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Influence of thermal plants cycling costs in the economic balance of renewables in Portugal

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I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

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Abstract

The main focus of this work is to evaluate if the cycling costs of the Portuguese thermal plants increased with the escalation of electricity produced from renewable energy sources, particularly variable sources, in the power system over the years, and to frame these costs in the total renewable overcosts. Then, these are compared with the total economic benefits from renewables. The work is important since there is still an argument used in disproval of renewable energies based on the cycling costs, which claims that these are unsupportable. It adds value since there are no previous works evaluating the cycling costs of each thermal plant in the Portuguese power system, and also by doing a quantification of the economic benefits of the renewable energy. Two models were developed for this, one in which evaluation of the cycling costs is done, and another to quantify the economic benefits. The results of these illustrated that the cycling costs represented less than 1% of the total renewable overcosts in the year analysed. It is concluded that the cycling costs did rose between the years analysed but are insignificant when compared both with the total overcosts and economic benefits.

Keywords

Renewable energies, electricity price, LCOE, MIBEL, intermittent renewable energy, cycling costs

Resumo

O principal objetivo deste trabalho é avaliar se os *cycling costs* das centrais térmicas portuguesas aumentaram com a subida de produção de eletricidade a partir de fontes de renováveis ao longo dos anos, particularmente de fontes variáveis, e para enquadrar estes custos no sobrecusto total das renováveis. Estes serão depois comparados com os benefícios económicos totais das energias renováveis. O trabalho é importante, uma vez que ainda há um argumento usado contra as energias renováveis com base no aumento dos custos das centrais térmicas, afirmando que estes são insustentáveis. Este trabalho acrescenta valor uma vez que não existem trabalhos prévios que avaliem os custos extra de cada central térmica no sistema de energia português devido às renováveis, e também quantifica os benefícios económicos da energia renovável. Dois modelos foram desenvolvidos para isso, um no qual a avaliação dos *cycling costs* é feita e outro para quantificar os benefícios económicos das renováveis. Os resultados destes ilustraram que os *cycling costs* representaram menos de 1% dos sobrecustos das renováveis no ano analisado. Conclui-se assim que estes custos aumentaram entre os anos analisados, mas são insignificantes quando comparados com os sobrecustos totais e os benefícios económicos das renováveis.

Palavras-chave

Energias renováveis, preço da eletricidade, LCOE, MIBEL, energia renovável intermitente, custos cíclicos

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List of Acronyms

APREN	Associação Portuguesa de Energias Renováveis
CCGT	Combined Cycle Gas Turbine
EDP	Energias de Portugal
EES	Electrical Energy Storage
ERSE	Entidade Reguladora dos Serviços Energéticos
LACE	Levelized Avoided Cost of Electricity
LCOE	Levelized Cost of Energy
MIBEL	Mercado Ibérico de Electricidade
O&M	Operation and Maintenance
OCGT	Open Cycle Gas Turbine
PPA	Power Purchase Agreement
PV	Photovoltaic
REN	Redes Energéticas Nacionais
RES	Renewable Energy Sources
SSG	Special Status Generators
TSO	Transmission System Operator
VRE	Variable Renewable Energy

Chapter 1

Introduction

The motivations and main purposes of this thesis are presented in this chapter, as well as its structure.

1.1 Motivation and Overview

The world is changing. It is impossible to deny that the pollution and the utilization of natural resources at a fast pace are some of the causes. Portugal, to fulfil the European Commission guidelines for 2030, agreed to commit to ambitious targets. One of these targets is a weight of 31% on final energy consumption in 2020 and 40% in 2030 from renewable energy sources (RES). To do so, it is expected to have 80% of electricity produced by renewable energy sources in 2030. Big investments in technologies have been made in order to improve the generation of electricity by renewable energy sources. Additionally, and due to its favourable climacteric conditions, Portugal is in a good position to make the transition to a power system less dependent on fossil fuels. It is not by chance that in 2016, Portugal was the sixth country in the European Union, ninth in Europe, with more electricity produced from renewable energy sources (57%) [IEAS18].

However, there are still arguments used to discredit these technologies, in favour of more conventional generation units. An argument used to discredit the use of electricity generated by renewable energy sources is that they will involve additional costs which arise in conventional thermal plants due to the intermittence of the wind and photovoltaic technologies. It is claimed that, some years ago, when there were only dispatchable generation units in the system, it was easier to plan the electricity that needed to be produced by each thermal unit. Having this in mind, the planning of a thermal unit could be more precise, reducing some costs. Nowadays, with the inclusion of intermittent technologies, it might become harder to do this planning. On the other hand, the intermittence has always been present in the system, due to the consumption, which varies during each day.

1.2 Objectives

The purpose of this thesis is to evaluate the growth of the cycling costs in the Portuguese thermal units due to the increase of electricity in the power system produced by intermittent technologies, namely wind and photovoltaic, and to frame these extra costs both in the total renewables overcosts and in the economic benefits from these sources. To do so, the thesis will focus on the following objectives:

- Describe and explain the functioning of the Portuguese wholesale electricity market;
- Analyse the evolution of the levelized cost of energy of the different technologies, focusing on renewable energy sources;
- Detail and explain the different cycling costs that thermal plants have;
- Quantify the impact of these costs in the Portuguese power plants;
- Calculate the monetary influence in the electricity wholesale market caused by renewable

energies;

- Frame the cycling costs in the economic benefits of the renewable energies;
- Compare these benefits with the total renewable overcosts;
- Calculate a final balance between the costs and profits.

1.3 Contents

The thesis is divided into six chapters. The first chapter presents the motivations and main purposes of this thesis, as well as its structure.

Chapter two starts by giving a brief description of the evolution of the electricity market and production. Then a contextualization of the European and Portuguese development of electricity production throughout the years is presented in two graphics. Afterwards, the growth of the Portuguese electric sector is discussed, and the chapter finalizes with an explanation about the current electricity market where Portugal is inserted.

In Chapter three, the Levelized Costs of Energy (LCOE) are described, as well as their evolution regarding the different technologies. The main focus will be renewable energy sources, since these were the ones with the biggest decrease in recent years. Then the different cycling costs are presented, emphasising the start-up and ramping costs.

In chapter four, the models created to do the analysis are defined. Two models were created to evaluate different aspects. On the one hand, it was necessary to evaluate what would be the cost of the electricity in the scenario where no energy from renewable sources was integrated into the system. On the other hand, it was required to identify the cycling costs which arise in thermal plants due to the volatility of some technologies, namely wind and photovoltaic RES. Finally, the official Portuguese calculation of all the costs due to renewable energy is presented.

The results and analysis of the models previously showed are presented in chapter five. To frame these results, the chapter starts by describing the conditions in 2010, the reference year, and 2016, an year with similar climacteric conditions. Then, the results from both models are shown, followed by an analysis of the cycling costs, as well as the overcosts. A final balance is presented in this chapter.

Chapter six finalises the thesis, summarising all the work developed for this thesis and highlighting its main conclusions.

Chapter 2

Portuguese Electricity System

The chapter starts by giving a brief description of the evolution of the electricity market and production. Then a contextualization of the European and Portuguese development of electricity production throughout the years is presented in two graphics. Afterwards, the growth of the Portuguese electric sector is discussed, and the chapter finalizes with an explanation about the current electricity market where Portugal is inserted.

2.1 Electricity market evolution

It was in the 19th century that the production, transportation and distribution of energy as an activity appeared, when, in 1882, the first electrical power plant was created in New York with the main function to give power to an electrical public grid. Thus, this plant is considered the beginning of electrical power grids.

The first electrical grids were small, due to their technical limitations, like the generation of continuous current with dynamos. However, the invention both the transformer and the induction machine allowed the mass production of electricity with alternate current. This, along with the technological evolution, permitted the increase of size and power of the electrical grids. Furthermore, for the same reasons, the large exploration of water resources became available, which led to the creation of bigger grids.

Moreover, most European countries had different electrical structures. It was only after the damage caused by World War II and the consequent rebuild of these structures that some countries nationalized and verticalized the electrical grid. After the Second World War, the world's economy was prospering, making it easy to plan and predict the economy, due to few uncertainties in the markets. This was important to the economies of scale, because it was easy to justify over dimensioned constructions, which would be later utilised. In the 70s, the first oil crisis took place in the world, contributing to the destabilization in the economy and leading to a major restructuring in the electrical market.

Up until 1976, Portugal had an electrical system based on the exploitation from private entities. In this year, the Portuguese electrical system was nationalized and reorganized, with the creation of Energias de Portugal (EDP). Some countries adopted a different structure, with different private companies responsible for the areas of production, transportation and distribution. Nevertheless, these companies were not direct competitors, since each one had a different set of clients and area associated.

The crisis, combined with the appearance of new energy production technologies, such as combined cycle cogeneration and the exploitation of renewable energy sources contributed to the reduction of economies of scale.

In the beginning of the decade of 1980, several economic activities related with social services, including the energy sector, began being restructured all over the world. In Europe, that restructuring began in Great Britain, in 1990 and with it, most European countries started to develop their energy systems. The reasons for the restructuring of the market were plenty, mainly as the new supervision and control techniques which the technological development created - and made the grids more reliable - the environmental issues with the utilization of nuclear energy and the importance of RES. More than this, it was necessary to create additional competition and transparency in a market which was vertically integrated and with no competition. As this was a sector which provides a first need service, it was very appealing for investors. One last important factor for the fast restructuring of the energy sector in Europe was the fact that there was already a big grid interconnection between countries, and if one of those countries was able to get a lower energy price due to restructuring, the nergy companies in the adjacent countries' energy companies would apply a big pressure on their governments to do similar restructures.

In Portugal, the privatization of part of EDP led to the division of the sectors of production, transportation and distribution, increasing the market competition. Entidade Reguladora do Sector Energético (ERSE), a regulator office free from industrial and political interests was created with the aim to regulate and create tariffs within the sector. In 2000, EDP was once again reprivatized, and the Portuguese government lost most of its capital.

Nord Pool was the first international market created. This happened in 1996 and, currently, it is the biggest power market in Europe, integrating nine countries: Norway, Sweden, Denmark, Finland, Estonia, Latvia, Lithuania, Germany and the UK [NORD17]. In 2001, Portugal and Spain decided to have a common energy market, creating Mercado Ibérico de Electricidade (MIBEL). However, the market only started functioning in 2007.

2.2 Electricity production

The production habits of electricity have been evolving during the years. The different technologies have all seen their shares being increased during some point in time, with the overall electricity production also increasing to keep up with the growing population. In this sector, the evolution of electricity production in the last decades will be assessed, as well as the Portuguese evolution.

In Europe, from 1990 up until 2008, the electricity production had a constant growth. It was in 2008, when an economical global crisis took place, affecting all sectors across the economy and, thus, provoking low demand, that the production was reduced [InEA10]. Figure 2.1 represents the production of electricity in the European countries by fuel type from 1990 to 2015. It is possible to observe some trends that happened during this period, for each technology:

- Coal's influence in total electricity production has had some decrease over the years. In 1990 it represented 39% of all the electricity production in Europe, and in 2014 it only expressed 25,3%;
- Oil has reduced the production, and nowadays it has almost no influence on the electricity production, representing only 1,82% of total European electricity production;
- Natural gas, on the other hand, had a big increase in the first two decades of analysis, peaking in 2008, when it signified 24,6% of the total production of electricity in Europe. This rise happened partly because of the environmental preoccupations, since coal plants are more harmful then natural gas'. From then, it has seen a decrease in its consumption, in part due to the increase in natural gas price. In 2014, these sources had a share of 15,5% of the total production;
- Nuclear sources of electricity had an increase in the first decade of analysis and remained stable from 2000 up until 2010. From then, it is possible to see a small decrease in the electricity produced from nuclear power plants; however it still represented 27,8% of the electricity produced in 2014;
- Renewable energy had the biggest variation among all the technologies, from 12,7% in 1990 to

29,5% in 2014. Hydro's production remained stable during the last decades. Biofuels have seen their influence on electricity production reduced in recent years, but the biggest part of this variation of electricity produced by renewable energy sources (RESs) is due to wind and solar, together with geothermal energy. As for the share of each RES in this contribution, hydro's generated electricity influence in the total share went down from 94% in 1990 to 44% in 2014, while all the others grew. Wind' influence went from 0% to 27%, and solar from 0% to 11%. Biofuels also grew its influence in electricity production, from 4% to 18% [EuEA17].

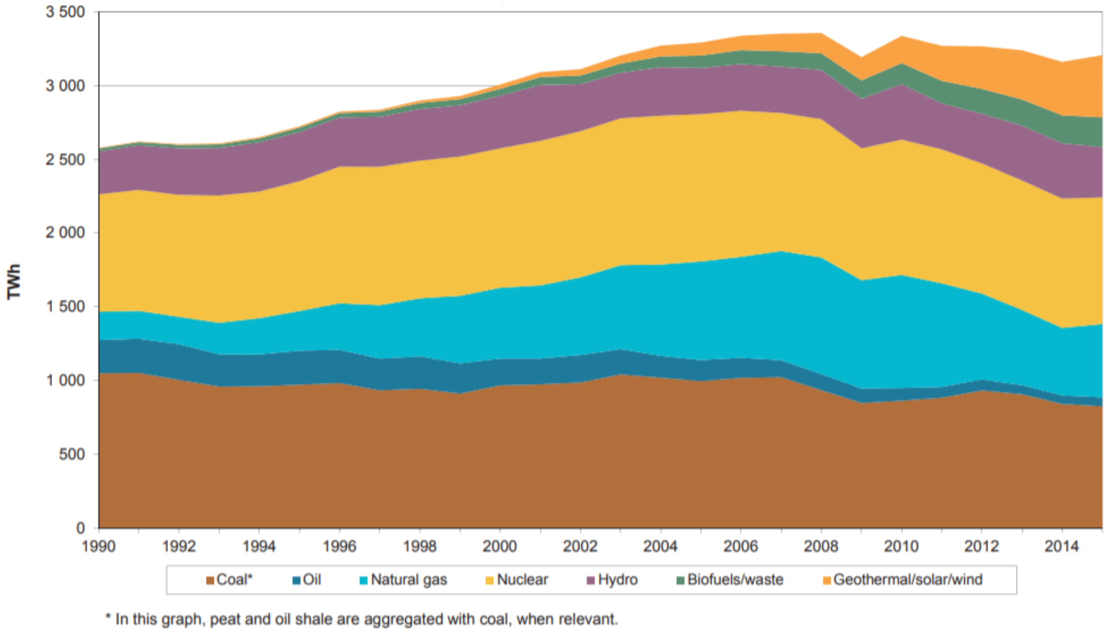


Figure 2.1. Electricity production in Europe 1990-2015 (extracted from [InEA17])

It is important to note that this statistic is for the electricity generation, not for the energy production, which in Portugal, just like in the rest of Europe, has also been having a huge increase in the past decades. The influence of the different technologies in the electricity production has been altered during the years:

- Coal thermal plants' production of electricity started growing in 1985, when Sines thermal plant, with a capacity of 1256 MW started functioning. The production of electricity by coal fuelled thermal plants grew almost every year until 2000. In the years following, it had a stable production, started decreasing in 2006. This decrease continued until 2010. From there, the production has started growing again. This growth in recent years is partly related with the price of coal, which has been decreasing, and natural gas, which is higher and has been increasing. Nonetheless, the two Portuguese coal fuelled thermal plants are expected to be decommissioned until 2025 [RMSA17];
- Electricity production from oil was relevant during many years, until the appearance of coal thermal plants. Together with hydro, it was the only relevant technology regarding the production of electricity. Due to the high prices of the fuel, its usage was deferred by the usage of coal, despite the higher polluting emissions of coal fuelled power plants. In 2010, the last oil-fired thermal plant was decommissioned. Since 2011, oil, as fuel to produce electricity, is mainly used

to start-up coal and natural gas thermal plants [EnDP17];

- Natural gas thermal plants appear in Portugal with the installation of Tapada do Outeiro power plant, which started functioning in 1998 at full capacity. Its usage as a fuel for the production of electricity varies accordingly with the price of the fuel. In recent years, due to the higher production of RES, and as it has a higher fuel price when compared to coal, its usage has been lower, in Portugal.
- Due to the geographical conditions of Portugal, hydro has been used for the production of electricity since always. In 1920, there were already some hydro plants with medium dimensions, like Lindoso, with the capacity of 28 MW. In the decade of 1950, the big hydro plants appeared, like Castelo de Bode plant, which stared functioning in 1951, and has the capacity of 138 MW. This explains why, in the beginning of the decade of 1970, the largest part of electricity production came from hydro. Nowadays, with the increase of other RES, the role of hydro in the Portuguese power system has changed, and the hydro plants with reservoirs are fundamental for a good functioning of the system, due to their capacity to quickly produce energy when other sources fail. The production of electricity by wind technologies starts being explored in the beginning of the 21st century. As it is visible in Figure 2.2, it had the biggest growth since then. More recently, this exploration was also started in PV technologies. In 2015, wind technology produced 11 334 GWh of electricity, and PV produced 755 GWh.

