production in the forecasts is proportional to the amount of REs capacity, which means the forecasts consider the same weather as the three reference years. It is the same with all other variables except the three studied.
- All exports can be sent abroad, there is no congestion.

6.6 Model

6.6.1 Decomposition and Stationarity of the Price

To better understand the pattern of this variable and to avoid failing to analyse any trends or seasonality, it might be interesting to decompose it. When decomposing a variable in R, I have to choose the frequency. After several tries, I have chosen 168, which corresponds to a weekly seasonality (=24*7 because we are dealing with hourly data).

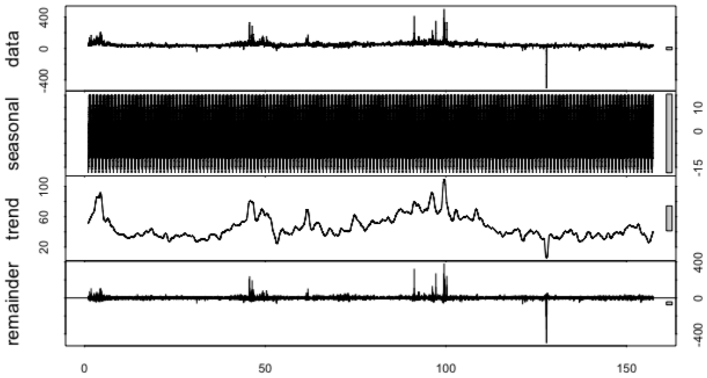
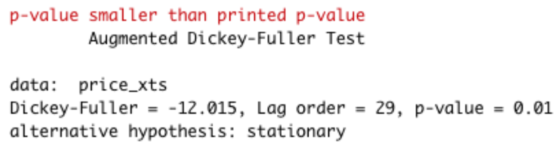


Figure 11 Price decomposition

The *x*-axis is in weeks. Therefore, it clearly shows a weekly seasonality and no obvious trends. When trying several seasonality parameters such as 24 (daily) or 2,190 (quarterly), the results also show strong seasonality.

Several approaches can be used to assess whether data are stationary. One method is the Augmented Dickey-Fuller test, which will run all the tests required to determine if H_0 can be rejected or not. The outputs of this test will be whether the hypothesis is rejected (*p*-value smaller than .05) and a negative value. The smaller the value is, the more stationary the series is. In other words, this test checks how much the previous observation impacts on the actual observation.



```
p-value smaller than printed p-value
        Augmented Dickey-Fuller Test

data:  price_xts
Dickey-Fuller = -12.015, Lag order = 29, p-value = 0.01
alternative hypothesis: stationary
```

Figure 12 Augmented Dickey-Fuller Test

Figure 12 says that the series is stationary even if visually it was not the case at all. Therefore, theoretically there is no need to take the first difference but in running the test with this difference, I obtained -37.4 which is a much better value. Therefore, taking the difference is often a useful means for ensuring a reliable standard error and decreasing autocorrelations' influence. To be certain, one can check the ACF and PACF graphs (Dalinina, 2017; Hyndman & Athanasopoulos, 2018; Mauritzen, 2020).

More than the stationarity, the ACF and PACF graphs determine the ARIMA's parameters. The ACF determines the moving average parameter (correlation between a value and the lags), while the PACF defines the autoregression parameter (the direct correlation between the i^{th} lags and the actual value).