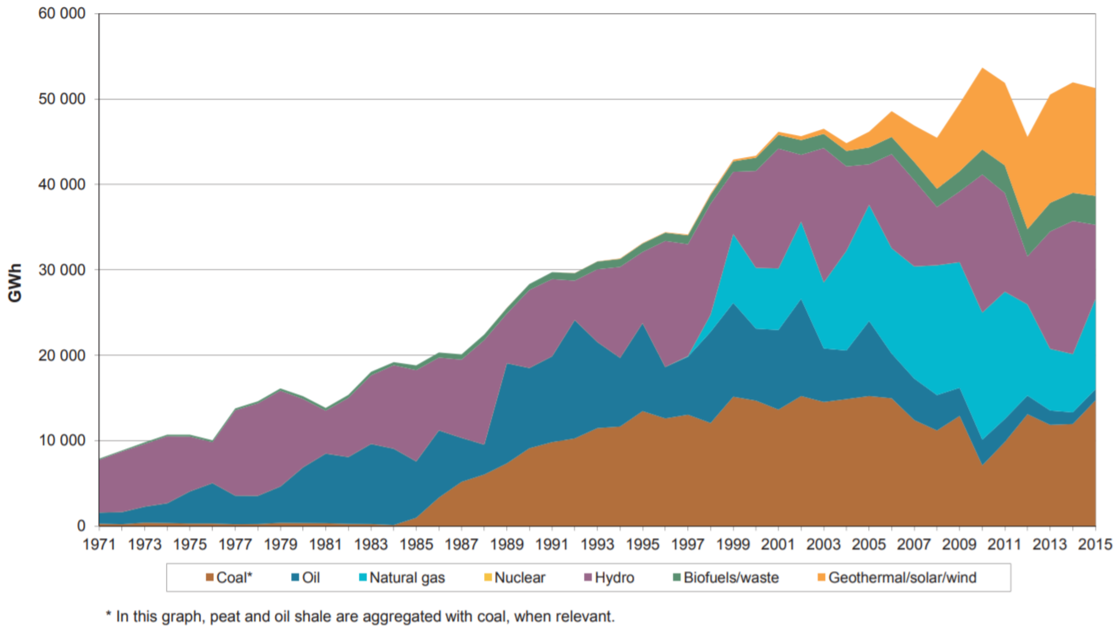


Figure 2.2. Electricity production in Portugal 1970-2015 (extracted from [InEA18])

Portugal, in accordance with the European Union guidelines, has committed to produce 60% of the electricity by RES in 2020 [EuCo18]. However, this goal might be hard to achieve, due to the dependence on the environmental conditions, which vary a lot. For instance, in 2016, 57% of the electricity was produced by RES. However, in 2017, only 40% was produced by these same sources. It is fundamental to continue investing in RES, particularly in photovoltaic (PV) solutions. [CaCr15] identifies a strong negative correlation in the Portugal with the production of energy from wind and solar sources, when annual totals are being studied. This means that both technologies can have a levelling effect in the grid, complementing each other production, during the year, a concern that is being raised with the increase of variable renewable energy in the system.

The future of the production of electricity includes the decarbonation of the Portuguese system. Nowadays, the two coal-fuelled power plants that exist in Portugal are the two most pollutant factories in the country. In 2017, the two were responsible for 17.6% of the CO_2 equivalent emissions by Portuguese factories [Zero18]. The decommissioning of these power plants, scheduled for 2025, is fundamental to the decarbonation of the country. The usage of some fuels emits CO_2 and other toxins to the atmosphere. In order to reduce these emissions, Portugal, in accordance with European Union measures, applies a tax to CO_2 emissions. The tax for CO_2 emissions is 6,85 € per ton of CO_2 [DiRE17]. In Table 2.1, it is possible to understand how much equivalent kilograms of CO_2 are emitted per megawatt hour (MWh) for each fuel type.

Table 2.1. CO_2 emissions (Adapted from [USEI17])

Fuel type	kg CO_2/MWh
Coal (anthracite)	30.41
Coal (bituminous)	27.36
Coal (lignite)	28.66
Coal (subbituminous)	28.51
Diesel fuel and heating oil	21.47
Gasoline (without ethanol)	20.91
Propane	18.48
Natural gas	15.57

The fuel types used in the thermal power plants are coal and natural gas. The prices of both fuels differ a lot, with coal prices being much lower. Thus, power plants fired by coal have a higher utilization than natural gas fired ones. Nonetheless, the two types of coal used in such power plants, anthracite and bituminous, are the two types of coal which emit more CO_2 to the atmosphere.

2.3 Portuguese Electric Sector

The electrification of Portugal began in the end of the XIX century when the big industries started installing small plants for their factories, which were located in the most important cities of Portugal. However, it was only after the First World War that Portugal began developing electricity grids in many cities.

During the XX century, several changes happened in the Portuguese electric system. In 1944, the Portuguese government published a law in which it would have a more interventionist position when regarding this sector. Big power plants, like the hydro power plant Castelo de Bode, were inaugurated after 1950, and the national grid also continued being developed, with bigger voltages being introduced. In April of 1975, the biggest electric companies were nationalized and EDP, as said before, was created the year after [Figu12].

EDP functioned as a verticalized company, with a monopolistic nature, until 1994. However, following different laws, which allowed the appearance of competition in the sector, EDP was divided. Different companies emerged in the areas of transportation, distribution and production. Rede Elétrica Nacional (REN), nowadays named Redes Energéticas Nacionais, was created, and in 1995, ERSE was also created.

After several changes throughout the years, the electric sector is currently divided in six different areas, production, transport, distribution, commercialization, electric market operations and logistics operations, whose function is to intermediate an exchange between sellers by a consumer. Each of these activities usually function independently and must respect the competition principles, in order to maintain and impulse a fair wholesale electricity market.

The production can be divided in two regimes. Ordinary Status Generation (OSG), which includes all the classic non-renewable thermal plants, as well as the big hydro plants, and Special Status Generators (SSG), which are all the producers which use renewable energy sources, except big hydro, and the cogeneration producers. OSG producers sell their energy in a free market regime. As for SSG producers, a special feed-in tariff is paid for the most of these projects, to make them economically interesting, so that Portugal continues its transition to a more environmentally sustainable production of energy. The current SSG are all the small hydro (until 10 MW), biomass and biogas, wind, solar and waves, urban and industrial waste and cogeneration, both renewable and non-renewable. [ERSE18a].

The transport is done exclusively by REN, the Portuguese Transmission System Operator (TSO). REN is responsible for the construction, well-functioning and maintenance of all the transmission lines, which are mostly lines of 400 kV, 220 kV and 150 kV. It is also responsible by the overall well-functioning of the Portuguese electrical system, coordinating all the production and distribution, to secure a reliable and safe system. These activities are sustained by tariffs which are paid by all the consumers. [ERSE18b].

The distribution can be divided into two categories: high and medium voltage, which have lines of 60/130 kV and 6/10/15/30 kV respectively [EDPD18], and the distribution is in charge of by EDP Distribuição; low voltage is responsibility of the cities, however, a big portion of these attributes the concession to EDP Distribuição as well. To maintain the quality, security and reliability of these lines, a tariff is paid by the consumers [Sarm15].

The commercialization sector, in charge of selling the energy to the consumers, functions mostly as a free market. The agents which sell energy will be named suppliers. The consumers in Portugal are free to change their energy supplier at any time. When a supplier operates in the Liberalized Market is considered a Free Supplier, e.g. Endesa, Iberdrola, EDP Comercial. On the other hand, when a supplier functions in the Regulated Market is considered a Last Resource Supplier. These sell their energy at a regulated price, by ERSE, and are obliged to provide service to the following clients [EnDP18]:

- Financially vulnerable clients;
- Clients with a contract under the terms of regulated tariffs or transitory tariffs, defined by ERSE;
- Clients whose energy supplier is no longer allowed to provide their services;
- Clients located in regions where there is no offer from free suppliers.

The feed-in-tariffs, paid to SSG, are also supported by Last Resource Suppliers. Rules are being applied to promote the migration from all the clients to the Free Market by applying a transitory tariff to the clients which are still on the Regulated Market. This migration started in 2013, however some delays have occurred during the process. Current legislation expects the transition to be made until the end of 2020 [ERSE18].

The electric market operations are controlled by the two poles, responsible by the control of the Iberian Electricity Market. The Portuguese pole, OMIP, and the Spanish pole, OMIE. Each has specific tasks, which include the management of day and intraday operations, by OMIE, and the management of the forward market, by OMIP. Figure 2.3 illustrates how the Portuguese Electric Sector is organized.

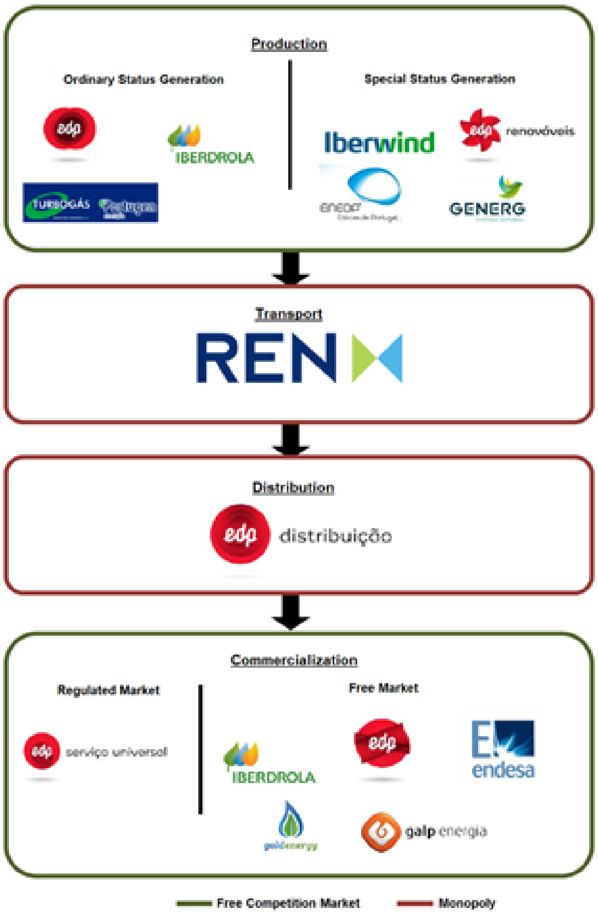


Figure 2.3. Organization of the Portuguese Electric Sector (Extracted from [Sous14])

2.4 Iberian Electricity Market

Just like the electric sector, the Portuguese electricity wholesale market has been being developed for some years. The current energy market operates together with Spain. This market is called Mercado Ibérico de Eletricidade (MIBEL). The negotiations between Portugal and Spain for the creation of MIBEL started in 1998. In 2001, a protocol was signed between the two countries to create MIBEL. In this, both countries agreed that this market would become available in 2003. Different measures and procedures were established to achieve this goal. An improvement os the Iberian grid system was required, meaning that new grid connections between Portugal and Spain were to be created and the ones which already existed were to be improved. REN and Rede Elétrica de España (REE) would cooperate to assure the well-functioning of this market [OMIP17]. These are the Portuguese and Spanish system operators, correspondingly.

In 2003, the first set of rules regarding the commercialization of electricity was approved. More than this, OMIP was created. OMIP is the Portuguese part of OMI, the Iberian market operator. Its purpose is to provide a platform in which the trading of energy can occur. The Spanish market operator, OMIE, already existed. In the following years, several accords were signed, but the market only started to function in July of 2007. This was the culmination of several years of cooperation between the two countries. The delays are part of every big negotiation, especially if different countries are among the negotiations.

The main purposes of MIBEL can be described as followed:

- Allow the consumers to consume energy from both countries;
- Set a reference price for the Iberian Peninsula, to be used in international markets;
- Structure a liberalized market;
- Create benefits for the companies of the sector;
- Create a free access market, with equality for all companies involved, with loyal competition among them.

2.4.1 Structure and Functioning of MIBEL

The liberalization of the energy sector requires trading platforms, independent from the traditional agents in the business of production and transport of energy. MIBEL is one of these platforms, and functions partly with a free market regime, where the producers of energy ensure energy production, and the agents who need to acquire energy buy it from that market. One other part of this market involves long term contracts, future market. Therefore, MIBEL is sustained by a set of categories of contracts which complement each other, controlled by OMIE and OMIP. These categories include:

- A future market, where commitments for selling and acquisition of electricity are established for the future, managed by OMIP;
- A spot market, in which is possible to negotiate energy for the day, make adjustments during the day and negotiate energy for the next day, managed by OMIE;
- A real time operator, which does balance adjustments in both production and consumption of

energy, so that the system is always functional, managed by both countries system operators;

- A bilateral contracting market, in which is possible to buy and sell energies in different timelines;

For the well-functioning of the spot-market, it is necessary to ensure that the grid interconnections between both countries are enough to support the energy flow, which is dictated by the market. If the connections are not enough, there is a market split between both countries and new energy prices are calculated. However, with the constant upgrades to the grid, this situation is not very frequent, nowadays. The price simulations in this thesis were done considering that there was no market split in 2016, for simplification purposes.

Table 2.2 represents the actual grid connections between Portugal and Spain. Whenever market splitting occurs, a tariff is paid, and the money saved by this tariff is used to improve the connections between both countries. In 2006, it was defined between Portugal and Spain that the objective for a sustainable MIBEL would include the increase of the interconnections between the countries until reach a stable minimum interconnection capacity of 3 000 MW in both ways. Nowadays this value is still not obtained, however it is predicted that with the inclusion of a new 400 kV line it will be possible to obtain this minimum capacity value in a sustainable way [ReEN17c].

Table 2.2. Grid connections between Portugal and Spain (Extracted from [ReEN17c])

kV	Transmission Line	Nominal Regime Capacity [MVA]	
		Winter	**Summer**
400	Alto Lindoso – Cartelle 1	1660	1390
	Alto Lindoso – Cartelle 2	1660	1390
	Lagoaça – Aldeadávila	1706	1469
	Falagueira – Cedillo	1663	1400
	Alqueva – Broalves	1386	1280
	Tavira – Puebla de Guzmán	1386	1386
220	Pocinho – Aldeadávila 1	435	374
	Pocinho – Aldeadávila 2	435	374
	Pocinho – Saucelle	430	360
130	Lindoso – Conhas	131	90

The future market is an organized market in which different energy buying and selling contracts are traded, with different timelines (week, month, trimester and year). These contracts can have different characteristics, depending on the needs of the agents, and are defined by OMIP.

Regarding the market price, MIBEL functions with a marginal system, meaning that, theoretically each energy producer sells their energy with the price that cost to produce one extra megawatt of energy (supply curve). This is known as the marginal cost. The offers of all the producers are organised in a price ascending curve. On the other hand, each agent who wants to buy energy also presents a price offer which is the maximum price that the agent is willing to pay for the energy (demand curve). These offers are organised in a descending curve. After this, the market price is defined by the point in which both curves intersect each other, which is the lowest price that guarantees that all the supply is satisfied by the demand [ERSE17a]. Figure 2.4 shows the aggregate supply and demand curves for the first hour of 2017, as well as the price of energy for that hour. As it is possible to understand by the image, the sales (orange line) and purchases (blue line) proposals are ordered by their prices with opposite criteria, the sales in an ascending price ordering, and the purchases with a descending ordering. The point where they match will be the price of energy in that hour. The proposals which were matched are represented in the figure by the red (sales) and beige (purchases) lines. This is a merit order organization.

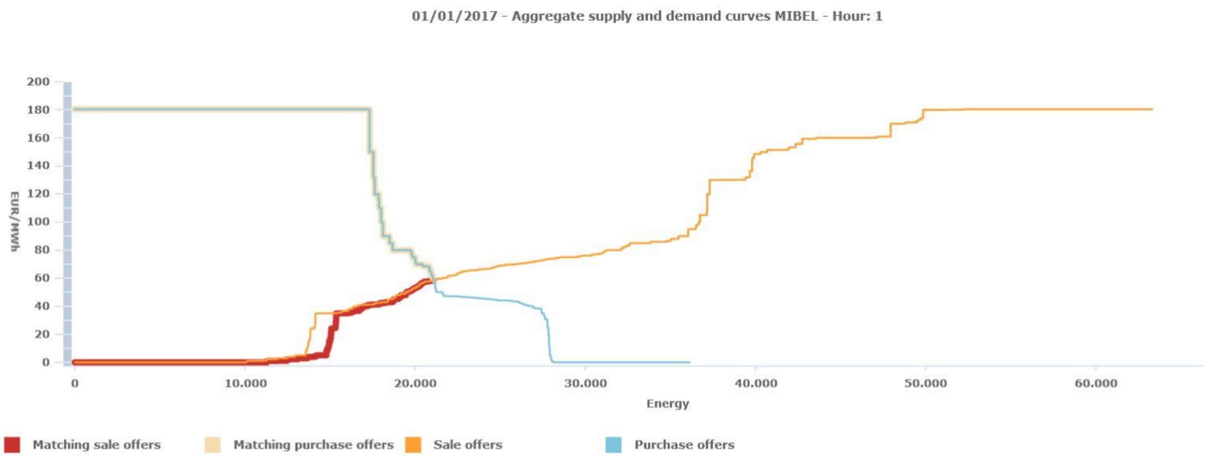


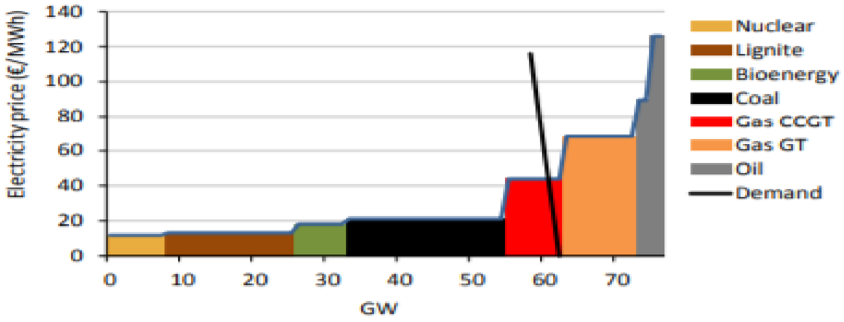
Figure 2.4. Aggregate supply and demand curves 1/1/2017 (Adapted from [OMIE17])

The future market solution started being approached after the energetic crisis in California, in the beginning of the century (2000-2001). This state in the United States started the deregulation of the electric sector in the beginning of the decade of 1990. The gross market was implemented, and all the energy was obliged to be transitioned in this spot market. Companies were created and required to buy the energy in the day-ahead market. After some years of transition, the wholesale prices were varying according with the demand, but the retail prices were regulated. The retail price during this transition was of 6 cent/kWh. The believe was that the deregulation of the market would make the wholesale energy prices to go down due to the competition, and it would allow the retail price to start going down as well, removing the transitory tariff. During this decade, there was no investment in thermal plants, despite the increase in demand. In the summer of 2000, a particularly hot summer, the wholesale prices had a huge increase, over 500% between 1999 and 2000. As the retail price had a fixed price, the final consumer did not notice this increase, not changing their consumption habits. This culminated with several blackouts throughout the state between 2000 and 2001, due to the fear by producers that they would not be paid what they deserved. Moreover, it led to the bankrupt of the electricity wholesalers, which were buy from a spot market, sometimes at more than 50 cents/kWh, but could change the retail price, of around 6 cent/kWh. It was then proved that the bigger producers had been inflating the price, for example, by turning of some generators at peak demand hours. This example shows how fundamental a good regulation for MIBEL and other energy markets is. It can also be concluded that the future contracts can have an important role in the markets, instead of negotiating all the energy at the spot market [ClLu01].

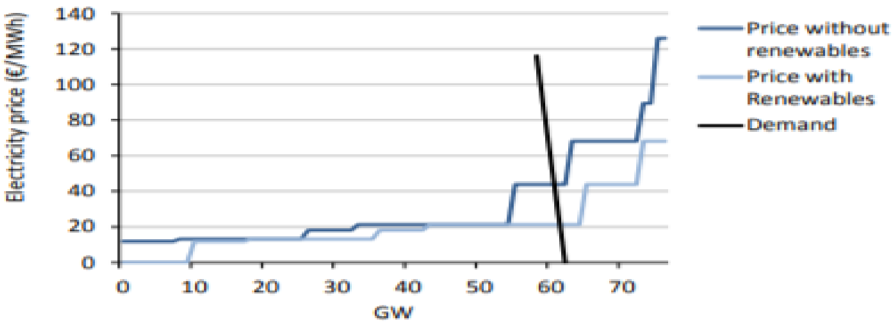
2.4.2 Merit-order effect

The supply curve, known as the merit order, of the available energy sources is organized based on the ascending marginal costs, as explained before. The integration of RES production in the market has shifted this supply curve to the right, due to the near zero marginal costs associated with these technologies [DCGE15]. Figure 2.5a represents a merit order curve without any production from RES on the system. In Figure 2.5b it is possible to understand how the inclusion of renewable energy in a system shifts the merit order curve to the right, decreasing the electricity price.

This electricity price reduction is a fundamental characteristic in renewable energy systems, making them economically viable.



(a) Merit order curve without RES



(b) Merit order curve with RES

Figure 2.5. Merit-order curve (extracted from [Scha13])

2.4.3 Energy tariff deficit

The tariff deficit are the shortfalls in revenues in the electric system, which are created when the tariffs for the regulated components of the retail electricity price are set below the actual costs that the energy companies have [LKMP14]. This has caused a big debt for the Portuguese government, in 2014 it represented a debt of 4 690M€ (3.1% of Gross Domestic Product), as it is presented in Figure 2.6, where the accumulated debt is being presented, as well ERSE's predictions for 2016, 2017 and 2018. The debt emerged due to two main reasons. In 2007 and 2008, a mismatch between the wholesale energy price and the price prediction applied in the tariff. For 2008, the price predicted was 50€/MWh, and the actual average purchase price of electricity was 73€/MWh. This mismatch, caused by the increase of fuel prices as well as a volatile year in the hydropower production, created a big debt. From 2012, the subsidies to energy, both renewable and conventional sources, led to a growing tariff deficit. The subsidies included support under the special regime, to renewable and co-generation sources, and also support for the ordinary regime, like power guarantee incentives and compensation for the early termination of long-term power purchase agreements [InEA16].

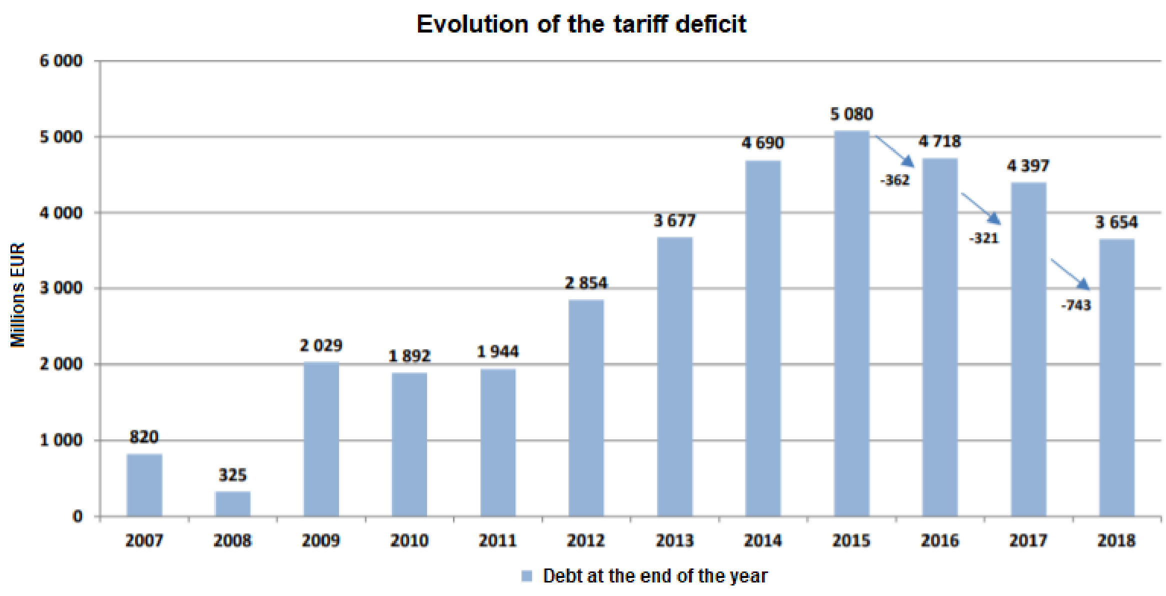


Figure 2.6. Evolution of the tariff deficit in Portugal (Extracted from [ERSE17c])

In recent years, the realization of the big debt that was being accumulated, the government, in accordance with ERSE, created several measures to decrease this debt. These measures were presented in three packages, the first in 2012, the second one in 2013, and the last one in 2014, after the realization that the measures which had already taken place could not be enough for the goals established. These include:

- Revise special tariffs on new renewable contracts;
- Renegotiate feed-in tariffs for wind-power and hydropower generation, as well as the conditions for cogeneration;

- New contributions regarding Sines and Pego coal power plants, applicable for seven years upon the expiry of the current framework;
- Modifications of the remuneration regime for public domain hydro terrains;
- Revise the tariff mechanism applicable to Madeira and Azores regions.
- The establishment of an Iberian natural gas market (MIBGAS);

Currently, there are no special tariffs for any RES technology. The energy produced by the new projects has to be sold either in the spot market or with a contract with a consumer, usually a selling agent. This causes some issues with the financing of new big projects. These are usually financed by banks, which need to have some economical guarantees that the project will be profitable. The spot market gives no guarantees that regarding the price of energy. The contracts with consumers will play an important role in the following years, to allow the continuation of the RES development.

All these measures, combined with some others, are expected to reduce the debt down to 600/700M€ by 2020.

Chapter 3

Power System Costs

This chapter starts by giving a description of the Levelized Costs of Energy (LCOE), and the evolution of the LCOE of the different technologies. Then, the different cycling costs are presented, focusing on start-up costs and ramping costs.

3.1 Levelized Costs of Energy

The integration of power generation originated from variable renewable energy sources has been growing for the last decades in the Portuguese electric system, including the islands of Azores and Madeira. Figure 3.1 presents the growth of installed power in the Portuguese system since 2000. In this year, there were 4832 MW of RES installed. In 2016, this number evolved to 13327, a growth of 275% [APRE17b]. In the beginning of the century, nearly all the installed renewable capacity was through hydro dams. In the first decade of the century there was a huge increase in the wind solutions installed capacity, growing from 83 MW in 2000 to 4 309 MW in 2011. Since 2010 are the photovoltaic solutions which are going through the most notable increase, although this technology still represents a very small share of the total installed capacity. Also, hydro has seen its installed capacity growing during this period, passing from 4 303 MW in 2010 to 6 835 MW at the end of 2016 [APRE18]. In Portugal, geothermal technologies used to produce electricity are present in the islands of Azores. In Madeira islands and in the mainland, there are no electricity production form this source of energy. As for fossil fuelled thermal plants, their capacity increased up until 2011, and started decreasing from that year.

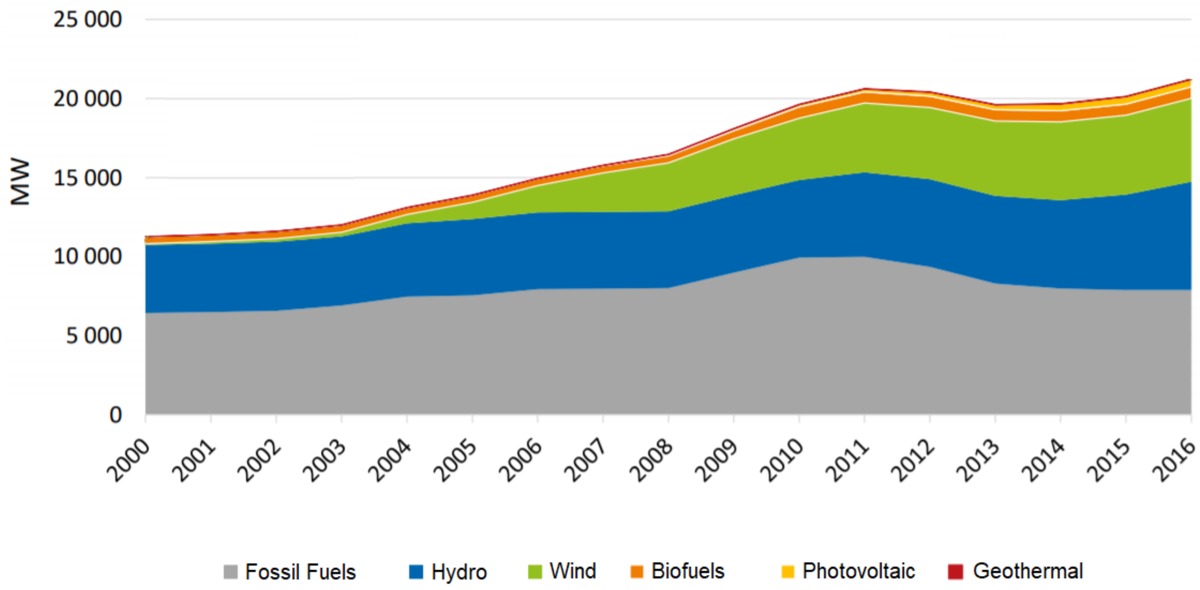


Figure 3.1. Installed capacity evolution (Extracted from [APRE17b])

The increase in the installed capacity of wind and most recently photovoltaic solutions is related with different factors, like the government incentives and the increased concern about the environment sustainability. However, one of the most decisive factors was the decrease in price of these technologies. The most common metric to compare the costs of the different technologies will be approached.

Due to the increase on RES in the system, it is important to do a correct economical assessment of the different technologies. Despite the many social benefits that the RES bring to a country, and to the environment, they will only be used if it is economically valuable. The Levelized Costs of Energy (LCOE) are a metric that is usually used to assess the economic value of a power generating technology and compare between technologies. LCOE can be described as the full life cycle costs, both fixed and variable, of a power generation technology per unit of electricity, €/MWh [UHLE13] and can be calculated as presented in equation 1.1.

$$LCOE = \frac{\sum(CAPEX_t + O\&M_t + FC_t + EC_t)\ (1+r)^{-t}}{\sum MWh_t\ \ (1+r)^{-t}} \qquad (1.1)$$

$CAPEX_t$ = Capital expenditures in year t

$O\&M_t$ = Fixed operation and maintenance costs in year t

FC_t = Fuel costs in year t, when applied

EC_t = Environmental costs in year t, when applied

MWh_t = Electricity produced in MWh in year t

$(1+r)^{-t}$ = Discount factor for year t

Fundamental inputs to calculate LCOE usually include all the financial and capital costs on the fixed costs hand, and variable operation and maintenance costs (O&M) and fuel and environmental costs on the variable costs side. A utilisation rate can also be used, particular for each plant type [USEI18]. In Figure 3.2 it is possible to see the evolution of LCOE of different technologies in the last eight years. This figure reflects the global cost decline/increase of the different technologies. The Utility Scale Solar reflects the mean between fixed-tilt and single-axis tracking crystalline photovoltaic (PV) installations, two of the most common technologies for PV installations. In fixed-tilt technology, PV panels do not have any movement, are fixed. On the other hand, tracking technology PV panels can “follow” the sun during the day, representing an increase between 15-30% regarding energy production. It is precisely in this type of technology where the biggest decrease of LCOE is verified. In the past eight years, the LCOE of PV panels has decreased more than 700%, representing an average annual decrease of 89%. Also, wind LCOE has had a decrease of 300% during this period. These two technologies represent the lower LCOE currently, according to [Laza17]. On the other hand, thermal plants did not have any big changes in their respective LCOE during these years. Coal technology had a decrease of 9% in the period of analysis, while Combined Cycle Gas Turbine (CCGT) decreased 38%.

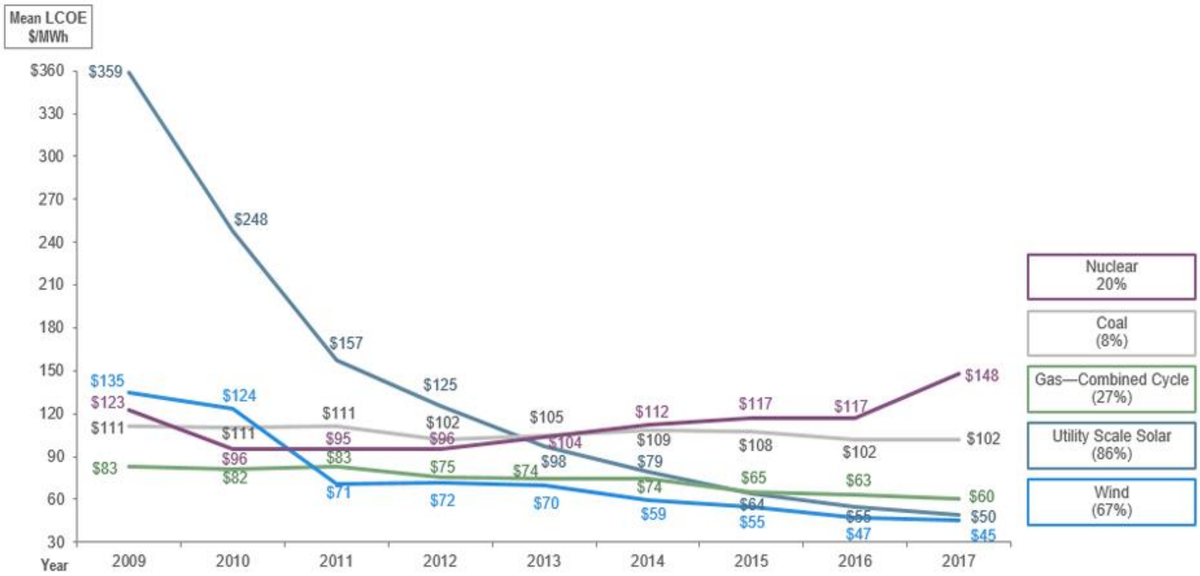


Figure 3.2. LCOE evolution of different technologies (2017 USD) (Adapted from [Laza18])

In Table 3.1, it is possible to see the LCOE of the different technologies relevant for the Portuguese system, from 2010 to 2017. These values are based on a different study, [IREN18], but present the same trend as in Figure 2.1Figure 3.2, with PV technology LCOE decreasing a lot and wind also having some decrease. Hydro technology presents the lowest LCOE, although slightly higher in 2017, and biomass LCOE have no changes during these years. The fossil fuels thermal plants LCOE range varies between 50$/MWh and 170$/MWh. Despite the tendency in both studies to be the same, with the LCOE of RES to be approached from fossil fuel thermal plants, the some of the LCOE values are different, specially PV LCOE. This might be due to the fact that [Laza18] study primarily reflects to North American alternative energy landscape, while [IREN18] calculations are based on data over 170 different countries.