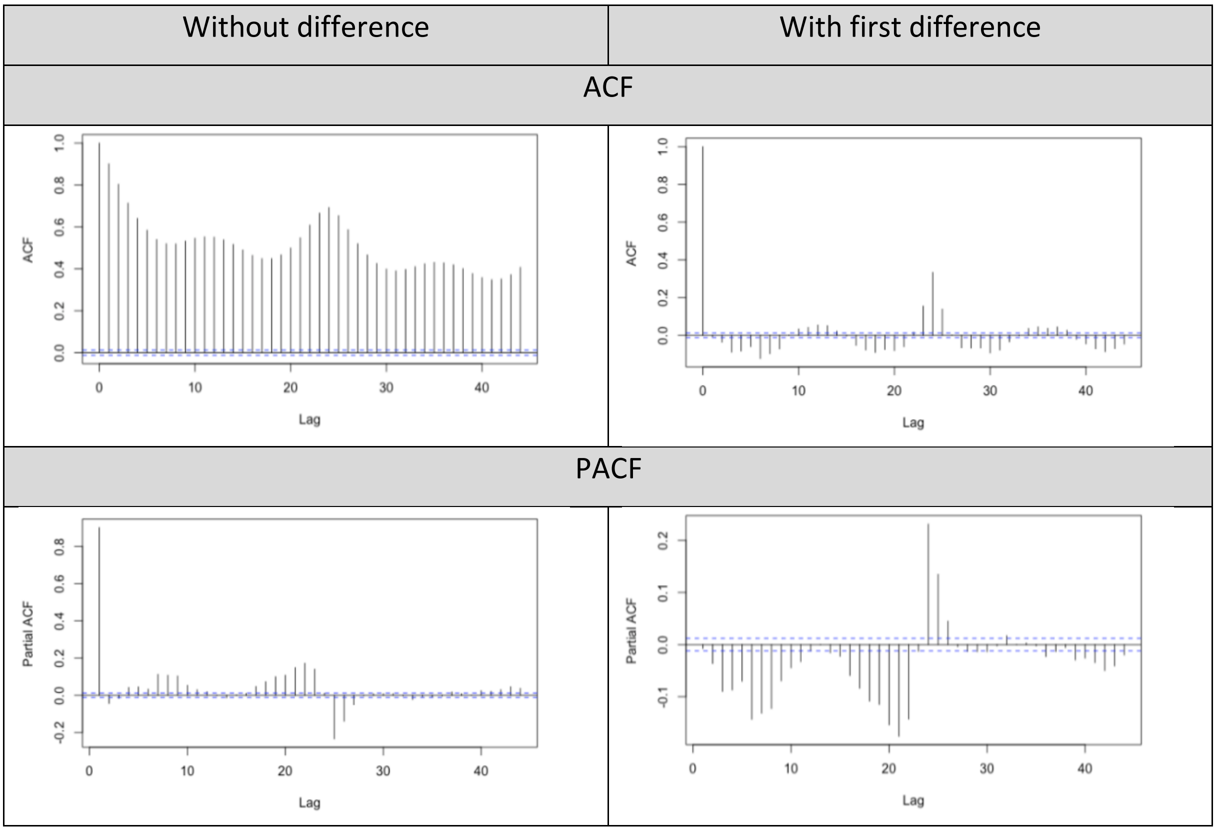


Figure 13 Model's ACF and PACF

The ACF without differencing shows obvious autocorrelations among the price and its lag values. Looking at the right-hand column, some correlations are significant, especially at lag 24, which is the same hour one day before. Based on these graphs, I tried some parameters and also the auto.arima function to determine the optimal solutions (this function does not always provide the best solution, however).

What is of interest here is determining the impact of an increase in transmission lines on the electricity price and the net exportation during periods with a high production through REs. Let us compare the relation among these variables in both cases, with all the data and only periods when renewable energies produced more than 2,000 MWh (arbitrarily chosen).

	With the whole dataset	**Only when REs produce more than 2000 Mwh**
Price ~ REs production	-0.0038	-0.0072
Exports ~ REs production	0.4360	0.5415
Price ~ Exports	-0.0018	-0.0039

Table 5: Arima model on the three variables

Results display in table 5 are interesting. In the ARIMA model's result, the numbers demonstrate the impact of an increase of one unit of the independent variable on the dependent variable. For example, the first line shows that when taking into account all data, an increase of 1 MW of production leads to a decrease of €0.0038 in price. This appears insignificant, but when the wind blows and the sunlight is abundant, an increase of 1000 MW produced results in a decrease of 3.8 €/MWh. The difference between these two scenarios is an increase of 89% in the decrease in price. The right column shows the results when only a period of high REs production occurs. For the three ARIMAs, the difference is significant. Using the example of high REs production once more, if the export increases by 24% because of the high REs production, then the price undergoes an increase in the decrease of 116%.

These relations can now be forecast for the case where REs production exceeds 2,000 MWh. Indeed, the literature review indicated that in this case a higher transmission capacity can help better integrate REs.

6.6.2 Influence of REs production on exports

I started to look at the influence of the REs production on the MWh exported. The three cases are represented in the figure below. The black lines are data from 2017 to 2020, and the blue lines are the three years forecast considering the REs capacity in 2040 for each scenario. Both are separated by the vertical dotted line.