Table 3.1. LCOE values in 2010 and 2017 (2016 USD $/MWh) (Adapted from [IREN18])

Biomass		Hydro		Solar PV		Offshore Wind		Onshore Wind	
2010	**2017**	**2010**	**2017**	**2010**	**2017**	**2010**	**2017**	**2010**	**2017**
70	70	40	50	360	100	80	60	170	140

Despite the favourable appreciation of RES by LCOE, this measurement has some failures, particularly when evaluating this type of plants. [Laza18], [HSSD17] refer several conditionings which are not taken into account by their calculations of LCOE, such as:

- Capacity value vs system value: the capacity of RES production to meet the demand reliably [NREL12] vs the non-assessed benefits that installing a plant in a particular location can bring;
- Permitting or other development costs;

- The costs required to integrate the energy produced by a new plant, named integration costs;
- Environmental regulation costs;
- Environmental externalities, such as long-term residual consequences of thermal plants, like the environmental impacts;
- System value. LCOE does not allow one to assess the system value of a RES plant, like the environmental benefits, or the benefits for the society where it is installed;

The integration costs are frequently mentioned when the LCOE failures are addressed, however these have slightly different definitions, although the overall meaning is similar. [MKHK13] defines integration costs as the extra costs in which a power system incurs when an unusual resource in integrated. [MEHK11] refers to integration costs as the costs which arise when wind and PV generation are added to the system.

Decomposing the integration costs, three components usually stand out [UHLE13], [HiUE15], [BiML13]:

- Grid costs arise from the location-specific characteristic of RES, meaning that it is costly to create conditions for the power transmission, in case the plant is located far from a load centre. The best locations for Variable Renewable Energies (VRE) are usually in places without a lot of demand, meaning that the system grid in these locations is not prepared to big injections of power;
- The uncertainty of RES can create balancing costs, due to forecast errors and intra-day adjustments, since energy produced by these, specially VRE sources, cannot be dispatchable. Overall, solar predictions are accurate during the day, due to the well understanding of the sun movement. However, sudden clouds can appear, and create some changes, and consequently costs. Wind, on the other hand, is less predictable, but it is still possible to identify daily and season patterns;
- The VRE sources create the need to have back-ups, due to its low capacity value, creating adequacy costs. System operators need to ensure the capacity of the grid to absorb any quick changes that might occur. More than this, in times of high VRE production, it might be necessary to shut down fossil-fuelled thermal plants. This creates cycling costs in these plants.

Studies have also been done to try to mitigate these problems. [BiML13] presents a list of solutions for these problems, some of them described below:

- The improvement of forecasts can reduce the adequacy costs. It proposes the improvement of day-ahead forecasts, as well as short-term forecasts. As for wind forecast, studies show that the improvement of forecast technologies reduce the costs due to forecast errors. As for solar, it is an area in development, since the biggest predictability of this natural resource;
- Faster dispatches of energy, which helps to management the variability of renewable generation. Historically, generators have been working with hourly predictions. If this period gets shortened, it makes easier the load following from these units. In Portugal, the high presence of hydro plants helps in these situations where just some peak load is needed in the system. Due to the fast functioning of hydro generators, it is easier to balance a grid with hydro technology.

[USEI18] presents a Levelized Avoided Cost of Electricity (LACE) as a complementary metric to LCOE. LACE measures how much would cost to the grid to generate the electricity which will be displaced by a new project. It provides a measure for the annual economic value of a candidate project. This avoided cost is then summed over its financial lifetime and then a conversion to a level annualized value occurs, by dividing it by the average annual output, developing LACE. This value can then be compared with LCOE, to understand if the project's value exceeds its costs when various technologies are available to meet the load.

Another technology frequently mentioned to reduce the variability induced on the grid by wind and solar technologies is the electrical energy storage (EES). There are many possible applications for this technology. According to the [CCYT09], EES can be the solution for some of the major problems of the grids. It would allow a lower dependency on fossil fuels, and consequently not being exposed to their price volatility. It would also allow the thermal plants to not need to function as peak-demand units. This would reduce their costs. Storage near VRE production would allow the decongestion of the grid in times of high production of these units, and at the same time it would provide a constant source of back-up electricity, improving the grid security. All these would help the improving of the power quality at the customer-side. The increase of VRE in the systems only reinforces the impact that EES could have on an energy system. There are different types of technologies to store energy, as Figure 3.3 illustrates, however pumped hydro energy storage is one of the few economically viable methods to store large amounts of electricity. In Portugal, around 2 437 MW of hydro pumps were installed in 2016. This technology uses gravity to store energy, pumping water uphill, ideally using the excess of energy that is being produced by VRE sources. The water is stored in reservoirs and it is released downhill when needed [AnWa16]. Other types of storage, like batteries, have been being investigated in the recent years, which highlights the importance of EES for the future well-functioning of the energy systems.

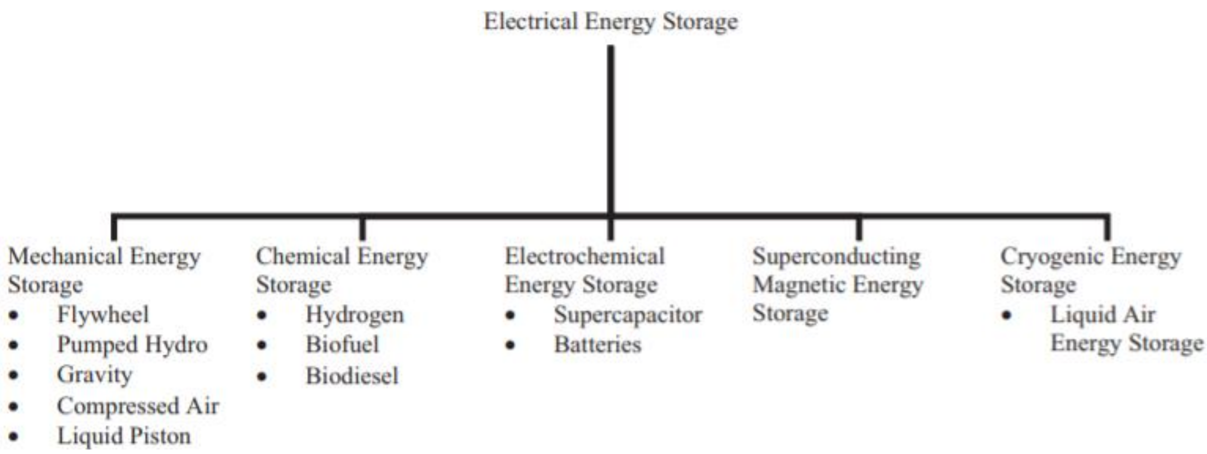


Figure 3.3. EES types and technologies

Concluding, LCOE evolution in the last years has shown a big decrease in the costs of renewable energy technologies, particularly wind and solar, making them as attractive as thermal plants in a cost perspective. However, this is an incomplete method to evaluate the total costs and benefits of renewable energy solutions, since it does not take in consideration some of the costs and benefits of RES. The adequacy costs, costs of a constant need to have a back-up in case solar or wind technologies fail due to fast climacteric changes, provokes costs in thermal plants. These can be mitigated by EES, but still need to be accounted for.

3.2 Cycling Costs

Adding more variability and unpredictability to a power system causes thermal units to have more start-ups, ramping and periods of operation at low load levels. These are considered cycling costs [TrDO10]. In this section, different definitions of cycling costs will be presented. These costs will be included in the model created in this thesis and, as such, they will be further discussed in the next chapter.

Due to the non-dispatchable properties of wind and photovoltaic technologies, these have priority in MIBEL, since this functions as a merit-order effect market. With the development of these technologies, their integration in the Portuguese energy system has been increasing throughout the years. This is one of the factors which has been forcing base-load units to operate in ways which they were not planned to work, having to deliver high variable outputs to meet the load at every instant. For instance, when wind power becomes available, the most expensive thermal units available need to slow down their production, and eventually be turned off. The deregulation of the electricity market is another factor which contributes for the cycling of the thermal units. The units were forced to be more flexible to remain profitable. In a competitive environment, a unit with more flexibility has more opportunities to increase profits [TrDO08] and [TrDO10]. Therefore, fossil fueled power plants, which were designed to be baseload units, have to work more as load following units.

The costs carried by the thermal plants due to the new ways of functioning that these are being subjected to will be explained. The costs of starting a unit are the more significative, however these are not the only ones which need to be taken into consideration.

3.2.1 Start-up costs

The biggest portion of cycling costs in thermal units are the start-up costs. In some analysis on the matter, other costs are even despicable, accounting only start-up costs [TrDO08], [ScPG17]. Generally, older thermal plants were designed to have non-cyclical baseload operations, with few start-ups per year. In Portugal, the same happened. The coal plant located in Sines dates from 1985, while the one in Pego dates from 1998. When these were installed, there was almost no power from VRE sources in the grid. With the appearance of new sources of energy, the system had to be adapted. To start-up a thermal plant, it is necessary to heat all its components, therefore all the energy spent until the components are in the proper conditions is only for internal usage, with no production for the grid. These components are represented in Figure 3.4. In the boiler, the fuel is burned, to provide thermal energy.

Then, this energy (usually gas or steam at high temperature and pressure) converts to mechanical energy by torque on a shaft. The mechanical energy is then converted into electricity by electromagnetic induction, with the remaining thermal energy being released to the atmosphere through a cooling tower [Agor17].

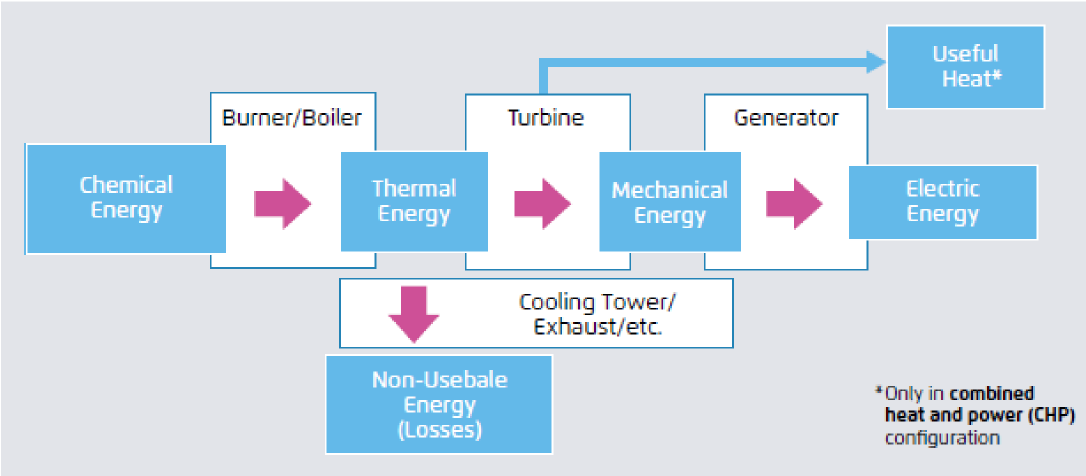


Figure 3.4. Typical components of a thermal plant (Extracted from [Agor17])

More than this, usually, when a power plant is started, it needs to be started until producing a minimum load, which differs between plants and technologies.

To start-up a unit, the Portuguese plants usually have fuel oil burners, which are used to start-up the boilers and steam generators [EnDP17], [AgPA07]. To start the fuel oil circuit, propane gas is utilized. The temperatures are then risen until the desired values are reached, and the steam generators start producing.

Also due to this, the start-ups of coal thermal plants can be defined in three different categories, which slightly vary between different authors [Agor17]:

- Hot start-up, when a plant has been without functioning at eight or less hours;
- Warm start-up, when a plant has not been working between eight and forty-eight hours;
- Cold start-up, when a plant has not been working over forty-eight hours.

CCGT thermal units' start-ups can have the same range of hours to distinguish between start-up times [Agor17]. However, in some studies these vary more. [HeBD17] refers to warm start-ups as start-ups in which the units have been offline between 8 and 50 hours, while in [LiSa12] hot start-ups are defined when the thermal unit is offline for 7 or less hours, and it is considered a cold start-up when a unit is offline for more than 17.5 hours. Usually, the colder the start-up is, the bigger the strain that the unit is subjected to. Table 3.2 presents a comparison with the different technologies regarding their flexibility. Coal-fired plants take the longest time to reach their minimum output, despite having the lower minimum load. CCGT power plants are faster than coal plants. In Portugal, there are no Open Cycle Gas Turbine

(OCGT) plants, however this reveal to be the faster technology for both starting up and ramping.

Table 3.2. Flexibility of different technologies (Extracted from [Agor17])

Property	OCGT	CCGT	Hard coal-fired power plant
Minimum load [% P_{Nom}]	40-50	40-50	25-40
Average ramp rate [% P_{Nom} per min]	8-12	2-4	1.5-4
Hot-start-up time [min] or [h]	5-11 min	60-90 min	2.5-3 h
Cold start-up time [min] or [h]	5-11 min	3-4 h	5-10 h

In [Pere12], it was conducted a study regarding the start-up times of Lares CCGT thermal plant. It concluded that the temperature of the steam turbines metal directly influences the start-up times, and the duration of stops do not have a direct influence. More than this, the real start-up times are bigger than the theoretical ones, due to the synchronisation until minimum output. Table 3.3 describes the start-up times up until the technical minimum output power, according with the temperature of the steam turbines metal. These values are in the same range as the ones presented in Table 3.2.

Table 3.3. Lares CCGT thermal plant real start-up times (Adapted from [Pere12])

State	Temperature [ºC]	Duration until producing minimum output (200MW) [h]
Hot	>500	01:22
Warm	>400	02:07
	<400	03:00
Cold	>204	03:45
	<204	04:30

When comparing the start-up costs between the two, CCGT start-up costs reveal to be higher in most of the bibliography revised. Due to the higher cost of natural gas when compared to coal, the start-up costs tend to be higher. However, because of the faster start-ups and ramping, these are more often used as mid-merit units. In Figure 3.5, it is possible to understand the differences between the start-up and ramping of the different technologies, in accordance with what was presented in Table 3.2. It is important to mention that nor the Portuguese CCGT units nor the coal-fired units are considered to be state-of-the-art units, as the ones referred to in the figure. This means that the start-up times and ramping rates of Portuguese coal units are lower than those presented. More than this, these are theoretical curves. The real units can take much longer to start-up. This figure is only as a comparison between technologies. As it is possible to infer, the start-up of CCGT units is faster than coal ones, so these are more adaptable to the demand quick changes.

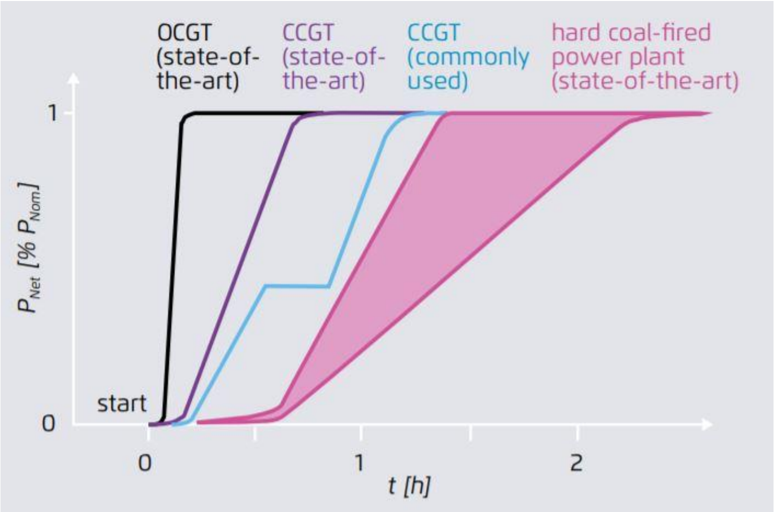


Figure 3.5. Start-up and ramping times of the different technologies (Extracted from [Agor17])

The extra need of fuel to start a plant, the maintenance required due to the wear and tear of the components, and the costs with staff necessary to be on the plant when a start-up or shut down occur, all need to be taken in consideration when mentioning start-up costs.

3.2.2 Ramping costs

The start-up costs occupy the biggest porting of the cycling costs. However, these are not the only costs that should be taken into consideration. The bigger variability on the load due to the integration of VRE leads the thermal plants to have to do quicker adjustments the follow the load. The ramp rate describes how fast a power plant can change its net power during the operation. Figure 3.6 highlights the ramp rate of a power plant load curve.

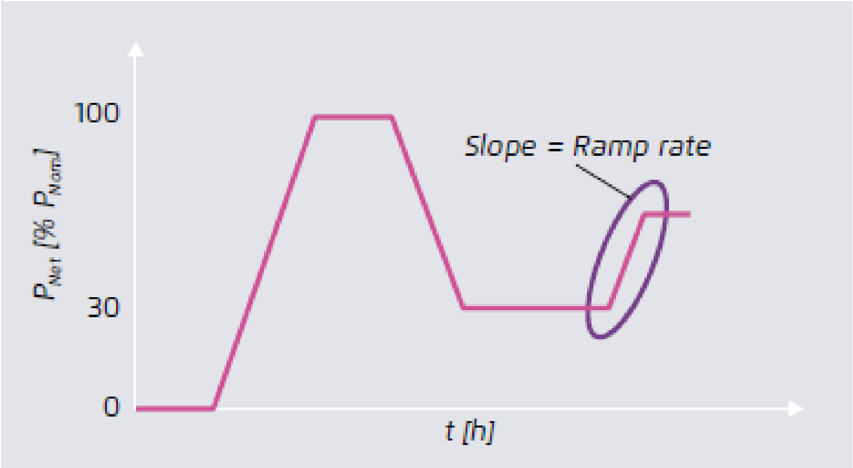
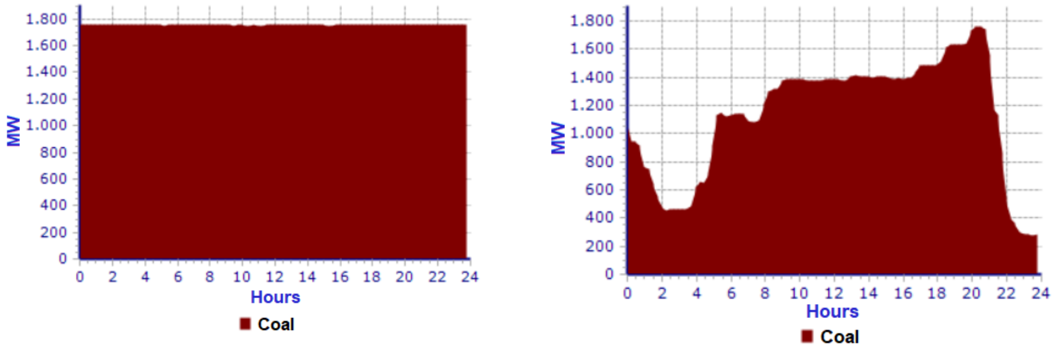


Figure 3.6. Ramp rate (Extracted from [Agor17])

The integration of power injected from VRE sources has forced thermal plants to haver faster ramp rates, to maintain the well-functioning of the grid, incurring in ramping costs. The variation of production leads to a quicker wear and tear of the components of the plants. Likewise, the operation and maintenance costs increase, to maintain the components of the thermal plants functional. In Figure 3.7, it is possible to observe the thermal production in two different days of coal power plants in Portugal. In Figure 3.7 (a) it is possible to infer that the coal production had nearly no alterations during the day, with almost any ramping costs. On the other hand, when analysing Figure 3.7 (b), it is understandable that, in this day, the production of energy from the coal power plants had a lot of ramp-ups and ramp-downs, some of them with a big ramp rate. This probably led to higher ramping costs in this day.