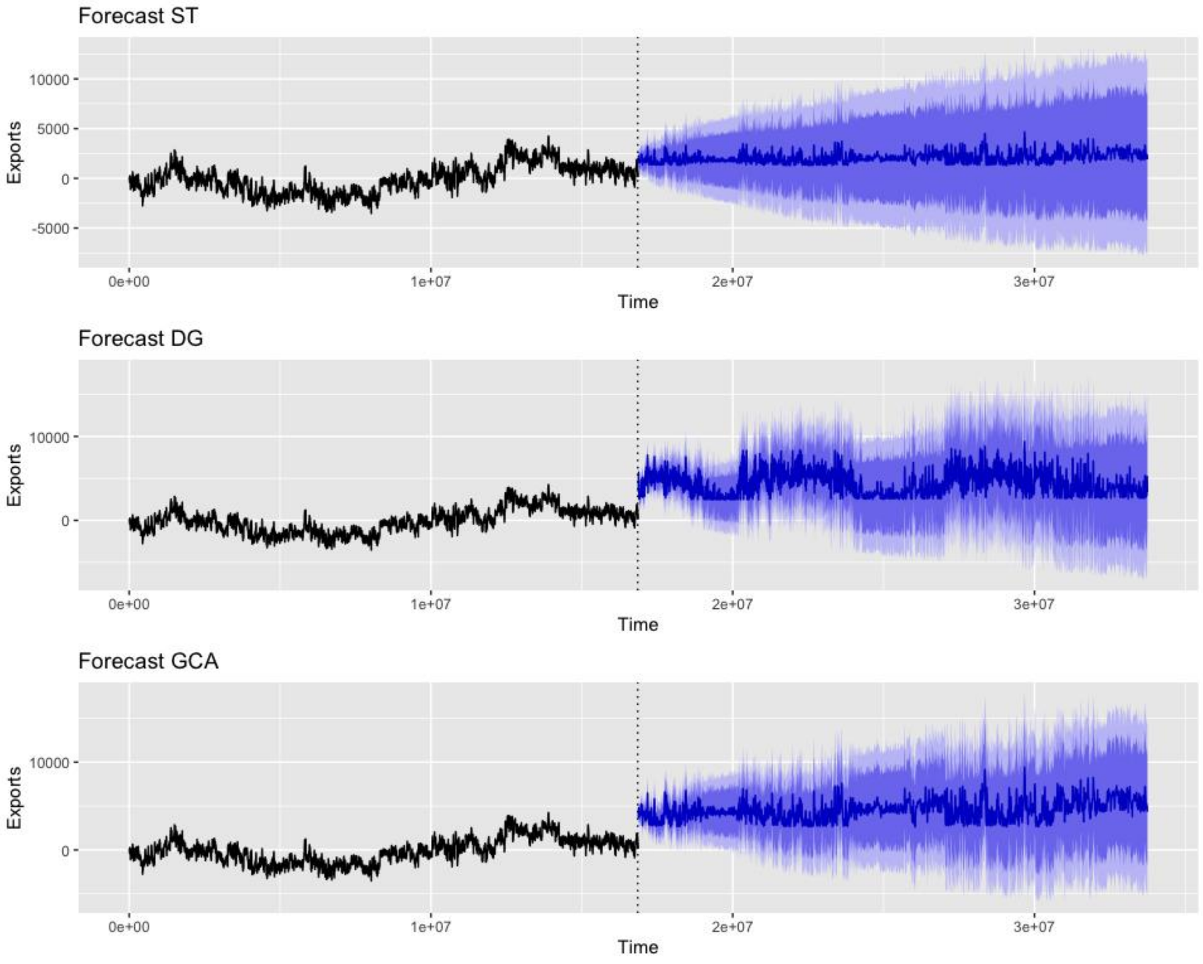


Figure 14: Forecasts of the influence of REs production on exports for each scenario

These three scenarios have different effects on the net export in 2040. Because the renewable capacity will not be the same, the differences are clearly evident. In the ST scenario, exports will be higher on average but not as high as in the two other situations. In the DG scenario, strong seasonality in exports will appear due to the high capacity in solar panels installed, and its exports will increase as much as in the GCA scenario, but the latter will be more stable. The increase in REs is less than in the DG scenario but more or less equally divided between solar, offshore wind and onshore wind. This outcome explains the difference in volatility between the DG and GCA scenarios. There is also some seasonality, but it is less obvious.

Again, these values must be relativised. The outcome depends on many additional variables such as the weather in neighbouring countries and the load, among others. What is interesting is the difference between scenarios and the exports volatility. Looking at numbers of the mean of the production exported in 2040 in the table 6, the difference between the ST scenario and the two others is clearly evident.