The extra O&M costs that arise from the higher ramping rates, as well as the extra fuel needed for these, need to be taken into consideration in the ramping costs.



(a) Low ramping costs (b) High ramping costs

Figure 3.7. Thermal production in two different days (Extracted from [ReEN17b])

3.2.3 Other costs

The two costs mentioned above are the most consensual cycling costs within the bibliography analysed. However, more costs are mentioned in some studies on the topic, and are relevant for this thesis. Both the start-ups and the ramping of the units lead to the quicker fatigue of the plants' components, as well as in their lifetime. The lifetime of a power plant depends upon other factors, but high load changes (above 50% of nominal power, e.g. passing from 40% to 100%) and cold start-ups are considered to put a lot of stress in some components of the thermal plants, decreasing their lifetimes. A thermal plant in Germany was modelled with a base-load mode and a dynamic operation mode, 50 more starts per year and a ramp-rate two times higher than at baseload operation. The accumulated annual lifetime consumption of the plant functioning as baseload increased 0.4% per year, while the dynamic operational plant increased the accumulated life-time consumption in 3.24%. However, this was only a model. The real plant would have frequent check-ups and maintenance to extend this lifetime [Agor17]. It is hard to put the lifetime consumption in monetary terms, since it depends in many factors which are hard to predict, like the future maintenance, repair strategies, future profits, etc.

In the same way, this leads to a decrease in their efficiency. The plants are planned for a certain utilisation rate, and, with extra start-ups and load following cycles, these components decrease their efficiency in ways which were not predicted when the units were projected. This is another cost which needs to be taken into consideration, although it is again hard to evaluate financially the decrease in efficiency of a component in a unit [BeDe15].

Chapter 4

Models Overview

This chapter describes the models created to do the simulations. Two models were created, to evaluate different aspects. On the one hand, it was necessary to evaluate how much would the energy cost if no energy from renewable sources was integrated into the system – the model for this is described in section 4.1; on the other hand, it was needed to have a model to identify the cycling costs which arise in thermal plants due to the volatility of some technologies, namely wind and photovoltaic RES – this is described in section 4.2. Finally, the official Portuguese calculation, developed by ERSE, of all the costs due to renewable energy is presented. These are used to frame the cycling costs in the total renewable overcosts.

4.1 RES production influence on the wholesale electricity price

In order to change the electric system to a cleaner but sustainable system, the RES solutions need to be economically viable. Wind and PV technologies are becoming each time more economically viable in a LCOE perspective. Yet, more than this, it is necessary to assess the reduction of the electricity price due to the merit-order effect caused by RES. In thus section, it is provided an explanation of the model used to calculate the wholesale electricity price reduction due to renewable energy, i.e., the reduction of the electricity price negotiated at MIBEL due to RES technologies, particularly wind and solar. This electricity price reduction will be addressed here as savings. To evaluate the savings due to RES in the Portuguese system a model was created. REN load diagrams [ReEN17b] have the information about the energy production of each technology. In Figure 4.1, an example of those Load Diagrams is presented, for the two first hours of 2016.

	DIAGRAMA DE CARGAS / LOAD DIAGRAM 2016 [MW]													
Date and hour	Coal	Fuel Oil	Natural Gas	Reservoirs	Run of River	Imports	Exports	SSG Hydro	SSG Thermal	SSG Wind	SSG Photovoltaic	SSG Wave	Pumping	Load Demand
2016-01-01 00:00	1179,6	0,0	498,0	78,4	433,8	0,0	275,2	143,5	681,4	1864,9	0,0	0,0	0,0	4571,6
2016-01-01 00:15	1179,6	0,0	407,6	138,4	448,0	0,0	266,9	140,9	656,1	1876,0	0,0	0,0	0,0	4546,9
2016-01-01 00:30	1179,2	0,0	244,0	296,7	442,7	0,0	260,6	139,5	657,5	1853,9	0,0	0,0	0,0	4523,5
2016-01-01 00:45	1181,6	0,0	214,4	295,9	421,6	0,0	255,0	139,3	656,4	1881,5	0,0	0,0	0,0	4504,8
2016-01-01 01:00	1180,0	0,0	240,8	106,2	305,6	0,0	71,3	135,5	658,4	1951,6	0,0	0,0	0,0	4475,7
2016-01-01 01:15	1178,8	0,0	196,0	114,3	213,4	0,0	132,1	137,6	663,1	2083,7	0,0	0,0	0,0	4424,0
2016-01-01 01:30	1180,0	0,0	51,2	100,8	215,0	0,0	100,1	137,5	661,3	2232,8	0,0	0,0	85,5	4362,6
2016-01-01 01:45	1181,2	0,0	0,0	97,5	214,1	0,0	115,7	136,7	660,0	2256,1	0,0	0,0	93,5	4296,0

Figure 4.1. Load Diagram (Adapted from [ReEN17b]).

As shown, all the technologies' generation is available in these Excel files. The technologies considered as renewable energy production are:

- Reservoirs;
- Run of River;
- Special Status of Generation (SSG) Hydro;
- SSG Wind;
- SSG Photovoltaic.

Reservoirs and Run of River are both big hydro plants. The difference between them is the ability to store water. As it sounds, reservoirs can store the water, i.e., it is possible to control when the generators produce electricity, meaning that the energy is dispatchable, while run of river technology has a little capacity of storing water [MTGL14]. Because both types of production of energy exist in the Portuguese electricity system for many years now, big hydro plants were not considered in the model created to evaluate the savings.

The SSG technologies benefit from a special tariff paid by the government to buy their energy. The thermal SSG plants include plants which produce energy from biomass fuel and cogeneration technology. The cogeneration technology, in turn, is a technology which, usually, utilizes natural gas has a source of energy. Therefore, and as it was not possible to distinguish the cogeneration production from biomass production, this technology was not considered to the study, since natural gas is not a renewable energy source. Waves energy was not also included in the study because there was still no energy in the Portuguese system produced by it in the years studied.

The hydro SSG, small hydro plants, despite not being considered as dispatchable sources of energy, might also have some capacity to storage water. Once again, as it was not possible to distinguish between the plants with and without storage capacities, and as energy from this technology only represents a small part of the production, it was not considered for the savings model.

As for non-renewable energy producers, the following exist in the Portuguese system:

- Coal;
- Natural gas;

To evaluate the electricity wholesale price without RES, the model developed simulates the electricity wholesale prices of the Portuguese system without the presence of wind and PV technologies. The whole process to the development of this model will now be explained, from the beginning, where hydro technologies were also considered, until the final model, where only wind and PV technologies were considered. Thermal SSG were excluded since the beginning since it was not possible to distinguish between biomass generation and cogeneration.

The load diagrams of the different technologies, Figure 4.1, are presented in fifteen minutes periods. To do a match with price data regarding the electricity prices negotiated at MIBEL, available by OMIE [OMIE17], it was necessary to do the hourly averages of the production, since these electricity prices are presented on an hourly basis. Figure 4.2 presents the total hourly production of electricity from the Portuguese RES during the year of 2016 (hydro, solar and wind, further referred as RES).

As it is possible to infer from the contour of Figure 4.2 (light blue), there were big variations in the production of electricity by RES in 2016. In this year, the hour with more RES production had 8954 MW of power injected into the system by RES, on the 13th of February. On the other hand, the hour with least power injected into the system by RES had only 167,6 MW injected, on the 31st of December.

Furthermore, in order to accomplish a better analysis of the information provided by the graph, the production was organized in a different perspective. The hourly production was organized as an accumulated diagram, starting in the hour with more RES production in 2016, until the hour with less production, as presented in Figure 4.3.

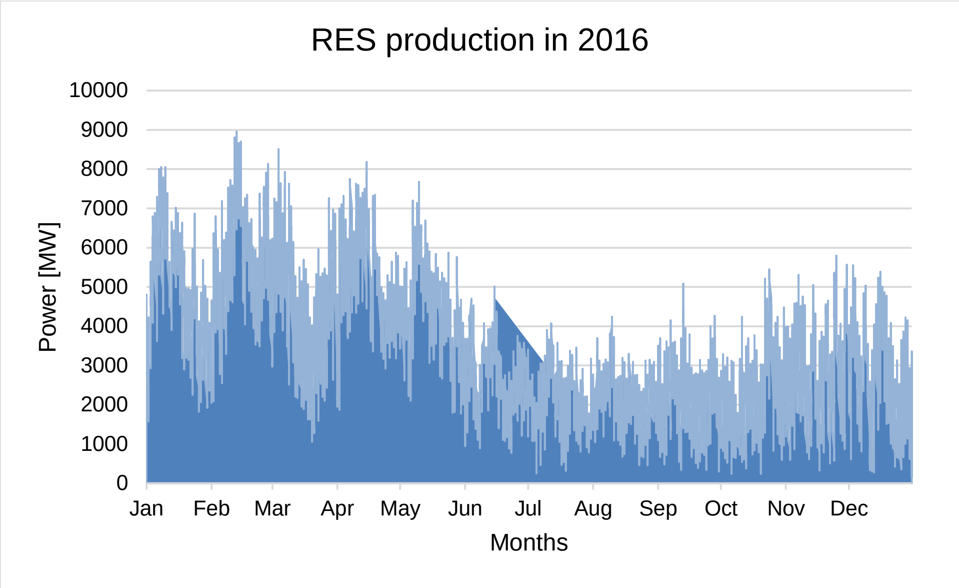


Figure 4.2. RES production in 2016

It is important to mention that this was a leap year, so there were 8784 hours during the year. As said before, the hour with more power from RES on the system had 8 954 MW of power and it will be referred to as X=1; the hour with least power, X=8784, had only 167 MW.

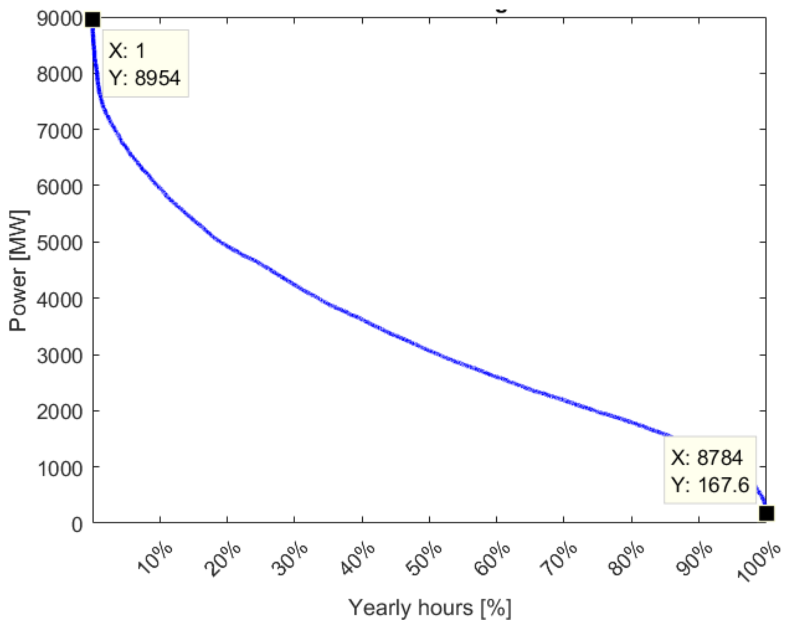


Figure 4.3. Load Duration Diagram 2016

After organizing the production in an accumulated load diagram, the hour referring to each of the power productions was identified, i.e., X=1 corresponds to a production of 8954 MW, X=2 corresponds to a production of 8950 W and so on. To know the hours in which the values of production were obtained, a match was done making use of Excel. After identifying the production corresponding to each hour, the electricity price in that hour was used. In Table 4.1 it is presented all the information for the five hours with more and less RES production, in 2016. X and Y correspond to the xx axis and yy axis of Figure 4.3, being that Y is the power output. As it was expected, the hours with more power from RES have lower electricity prices than the hours with less RES' production.

Table 4.1. Hour match with MIBEL price

X	Power output (Y) [MW]	Hour of the year	Month	Day	Hour of the day	MIBEL price [€/MWh]
1	8 953.8	1052	Feb	13	20	27.51
2	8 950.8	1053	Feb	13	21	29.06
3	8 808.1	1027	Feb	12	19	36.95
4	8 749.8	1029	Feb	12	21	41.07
5	8 744.7	1028	Feb	12	20	41.38
8780	238.5	7035	Oct	20	3	63.46
8781	237.9	6699	Oct	6	3	60.10
8782	235.3	8764	Dec	30	4	56.67
8783	192.2	8763	Dec	30	3	53.75
8784	167.6	8762	Dec	30	2	55.61

After doing this matching for all the hours, it was necessary to decide how many hours were required to be analysed so that a good simulation of the electricity price with and without RES was done. To do so, it was decided to approach this problem using hour percentages, i.e., if it is referred that 10% of the hours were used, it means that the 878 hours with more and less RES on the system were analysed. Additionally, for the purposes of this thesis, the percentage of the hours with more RES on the system represents a system with electricity produced by RES while the percentage of hours with less RES on the system represents a system with no production from this source.

After various initial simulations, it was noted that the percentages of hours analysed had a big difference in the savings, i.e. the electricity price difference between the hours with more and less power from RES in the system. More than this, the influence of each technology in the savings also differed a lot. For this reason, it was necessary to do specific simulations for each technology, and groups of technology, as well as for different hour percentages. This way, it was achieved a solid method to understand the influence of each technology in the electricity price.

Renewable energy technologies do not exhibit the same characteristics between the different sources. The relation between the production of energy by a hydro source and its influence on the electricity price is different from the relation between the production of energy by a wind source and its influence on the price. As an example, reservoirs are a dispatchable source of energy, i.e. its integration on the grid can be controlled. Hence, energy produced by these sources is commonly used in peak load situations, due to the fast start that these plants usually have. Contrarily, non-dispatchable renewable energy sources need to have their energy dispatched immediately. Due to this characteristic, there is a direct relation between non-dispatchable renewable energy production and the reduction of electricity price, but there is no relation between the higher production of hydroelectricity and the reduction of the price. Frequently, the bigger power output of hydro plants occurred when there was no production from wind and PV technologies, and the electricity price was high. This, together with the fact that hydro plants exist on the Portuguese system for many years now, were the reasons for this technology to not be considered in the model. Moreover, although only reservoirs are considered a dispatchable energy source, both run-of-river and small hydro technologies might have the capacity to hold water for hours/days, meaning that, although they are not considered dispatchable sources of energy, it is possible to have some control over when the energy is produced, so these were not considered as well. For the final simulations, only wind and PV productions were considered.

To try to have a better perspective of the influence of these technologies in the price of energy, sensibility analysis with the data was performed. Simulations were done with 5%, 10% and 15% of the hours with the most and the least energy from RES on the system, and then for the hours with most and least wind and photovoltaic. Figure 4.4 illustrates the hour percentages studied. To understand the different behavior of the hydro technology, the same simulation was executed for this technology. These simulations were performed for the years of 2014, 2015 and 2016, although only the data of 2016 analysed further.

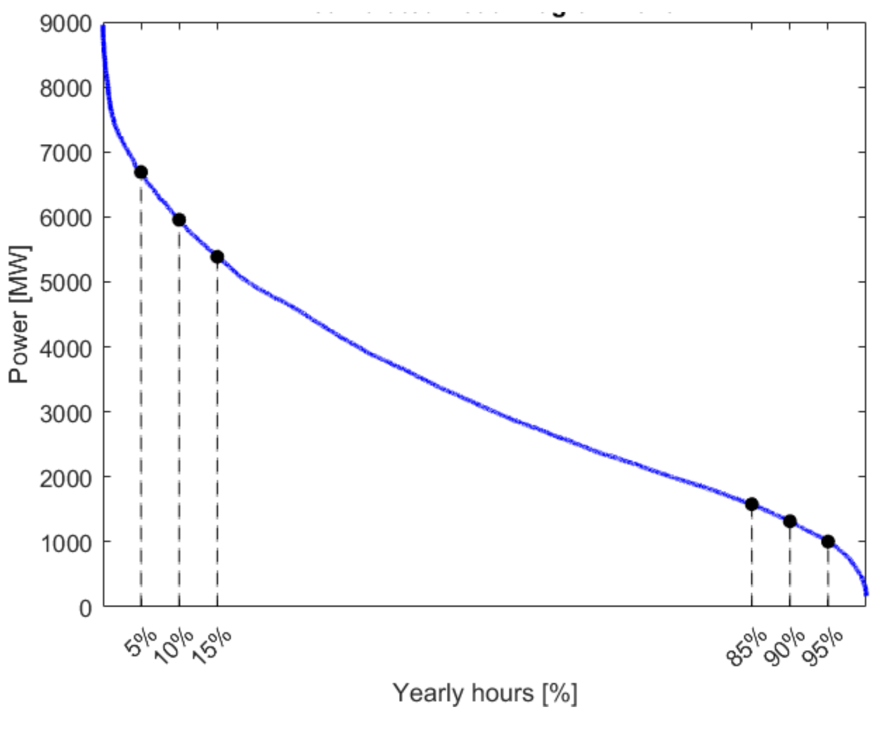
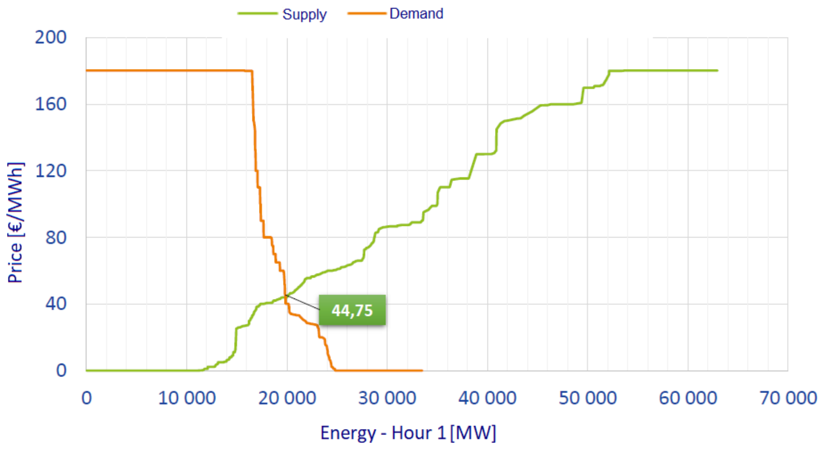


Figure 4.4. Analysed percentages of the Load Duration Diagram 2016

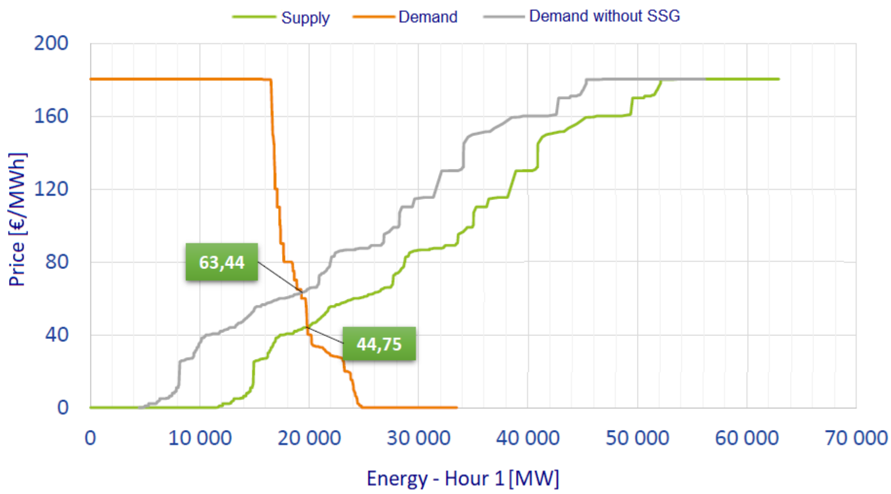
To validate the results from this model, which will be presented in section 5.2, Associação Portuguesa de Energias Renováveis (APREN) made available the results from their own model. To calculate what would be the price of the energy if no renewable energy from SSG existed in the system, APREN developed a model in which they organize all the offers from producers in one hour from the lower price to the higher one. For the same hour, they do the same with all the offers from the buyers of energy, organizing these from the highest price to the lowest. This is the normal market organization, where the intersection between these two lines gives us the energy price in that hour. Afterwards, to calculate the energy price if no power had been injected by SSG, all the offers made by these are removed to this diagram. This means that the new price will have only in account the selling offers from non-SSG.

In Figure 4.5 it is possible to understand the procedure. This corresponds to the diagram for the first hour of 2016. In Figure 4.5 (a), the actual price of energy is presented for that hour, 44,75 €/MWh. If there was no energy produced from SSG sources, the price would be the one described in Figure 5.4 (b), 63,44 €/MWh. This means that, in the first hour of 2016, the savings in the price of energy due to renewable energy were around 18,69 €/MWh.

It is important to mention that APREN's methodology, similarly to the one created in this thesis, does not include big hydro technologies.



(a) Price with RES production



(b) Price without RES production

Figure 4.5. APREN's method to estimate savings from RES production (Adapted from [APRE17a])

4.2 Cycling costs model

Besides a good evaluation of savings due to renewable energies, a model to know the extra costs due to cycling effects, as is detailed in Section 3.2, was necessary. In order to evaluate this increase, the year of 2010 was used as the reference year with less VRE, and then compared with 2016. Although there was already a lot of wind capacity installed in 2010, this was the oldest year in which was possible to gather information about the production of electricity by each thermal plant, which is available in [ReEN17d]. In 2010, there was still a small production of electricity by the thermal plant located in Carregado, which functioned by fuel-oil. However, this thermal plant was decommissioned during that year, having a very small production of energy. This way, it was not considered.

The integration of renewable energies in the system entails some costs, as described in Section 3.2, including the cycling costs. In this section, different perspectives of the cycling costs will be presented. Different papers on the matter will be analysed.

The integration of renewable energies in the grid causes a big variability in the production of thermal plants. [BeDe15] evaluates how the various parameters influence a generation portfolio and defines 5 types of cycling costs due to this variability:

- Direct start costs, which are the costs of fuel, CO_2 emissions, and auxiliary services during a start-up of a thermal plant;
- Operation and maintenance costs, created by a start-up, referred to as indirect start costs;
- The cost of forced outages due to cycling, which is the opportunity cost of not generating during an outage;
- O&M costs due to load following, referred to as ramping costs;
- The cost of having a less efficient plant due to cycling;

To do the evaluation of the costs, it is presented a table with the costs associated with each of these problems for the various thermal plant technologies, Table 4.2.

Table 4.2. Cycling costs (adapted from[BeDe15])

	Direct Start costs [€/ΔMW]	**Indirect start costs [€/ΔMW]**	**Forced outages [h/cycle]**	**Ramping [€/ΔMW]**	**Efficiency decrease [%-p/cycle]**
Coal	25	55	0,63	1,8	0,44
CCGT	5	40	0,69	0,8	0,1

By studying the table, it is possible to infer that all direct, indirect and load-following costs have a direct application. Regarding forced outage costs, these are about 5% of total cycling costs. As for the decrease of the thermal units' efficiency, it can be expressed in the cycling costs as the difference between the generation costs of a system with all generation at decreased efficiency and a system with the original efficiency. Since these generation costs are not available, the decrease in the efficiency of the units is not accounted for in the model developed.

The authors of the paper conclude that a good unit commitment scheduling can reduce cycling costs up to 40%. More than this, it is concluded that cycling costs increase with increasing technologies. However, the total system costs reduce with the increase of renewable generation.

In a similar perspective, the implications of incorporating short-term dispatch into the planning of energy generation are studied in [ViMa14], doing a case study of a system with multiple technologies. To evaluate cycling costs, the value of the start-up fuel cost is presented. Then, to considerate other cycling costs, this value can be multiplied by a factor between 2 and 5, depending on the technology, as shown in Table 4.3.

Table 4.3. Thermal plants characteristics (adapted from [ViMa14])

Characteristics	Coal	CCGT
Unit size (MW)	600	500
Start-up fuel costs (€/start)	40 665	6 384
Other start-up costs (€/start)	203 325	19 153

The authors of the paper consider coal plants as having the highest possible start-up costs, multiplying the start-up fuel costs by a factor of 5. As for CCGT units, these are considered to have other start-up costs 3 times more expensive than the start-up fuel costs, according with the authors. These other costs are associated with the cycling of a unit, such as O&M, forced outages, the unit heat rate, meaning the decrease in efficiency of a power plant that happens when more cycling occurs, and manpower. The conclusions of the paper point for the fact that the costs associated with cycling are highly dependent on the portfolio studied.

Another study, [TrDO10], assessed the costs due to wind penetration in a base-load unit by simulating the 2020 Irish system, due to its unique characteristics. Table 4.4 was adapted from this study and presents the characteristics of a CCGT and Coal units simulated on that system, including the start-up costs.

Table 4.4. Thermal plants characteristics (adapted from [TrDO10])

Characteristics	Coal	CCGT
Unit size (MW)	260	400
Start-up costs (€/start)	5 080	12 440

By performing simulations with different wind percentage penetrations, the study allowed to conclude that CCGT units have the highest increase in costs, since they are displaced to mid-merit operation. It is also stated in the paper that, at very high wind penetration (6000 MW), the storage of energy can decrease the start-up costs. However, although it is mentioned that the increase in cycling operation will lead to increased outages and plant depreciation, these costs were not included in the simulation.

In a similar context, the Irish electric system is simulated to evaluate the impact of increasing wind generation in [TrDO08], with the purpose of evaluating the extra start-up costs incurred in base-load generators by the variability that wind causes in the system. Table 4.5 presents the start-up costs of base-load units, both coal and CCGT.

Table 4.5. Thermal plants characteristics (adapted from [TrDO08])

Characteristics	Coal	CCGT
Start-up costs (€/start)	7 630	15 366

It is mentioned that, with the increase of the wind penetration, some of these units start functioning as mid-merit units. It concludes that the cycling of base-load units is increased with the growth of wind penetration.

As for the Portuguese system specific values, [Faia15] addresses the implications of the increase of RES in the Portuguese energy system by evaluating the start-up costs of the Portuguese thermal units were assessed. Table 4.6 shows the costs of each start-up for the Portuguese units' generators. It is assumed that, when a start-up occurs, the unit must start functioning at least at a minimum power, 1/3 for coal plants and 2/9 for CCGT plants. The start-up costs are divided into three categories:

- Abrasion costs, which are the costs resulting from the corrosion of the units due to start-ups;
- Fuel consumption costs, referring to the costs of fuel necessary to start a plant until minimum power;
- CO_2 emissions costs, the costs regarding the CO_2 emissions.

Table 4.6. Start-up costs (adapted from [Faia15])

Technology	Unit	P max [MW]	P min [MW]	Abrasion	Fuel Cons. [€]	CO_2 [€]	Total Cost [€]
CCGT	Lares	431	96	3448	2213	393	6053
	Outeiro	330	73	2640	1686	300	4626
	Ribatejo	392	87	3136	2010	357	6503
	Pego	418	93	3344	2146	381	5870
Coal	Sines	298	99	1490	4898	4955	11343
	Pego	292	97	1460	5279	4855	11594

Having the information of the papers and thsesis previously presented gathered, to assess the cycling costs of the Portuguese thermal plants, an analysis was done based on the characteristics of the units. A model was developed to do the simulations, in which it allows to do a quicker analysis of the data, returning the extra-costs due to the cycling of a thermal plant. It makes the distinction between start-ups and load-following of a plant, counting the number of start-ups. In this way, all the models previously presented could be tested for the Portuguese electric system.

For that model, the data from each individual Portuguese thermal was extracted from the Excel files into MATLAB. It analyses the hourly production of a thermal plant, calculates the costs of each start-up that occurs during the year, and returns the total cost value. When applicable, it also adds the load-following costs. This program was run for each coal and natural gas thermal plant in function for the years of 2010 and 2016. The results are presented in Table 4.7 for the year of 2010 and in Table 4.8 for the year of 2016.

Regarding the two papers which include load-following costs, [ViMa14] and [BeDe15], the total cost values between both differ a lot. This is partly due to the methodology used in the papers. Although both take into consideration different cycling costs, according to [ViMa14], these are all calculated based on the number of start-ups and depending on start-up fuel costs. This way, as it is considered that coal plants have high start-up fuel costs, due to the emission costs, as well as the power needed to start-up all the auxiliary components, this emphasises the rest of the costs in these type of plants, since the start-up costs are multiplied by a factor 5 to calculate them, whereas the CCGT units have lower costs. Hence, although the number of CCGT start-ups is much higher, it is possible to infer that, in 2010, the coal costs represent 68,5% of the total cycling costs. In 2016, even with the increase of CCGT start-ups, the reduction of start-ups in coal plants reduces the total cycling significantly, though they are still higher in comparison with [BeDe15] costs. In regards of [BeDe15] methodology, analyzing both years, it is clear that cycling costs were higher in 2016, due to the increase of cycling costs in CCGT units. This indicates that, alongside with the increase in the number of start-ups, the small variations due to load-following were more intense, increasing the cycling costs.

After this literature review and analysis of the applications in the Portuguese system of each paper, two have better approaches than the rest regarding the total cycling costs. Within the papers which only consider start-up costs, [Faia15] has a specific approach for the Portuguese units, which is exactly what is being discussed, standing out because of this. As for [BeDe15] and [ViMa14], which have more detailed approaches, since more than start-up costs are accounted in these studies, [BeDe15] is more complete, due to the extensive cover of different costs and to the fact that the paper's values are framed within all the papers The coal start-up costs presented in [ViMa14] are too disrupting when compared with the other papers, with no justification.

Therefore, even considering the specific Portuguese units costs in [Faia15], the values adopted in this thesis were the ones presented in Table 4.2, by [BeDe15], since these have more information on different cycling costs, not only start-up costs.

Table 4.7. Portuguese thermal plants cycling costs' in 2010

2010							
	Thermal Plant	**Yearly start-ups**	**[BeDe15] [€]**	**[ViMa14] [€]**	**[TrDO10] [€]**	**[TrDO08] [€]**	**[Faia15] [€]**
CCGT	**Lares**	34	287 960	868 278	542 368	522 444	411 672
	Outeiro	66	1 377 200	1 685 480	1 052 832	1 014 156	915 948
	Ribatejo	106	1 984 626	2 706 984	1 318 640	1 628 796	538 318
	Total	**206**	**3 649 831**	**5 260 743**	**2 562 640**	**3 165 396**	**1 910 938**
Coal	**Pego**	38	831 620	9 271 609	78 014	289 940	881 144
	Sines	14	762 698	3 415 856	71 120	106 820	317 604
	Total	**52**	**1 594 320**	**12 687 465**	**264 160**	**396 760**	**1 198 748**
	Total (CCGT+Coal)	**258**	**5 244 151**	**17 948 209**	**2 826 800**	**3 562 156**	**3 109 686**

Table 4.8. Portuguese thermal plants cycling costs' in 2016

2016							
	Thermal Plant	**Yearly start-ups**	**[BeDe15] [€]**	**[ViMa14] [€]**	**[TrDO10] [€]**	**[TrDO08] [€]**	**[Faia15] [€]**
CCGT	**Lares**	32	762 970	817 202	510 464	491 712	387 456
	Outeiro	145	3 922 238	3 702 950	2 313 040	2 228 070	2 012 310
	Ribatejo	96	2 200 303	2 451 608	1 531 392	1 475 136	1 584 864
	Pego	87	1 398 035	2 221 770	1 387 824	1 336 842	1 021 380
	Total	**360**	**8 288 546**	**9 193 532**	**5 742 720**	**5 531 760**	**5 006 010**
Coal	**Pego**	19	607 849	4 635 804	39 007	144 970	440 572
	Sines	16	1 195 884	3 903 835	32 848	122 080	725 952
	Total	**35**	**1 803 734**	**8 539 640**	**71 855**	**267 050**	**1 166 524**
	Total (CCGT+Coal)	**395**	**10 092 280**	**17 733 172**	**5 814 575**	**5 798 810**	**6 172 534**

4.3 Renewables overcosts

Most of the RES are considered to be special status generators. Although an effort was put to evaluate the extra costs that RES's induce in thermal plants, there are many other costs which need to be taken into consideration. The most relevant one is the price paid by the eletricity produced by RESs. As explained in Section 2.4.1, the Portuguese energy market buys the electricity according to their marginal cost, which is the cost to produce one more MW of energy. Usually, renewable energies have no marginal costs, meaning that their energy is offered in the electricity market at 0€/MWh. However, renewable energy producers get paid a special tariff to produce renewable energy, which is usually higher than the wholesale market price of the electricity. This tariff was created to encourage the investment in renewable energy producers. These tariffs vary according with the year in which the plant started producing electricity. So, if the energy in 2016 was sold at, on average, 68,76€/MWh but the producers got paid a tariff higher than that price, this creates a big cost for the consumers.

To evaluate how much is spent on payments to renewable energy producers, it was necessary to know the difference between the energy costs using regulated market price and using the real price of energy. It was decided to apply the methodology used by ERSE to calculate the costs due to RES production, since it is this regulator that calculates the official costs of the RES in Portugal. The formula applied to the costs is based on ERSE's calculation. During the year, ERSE publishes information about SSG, including the power injected by them on the grid and the costs of each technology per month. According to the Portuguese government, the extra costs arising from SSG are:

$$\mathrm{EC} = \mathrm{C} - \mathrm{R} \tag{4.1}$$

Where:

- EC corresponds to the extra costs, i.e. all the costs but the costs of acquiring the energy from SSG;
- C represents the costs of acquiring the energy from SSG;
- R corresponds to the revenues from selling it in the wholesale market.