		Mean export 2040		
	Mean export 2020	**ST**	**DG**	**GCA**
Mean	-51.32994	2128.973	4551.453	4633.756

Table 6: Mean of the forecasted production exported for each scenario

The mean in 2020 is not relevant when comparing with the future. The REs production enlarges exports, which results in only positive values in the predictions because it does not depend on other countries' production in this model. However, this projection highlights the differences between scenarios. Thus, in the EU's vision to increase international electricity trade, the projections are most favourable in the GCA scenario. Even if it is more or less the same amount exported, the seasonality is weaker because this graph only considers periods with a high REs production, avoiding a huge spike to prevent congestion.

6.6.3 Influence of REs production on prices

The results of the model on the influence between REs production on prices are shown visually in the figure below. The graph is built in the same way as the previous one.

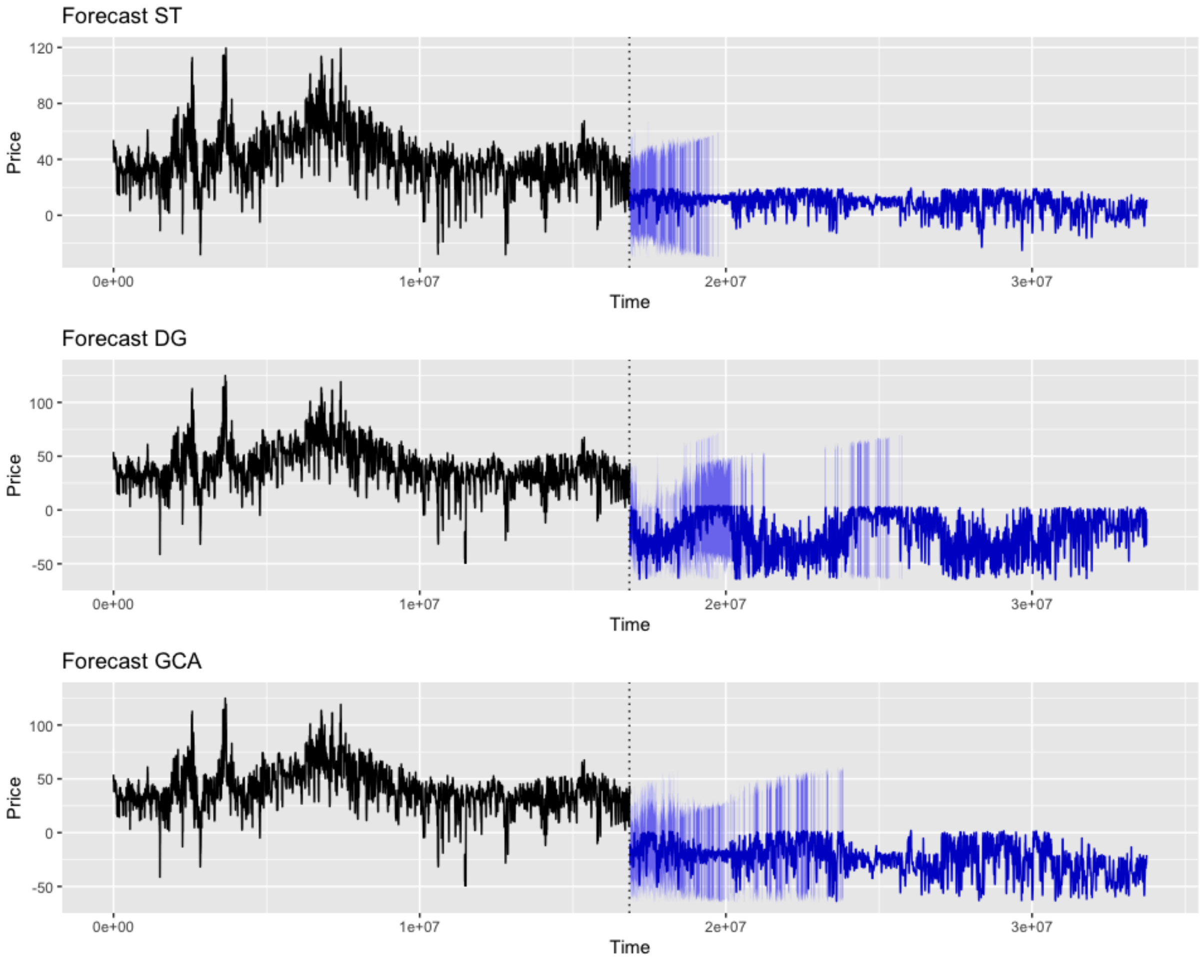


Figure 15: Forecasts of the influence of REs production on prices for each scenario

In the three scenarios prices decrease significantly. The ST projection displays low prices which are sometimes negatives, while the DG and GCA projections display opposite results: negative prices with occasionally positive values. The seasonality in price for the DG scenario is the opposite of the figure 15. It follows our first results display in table 5. The REs production has a negative effect on prices but a positive effect on exports. The GCA outlook is again less sensitive to seasonality but displays some important changes in the future price’s variance. Because the ST scenario encompass less REs in its electricity mix, the price is more stable than the two other scenarios. This projection is even more stable than during the three years analysed.

		Price 2040		
	Price 2020	**ST**	**DG**	**GCA**
Mean	38.96	8.22	-23.54	-24.62

Table 7: Mean of the forecasted price for each scenario

Again, price displays in table 7 between the DG and GCA scenarios is close on average but not in terms of seasonality.

6.6.4 Relation between forecasted variables

As table 5 indicates, when exports increase by 1 MWh, prices decrease by €0.0039. In the two previous subsections, these two variables have been forecasted by the future RE production determined by Elia using the weather data of the three reference years. Based on that, it is possible to run the same ARIMA model with prices as dependent variable and exports as independent variable. **The result of this model is that when exports increase by 1 MWh, prices decrease by €0.013**. This outcome means that by 2040, exports (based on REs) will have three times more impact on prices. In other words, the influence of exports on prices by 2040 will lead to a more volatile price. The consequences of such a result are discussed in the next section with a comparison to the literature review.

7. Conclusion

At first glance, the results seem reasonable. When a significant amount of REs are produced, knowing that conventional power plants' production and load have to remain equal, prices decline.

Let us compare this result to the other studies mentioned in Section 4.7. First, the increase of cross-border transmission lines will enable a better flexibility for European countries, a better management of short-term load variability and a higher amount of RE managed by the grid.

The model run in this thesis demonstrates a stronger negative influence on the price than for the reference years. Normally, if it is more flexible, the result would have been a number larger than -0.0039. However, here it is -0.013, which is more than three times smaller. Based on this outcome, Belgium will not enjoy this higher flexibility. Several parameters other than the model hypothesis might explain this finding. Belgium is geographically situated in a location through which much electricity from the North Sea region is transmitted as well as in the middle of the North-South corridor. Elia forecast more congestion in 2040, and this result can partially explain this future phenomenon.

More RE will be integrated into the grid. This expected outcome is suggested by the fact that the REs capacity will increase, requiring a higher amount of cross-border capacity. However, with a result of -0.013, doubtless more RE will be managed by the grid, although it reveals that the transmission lines capacity foreseen by Elia is not sufficient, especially in the DG scenario which requires more flexibility due to the high amount of solar energy produced. Moreover, these transmission line capacities do not rely on change among scenarios, while REs capacity will increase significantly but differently in the three scenarios. Here, the main purpose of Elia is not only the integration of REs but also concerns economic factors and the company outlook, as when they examine the total welfare which is not encompassed in these scenarios.

Considering the differences between scenarios, the best one for Belgium for having a trade-off between reaching CO_2 reduction targets and getting a fair price for the green energy it sends abroad is the GCA scenario. This scenario foresees a more significant increase in REs capacity than the ST scenario and leads to less variability in prices and exports than the DG scenario.

To build further on this study's findings, it might be interesting to analyse when congestion will occur depending on different scenarios. In the scenarios considered here, there is no congestion and all REs not consumed in Belgium are exported. The case when all lines are at the maximum of the capacity will lead to a greater decrease in price due to the impossibility to send the excess energy abroad and the obligation to consume it.

It is important to recall the assumptions of this research. The model studies three variables and seeks to forecast the influence of one variable on another. Other variables were not considered to avoid hiding the effects of the ones I wanted to study. Therefore, other variables might increase prices or even push them further down. These additional variables could also explain a larger percentage of the final price. For example, load was considered the same as reference years. If one considers an increase in the load due to the electrification of certain sectors, it can be assumed that exports will decrease, while prices will increase which will compensate for the effects of REs.

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