However, this formula is incomplete, since there are more costs with the SSG than the costs of acquiring their energy, which were described before. ERSE tries to assess some of these costs. More than this, not all the sales are done to the wholesale market, exists the possibility to sell the energy to a future market. Therefore, ERSE uses the following equation to calculate the costs of SSG.

$$\mathrm{EC} = \mathrm{C} - \mathrm{R} + \mathrm{FC} + \mathrm{OC} \tag{4.2}$$

In this equation:

- FC represents functioning costs, such as the costs regarding the well-functioning of the structure which carries the buying of energy from SSG.
- OC represents the other costs which need to be considered in this calculation, like the costs

which are paid to REN for the usage of Portuguese system grid by SSG.

Chapter 5

Results and Analysis

In this chapter, the results and analysis of the models showed in Chapter 4 are presented. To frame these results, the chapter starts by describing the conditions in 2010, the reference year, and 2016. Then, the electricity price without the presence of PV and wind in the system is calculated. Following this, the cycling costs of the Portuguese system are presented and analysed. An official methodology is used to calculate the renewables overcosts, and the chapter finalizes with a closing balance.

5.1 Comparison between the conditions in 2010 and 2016

As it is important to appreciate the grow of installed capacity of VRE, in this section, the years of 2010 and 2016 will be described, in terms of installed capacity, demand and generation of electricity, as well as the meteorological conditions.

In Table 5.1, the installed capacity of all the different technologies that exist in the Portuguese system is showed, both for the year of 2010 and the year of 2016. For this thesis, the focus was directed to the evolution of the installed capacity of wind and solar energies. As it is possible to verify, wind technology had a growth, in installed capacity, of 36% during these years, and Solar had 3.59 more capacity installed in 2016 than in 2010. Despite the observations, when comparing the absolute values of installed capacity for both technologies, it is possible to understand that, in the same interval, there was a lot more wind capacity installed than solar.

The section 'Others' refers to different non-renewable sources other than coal and natural gas, which in the year of 2010 still had a lot of installed capacity. This include, for example, fuel-oil, which was used in the thermal plant of Carregado that was only decommissioned in this year.

Table 5.1. Installed capacity of the different technologies in the Portuguese system [MW] (Adapted from [ReEN11] and [ReEN17a])

	Technology	2010	2016
Non-Renewable	**Coal**	1756	1756
	Natural Gas	4481	4657
	Cogeneration	652	828
	Others	2190	60
	Cogeneration	355	0
Renewable	**Hydro**	4988	6945
	Wind	3705	5046
	Solar	122	439
	Biomass	557	615
	Total	17799	19518

In addition to the installed capacity, it is also relevant to analyse the total generation of electricity in each of the years. Table 5.2 presents the total generation by each technology, again for the years of 2010 and 2016. When looking at the total demand, it observable that more electricity was consumed in 2010 than in 2016. Additionally, because more electricity was produced ('Total Generation') in 2016, more electricity was exported in this year. Regarding the VRE sources, both of their contribution increased. Wind produced more 3 164 GWh in 2016, more 35% than in 2010, while solar produced 574 GWh more, representing a growth of 377%. The increase of these technologies' production is in accordance with the increase in their installed capacity, because, since these are non-dispatchable technologies, the energy produced by them has priority in the market, so, as the weather conditions are similar in both years, more capacity installed represents more energy produced. It is also noticeable that coal production was 80% higher in 2016 than in 2010, although no installation occurred during this period, due to the lower prices of coal in 2016. As for natural gas, it was generated more energy in 2010 than in 2016.

Table 5.2. Net demand and generation by different technologies in the Portuguese system [GWh] (Adapted from [ReEN11] and [ReEN17a])

	Technology	2010	2016
Non-Renewable	**Coal**	6 553	11 698
	Natural Gas	14 400	11 571
	Cogeneration	3 700	4 197
	Gas-oil	47	0
	Others	1 352	318
Renewable	**Hydro**	16 248	15 413
	Pumped Storage	512	1 217
	Wind	9 024	12 188
	Solar	207	781
	Biomass	2 262	2 687
Market	**Import**	4 350	1 973
	Export	1 718	7 055
Total	**Total Generation**	50 605	55 873
	Total Demand	52 204	49 269

Another important factor to characterize the two years of analysis is the capability factor of Hydro and Wind technologies. The capability factor is an indicator that allows to quantify the difference between the production of energy in a certain period when compared with the energy which would have been produced in an average weather scenario in the same period. This analysis is particularly important for hydro technology, both due to the fact that this has a big influence on the total generation of electricity, representing 32% of all the generation in 2010 and 28% in 2016 and the fact that, being a dispatchable energy source whose generators can start functioning within minutes, it is commonly used to lower the energy price when this is very high and no other RES available. More than this, throughout the years, hydro capability factor is the one which might vary the most. While wind and solar have bigger variations during the day, their yearly production is more constant, when compared with hydro. Figure 5.1 shows the capability factor of these three technologies from 2007 until 2016. In the years of analysis, 2010 and 2016, both hydro and solar technologies have similar factors. By analysing the definition of capability factor, this allows to conclude that the meteorological conditions were similar in both years. Even though the wind technology exhibited a higher variation in its values, this is not relevant enough to influence the results.

Concluding, the meteorological conditions were similar in both years, meaning that the extra production of renewable energy in 2016 was in fact due to the extra installed capacity and not due to more wind, solar or hydro during that year.

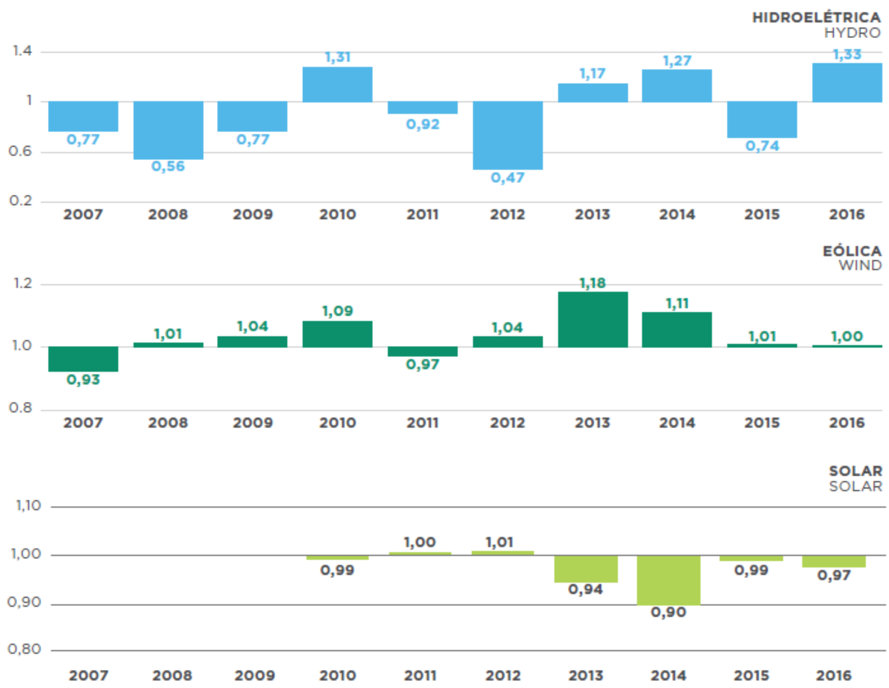


Figure 5.1. Capability factor for Hydro, Wind and Solar technologies (extracted from [ReEN17b])

5.2 Energy price with and without VRE in the system

In this section, the results from the simulations done to evaluate the price difference with and without electricity production from wind and PV on the system will be explained. Following the procedure detailed in Section 4.1, a model was created to simulate the price of electricity of a system without any power from wind and PV sources in the Portuguese grid.

Firstly, simulations were performed for the years of 2014, 2015 and 2016 using the wholesale prices of electricity of the 10% of the hours of the year with more electricity produced by RES, including hydro, and the 10% of the hours of the year with less production. These results are presented in Table 5.3, where the difference of the electricity prices in both scenarios are named of savings.

Table 5.3. Savings from RES analysing 10% of the hours [€/MWh]

Year	2014	2015	2016
Electricity price of the hours with more RES production	41.11	58.73	36.26
Electricity price of the hours with less RES production	57.43	59.01	52.19
Savings	**16.32**	**0.28**	**15.93**

After analysing the results, it was clear that this approach was not sufficient to give a good value for the potential cost of the electricity in a scenario without renewable energy on the system, due to the dispatchable technologies. For example, in 2015, the price of electricity with the most and least renewable energy on the system was almost the same.

Therefore, the same 10% of the hours with more and less production of electricity from hydro were analysed alone, as well as the 10% of the hours with more and less production from VRE technologies, which include only wind and PV. In Table 5.4, the results are presented for the years of 2015 and 2016. Although the year of analysis was the year of 2016, the results of 2015 are also presented, for one to understand the influence of the different technologies in the price of energy.

Table 5.4. Savings from the different technologies individually [€/MWh]

Technology	Hydro		Wind and PV	
Year	2015	2016	2015	2016
Electricity price of the hours with more RES production	69.89	43.28	51.08	38.09
Electricity price of the hours with less RES production	55.66	49.16	65.47	54.17
Savings	**-14.23**	**5.88**	**14.39**	**16.08**

From the results, it is possible to conclude that there are big discrepancies in prices between both years, with the energy prices in 2015 being overall more expensive than in 2016. One of the most important reasons for the high price of the energy in 2015 was the fact that this was a dry year, with a small hydro capability factor, 0.74, when compared to the factor of 2016, 1.33. This means that the amount of energy produced from hydro technology in 2016 was much higher than in 2015, from 8 453 GWh to 15 413 GWh in 2016, a variation of 82%. When looking solely at this source, for year of 2015, the price of energy in the hours with more production of energy from hydro was 14,23 €/MWh higher than the hours with less production. The reason for this is also the fact that 2015 was a very dry year.

This sustains the fact that, as hydro is a dispatchable source of energy, a high production of energy from hydro sources does not mean that the energy is cheap during these times. In 2016, the prices regarding the hydro production have a slightly different behavior, but the difference of prices between the hours with more and less hydro production is still small, only 5,88 €/MWh. On the contrary, the hours with the most and least VRE production have a direct influence on the price of energy in those hours, as it is possible to see in Table 5.4, in both years. The hours with more production of wind and solar have a price 14,39 €/MWh lower in 2015 and 16,08 €/MWh in 2016, when compared with the hours of less production. Consequently, only wind and PV technologies were taken into consideration for the final model that was developed.

Finally, a sensibility analysis was performed, regarding the percentage of the hours that was more appropriate to use in the model. When analysing Figure 4.4, it is possible to see the big difference in power injected on the grid by RES when analyzing the electricity prices of the top and bottom 5% of the hours with more and less production, when compared with 10% and 15%. Due to this, calculations were done for the three percentages above mentioned, and the results are presented in Table 5.5, for the wind and solar technologies, for the year of 2016.

Table 5.5. Sensibility analysis of the percentage of hours analysed [€/MWh]

2016		[€]
5%	More wind and PV production	36.52
	Less wind and PV production	54.53
	Savings	**18.01**
10%	More wind and PV production	38.09
	Less wind and PV production	54.17
	Savings	**16.08**
15%	More wind and PV production	38.73
	Less wind and PV production	53.67
	Savings	**14.94**

After performing calculations, it was concluded that the percentage of hours analyzed has a considerable influence on the price difference. When considering the 5% of the hours with more and least power injected by wind and solar technologies, the difference in the price of energy is 18 €/MWh. However, when considering the higher percentage, this difference goes down to around 15 €/MWh.

To validate the results, and to decide which of the percentages should be applied, it was asked for a validation using the software developed by APREN. In Table 5.6, the results from APREN are presented, for the years of 2016.

Table 5.6. Savings according with APREN methodology [€/MWh]

Year	2016
Price	**39.4**
Price without Wind and PV production	**61.3**
Savings	**21.9**

Regarding the year of analysis, it is possible to understand that the model values which are more similar with APREN's values are the 5% share of the hours. This way, the values used for the savings in 2016 due to the supply of energy by RES are presented in Table 5.7. These are the savings used in the model developed for calculating the price of electricity, representing here a system with and without RES, respectively.

Table 5.7. Savings [€/MWh]

2016	[€/MWh]
Price with Wind and PV supply	36.52
Price without Wind and PV supply	54.53
Savings	**18.01**

By looking at the table, it is easy to conclude that, in 2016, the integration of the RES in the Portuguese system created a saving of 18,01 €/MWh. After some calculations, and because there were 49 501 GWh traded in 2016, that value reflects in 891 513 010 € of total savings for the year. From these results, it is easy to conclude that the cycling costs are irrelevant when compared with the economic benefits. However, these still need to be scrutinised and compared with the total overcosts, which will be done in the next sections.

5.3 Cycling costs analysis

In this section, the results from the model developed based on [BeDe15], and described in Section 4.2 will be analysed. In Table 5.8 the values of the different costs assessed are described for the year of 2010, while inTable 5.9 the same are described for year 2016. By analysing the two tables it is possible to see, first of all, that the cycling costs of CCGT plants in 2016 are much higher when compared to

2010, showing an increase of 277%. Additionally, the coal cycling costs exhibit a small increase of 13% in 2016. Furthermore, 137 more start-ups occurred in total in 2016, however, the number of start-ups in coal thermal plants was reduced, from 52 in 2010 to 38 in 2016.

The thermal plant of Outeiro has the biggest variation in of costs, more than tripling its costs in 2016. Overall, all the thermal plants increase their costs in 2016, with Pego coal thermal plant being the exception, since it had a small reduction in total costs between the two years.

Table 5.8. Components of cycling costs in 2010

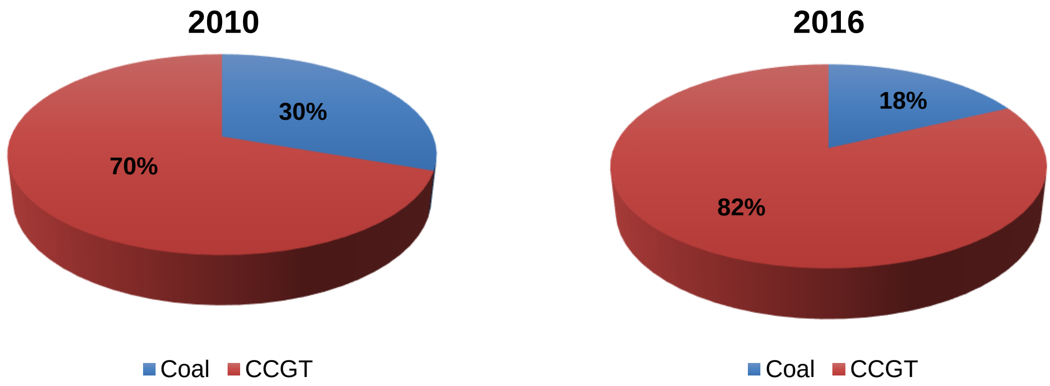
	Thermal plant	No. of Starts	Direct costs [€]	Indirect costs [€]	Ramping costs [€]	Forced outages [€]	Total costs [€]
CCGT	**Lares**	34	25 450	203 600	58 913	14 398	287 963
	Outeiro	66	136 873	1 094 984	145 385	68 862	1 377 242
	Ribatejo	106	209 524	1 676 196	98 906	99 231	1 984 626
	Total	**206**	**371 847**	**2 974 780**	**303 204**	**182 491**	**3 649 831**
Coal	**Pego**	38	193 567	425 848	212 207	41 581	831 622
	Sines	14	94 000	206 800	461 898	38 134	762 698
	Total	**52**	**287 567**	**632 648**	**674 105**	**79 716**	**1 594 320**
Total (CCGT + Coal)		**258**	**659 414**	**3 607 428**	**977 309**	**262 207**	**5 244 151**

Table 5.9. Components of cycling costs in 2016

	Thermal plant	No. of Starts	Direct costs [€]	Indirect costs [€]	Ramping costs [€]	Forced outages [€]	Total costs [€]
CCGT	**Lares**	32	72 038	576 300	83 062	36 570	767 970
	Outeiro	145	404 810	3 238 500	92 155	186 773	3 922 238
	Ribatejo	96	226 518	1 812 148	56 861	104 776	2 200 303
	Pego	87	144 415	1 155 320	31 727	66 573	1 398 035
	Total	**360**	**847 781**	**6 782 268**	**263 805**	**394 692**	**8 288 546**
Coal	**Pego**	19	145 450	319 990	113 464	28 945	607 849
	Sines	16	285 625	628 375	224 938	56 946	1 195 884
	Total	**35**	**431 075**	**948 365**	**338 402**	**85 892**	**1 803 734**
Total (CCGT + Coal)		**395**	**1 278 856**	**7 730 633**	**602 207**	**480 584**	**10 092 280**

In light of these conclusions, it is relevant to compare the cycling costs by technology. Firstly, it is interesting to present the influence of each one of these technologies in total cycling costs, showed in

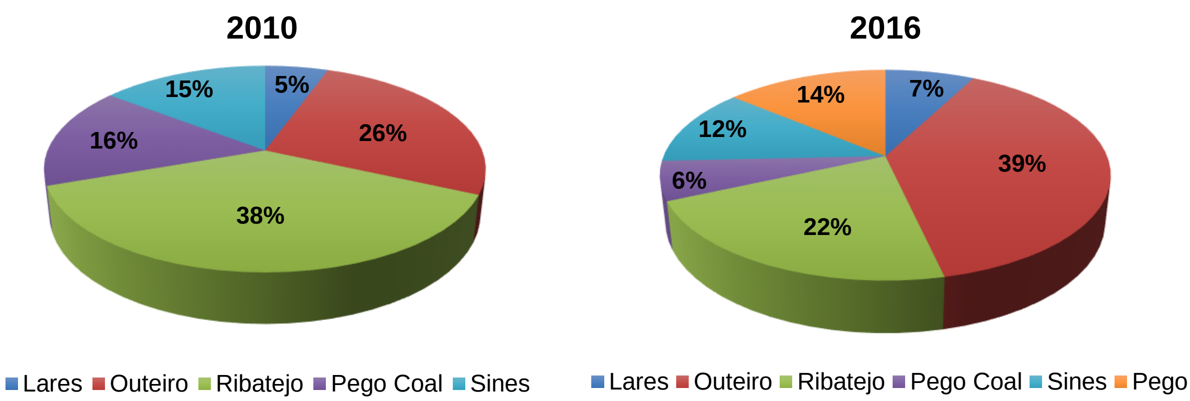
Figure 5.2. It is perceptible that, in 2016, the cycling costs related with coal are a smaller portion of total cycling costs when compared with 2010. However, the more important information that is gathered from this comparison is the discrepancy between both technologies. The functioning as base-load units from coal thermal plants leads to less cycling costs. More than this, there are more CCGT capacity installed in Portugal than coal. This, together with the functioning of coal plants as base-load units is sufficient to create the percentages observed in Figure 5.2, where CCGT units have responsibility for 70% in 2010 and 82% in 2016 of total cycling costs.



(a) 2010 (b) 2016

Figure 5.2. Share of each technology in total cycling costs

From the two tables above, it is seen that, within each technology, the thermal plants did not exhibit the same costs. In Figure 5.3, it is possible to visualize the influence of each thermal plant in total cycling costs for the two years analysed. The thermal plants of Ribatejo and Outeiro are responsible for the biggest shares of the cycling costs in the Portuguese system, in both years.



(a) 2010 (b) 2016

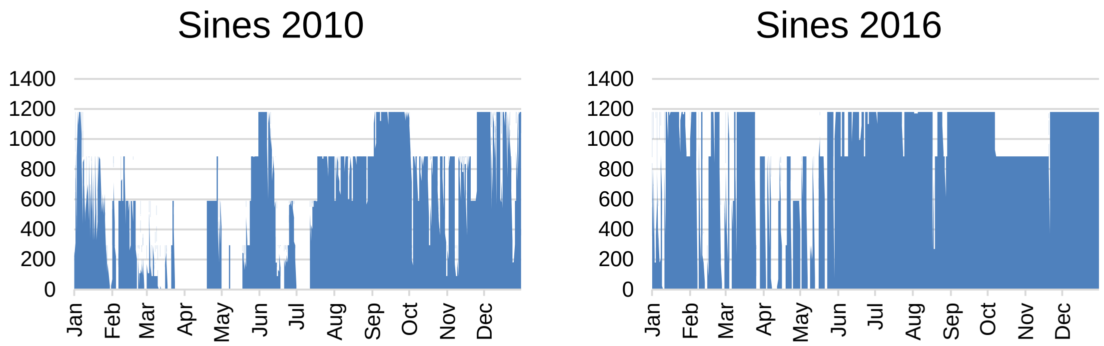
Figure 5.3. Share of each thermal plant in total cycling costs

To illustrate the differences of generation behavior of both technologies, in Figure 5.4 the annual production of a Portuguese unit of coal, in Sines, is presented. In Figure 5.5, the cycling of a CCGT

Portuguese thermal plant is shown, Tapada do Outeiro. In the coal power plant, the higher cycling costs in 2016 are justified due to the faster ramping rates. In 2016, most of the start-ups required higher outputs than in 2010, some of them even to the maximum output of the plant, leading to higher costs. It is also possible to verify that in 2016 there was more energy produced in Sines coal thermal plant than in 2010.

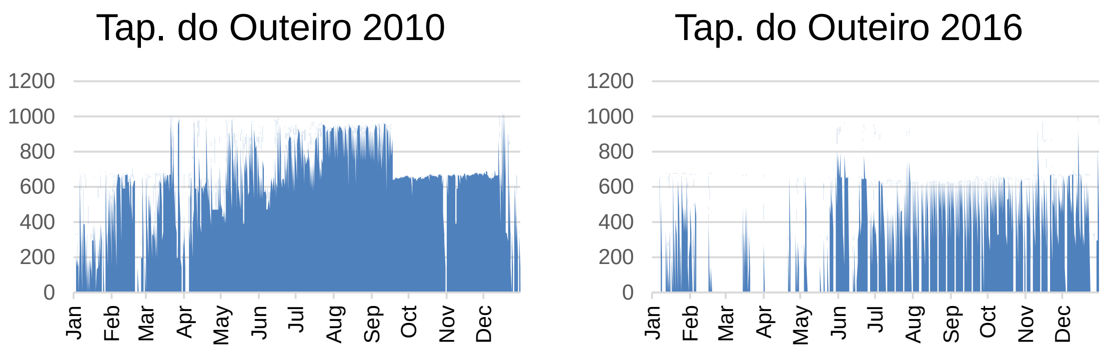
Regarding the Outeiro unit, its usage is 2016 is rather limited, barely never working at full capacity and with several start-ups to produce limited quantities of energy, while in 2010 it has bigger periods without shutting down and variations of production. This is in accord with the total production of both technologies, in which coal increased its total production significantly in 2016.

The planning of thermal plants production is not focused on cycling costs, rather in other factors like the cost of production. This cost integrates many other factors, from which cycling cost is only a small part, meaning that the cycling observed in the following images were not planned to obtain the lowest possible cycling costs. These images also reflect the fact that CCGT units had a more mid-merit utilization in 2016, while coal units, with the increase of production, had a more stable production of energy, with less variations throughout the year.



(a) 2010 (b) 2016

Figure 5.4. Coal power plant production

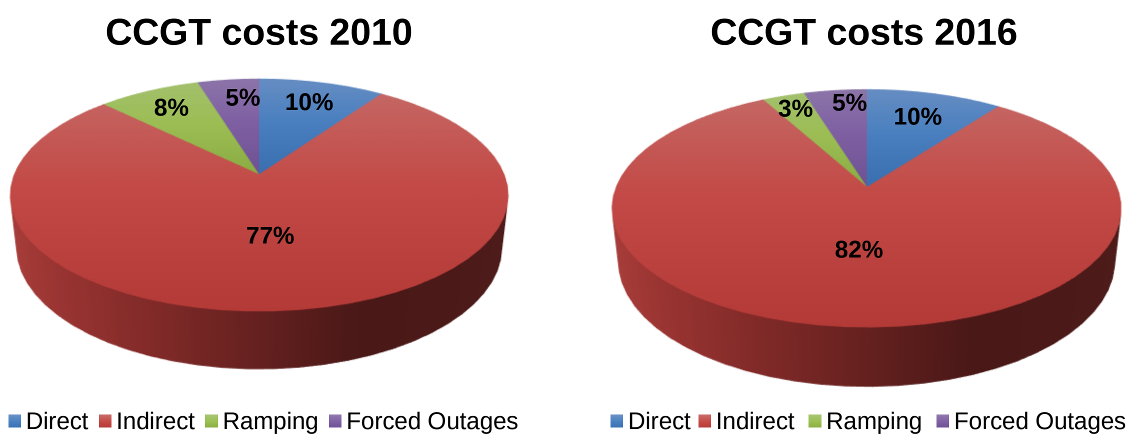


(a) 2010 (b) 2016

Figure 5.5. CCGT power plant production

One more reason to explain the differences in both years is the cost of the fuel. This cost plays the biggest role for the usage planning of the power plants, since it corresponds to its biggest cost. In 2010, the cost of the coal was more expensive when compared with 2016 (78 $/mton in 2010 and 57,6$/mton in 2016) [WoBG13, WoBG17]. Consequently, there was a big search for alternative energy sources, with special focus on natural gas, since the installed capacity of renewable energies was not enough for the needs at the time. In 2016, with lower coal costs, the usage of these plants was pushed to the limits, which is confirmed by the energy produced in each of these years by these plants. Simultaneously, the installed capacity of wind and PV increased. All this contributed for the increase of start-ups of natural gas plants, which, in 2016, were used more as back-up units.

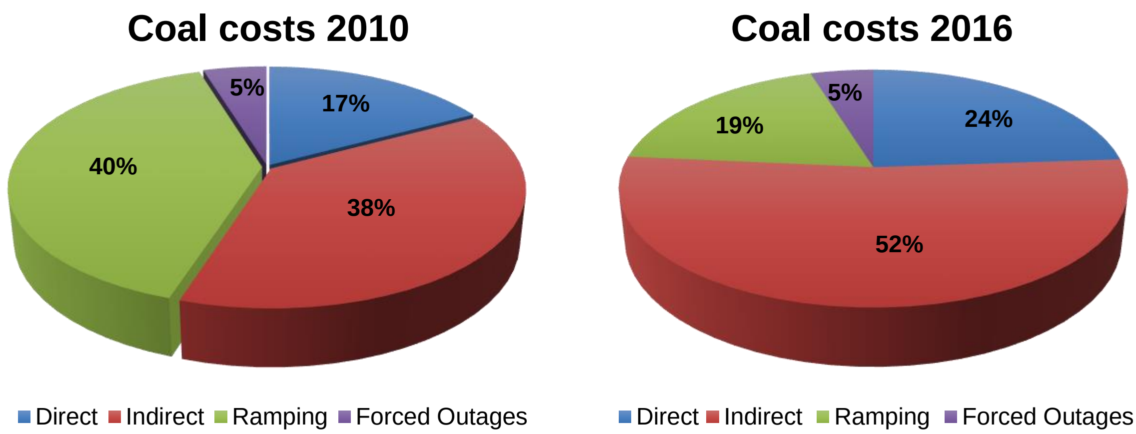
As explained before, four types of costs were assessed in this model. Direct and indirect costs are related with the start-up of a unit. Direct costs are all the fuel, CO_2 emissions and auxiliary services costs, while all the maintenance costs due to a start-up are referred as indirect costs. The O&M costs caused by load following are mentioned as ramping costs. Finally, forced outages costs were also added to the model. In Figure 5.6 it is presented the influence of each type of cost in the Portuguese system for CCGT thermal plants. As it was expected, start-up related costs have the biggest influence on the costs. Between both years, there is no big difference. However, there is a noticeable decrease of the share of ramping costs, in green, suggesting that CCGT units were more often turned down and turned back up, rather than kept on lower levels of production. This in accordance with the big increase of start-ups in 2016.



(a) 2010 (b) 2016

Figure 5.6. Cost sharing of CCGT thermal units

The same display can be presented for Coal power plants. As it is shown in Figure 5.7, the cycling costs for coal power plants suffered some differences in both years of analysis. Once again, the ramping costs The increase of direct and indirect costs suggests that despite the fact that the number of start-up decreases, these required higher outputs, in 2016, a fact confirmed by Figure 5.4.



(a) 2010 (b) 2016

Figure 5.7. Cost sharing of coal thermal units

5.4 Renewables overcosts calculation

In this section, the costs generated by SSG will be calculated. As explained in Section 4.3 the methodology applied to calculate the costs due to SSG was the same that is used by ERSE as official values. In Table 5.10 presents part of the information that is available by ERSE [ERSE17b] for the year of 2016. Only the data important for the calculation of the costs due to SSG is presented.

It is important to mention that, in the document available, this information is separated by cogeneration production and generation for self-consumption on one hand, and all the other SSG on the other. In the context of this thesis, since the production in thermal cogeneration plants is partly fuelled by natural gas, and self-consumption generation is not significant, it was decided to not assess the costs of these technologies. This way, the costs calculated integrate the following technologies:

- Wind;
- Hydro;
- Biogas;
- Biomass;
- Photovoltaic;
- Waves,
- Urban toxic waste.

Table 5.10. ERSE costs (Adapted from [ERSE17b])

	2016	[€]
C	**Costs**	1 560 121 000
R	**Revenues**	581 339 000
OC	**Other Costs**	5 221 000
FC	**Functioning Costs**	4 267 000

As it is possible to infer, in 2016, the costs due to the buying of energy from the sources above mentioned, C, were much bigger than the profits selling that energy, and clearly represents the biggest portion of total costs.

Applying the equation 4.2:

$$\mathrm{EC} = 1\,560\,121\,000 - 581\,339\,000 + 5\,221\,000 + 4\,267\,000 = 988\,270\,000€ \tag{5.1}$$

Therefore, in 2016, the costs due to the SSG were around 988.3 M€.

5.5 Final Balance

There are two different considerations which need to be done to frame the results of this thesis. On one hand, it is clear that the cycling costs in 2016 were higher than in 2010, with an increase of 92%, as presented in Table 5.11.

Table 5.11. Cycling costs

2010 [€]	2016 [€]
5 244 151	**10 092 280**

However, the plants do not program their usage based on cycling costs, but mainly based on fuel costs. This means that the extra costs due to cycling costs is only partly related with the intermittence provoked by wind and PV on the grid, and it can be misguiding to analyse these values without having this in mind.

On the other hand, it is imperative to contextualize these costs in the overcosts of the system due to SSG, according with ERSE, as well as in the benefits. Table 5.12 summarizes the savings and costs due to renewable energy production.

Table 5.12. Costs and savings in 2016

Total Overcosts [€]	Total Savings [€]	Cycling Costs [€]
988 270 000	891 513 010	10 092 280

Different conclusions can be reached from this table. Regarding the main focus of the thesis, the cycling costs, it becomes obvious that the magnitude of these is insignificant. When compared with the total overcosts of the renewables, it represents only 1.021% of these. When compared with the total savings, it represents 1,13%, which indicates that it is totally worth it.

Another conclusion is the fact that the total costs are bigger than the total savings. This can be explained by several reasons, such as the high tariffs which are being paid to older plants and are much higher than what the market dictates, or the investments made on the grid which are still being paid, or the social measures.

For new renewable plants to arise, and the technologies continue to develop and improve their profitability and efficiency, it is imperative to find different solutions, which do not overload the government with more expenses, but in which the can still to have return on their investments. One of these solutions can be by implementing Power Purchase Agreements (PPA). A PPA is a contract signed between an energy producer and an energy supplier. The supplier then sells the electricity to the wholesale market or applies another solution available in the market. This solution allows the producers to guarantee financing to their plants, because the electricity is sold at a fixed price. At the same time, the energy suppliers are able to sell the electricity bought at a higher price. In 2018, it was signed the first PPA in Portugal, being the biggest in the Iberian Peninsula, at the time.

Another possible solution is to change the structure of the electricity tariff paid by the consumers. Nowadays, the tariff is divided in two main components:

- A variable part, which is related to the amount of electricity consumed;
- A fixed part, which depends either on the contracted power or simply a fee paid by the contract (€/month).

At the same time, the costs behind the tariff can also be divided in two categories:

- Third-party access, which includes the network costs, policy costs, like the renewables overcosts, tariff deficits and most of the taxes. These are mostly fixed-costs, not varying with the amount of electricity consumed, and it is equal for all the energy suppliers;
- Energy, which is the price paid in the wholesale market;

This difference in the tariff paid by the consumers and the costs behind the tariff provoke a big impact. In Portugal, about 90% of the revenues in the sector are collected through charges on the variable part of the tariff paid by the consumers, but only 30% of the costs are variable [EnDP18b]. An approximation between the tariff being paid by the consumers and the costs behind the tariff would be helpful to strengthen the system in case some unpredicted changes happen.

Chapter 6

Conclusions

This chapter summarises all the work developed for this thesis and highlights its main conclusions.

The main objective of this thesis was to evaluate the extra costs that conventional thermal plants had due to the growth of electricity produced by renewable energy sources in the system. In order to do that, the year of 2010, the reference year, was compared to 2016. To do so, different papers, where the cycling costs are described, were analysed. The methodology and results from the more reliable paper were chosen, [BeDe15], to be used in the Portuguese system, once it contains more details on cycling costs. The ideal scenario would have been to use information from an older year, since in 2010 there were already 3 705 MW of wind capacity installed; however, there is no detailed information about the production of each coal and CCGT plant available before that year.

The results exposed an increase of the cycling costs when comparing both years, from 5 244 151 € to 10 092 280 €. Additionally, more 137 start-ups occurred in 2016. The reason for this increase can be justified by different arguments. First, the fuel costs, which are the most influent parameter when deciding when a thermal plant in turned on, were different in both years, with coal being much cheaper in 2016. This resulted in coal thermal plants producing 5 154 GWh (78 %) more in 2016. Second, at the same time, one more CCGT thermal plant became functional in this period, in Pego, in 2011, increasing the number of start-ups of natural gas thermal plants, despite the fact that these produced less 2 829 GWh in 2016 than in 2010, when they produced 14 400 GWh. It was also noticed that the main share of the cycling costs are the indirect costs, i.e. the maintenance costs due to a start-up, representing around 80% (77% in 2010 and 82% in 2016) of the total costs.

Considering these results, it was necessary to recognise how relevant the costs were when compared to the economic impact that the RES have on the wholesale electricity price. To understand this, a model was developed. The price of the 5% of hours with more and less electricity produced from non-dispatchable RES was evaluated, simulating a system in which no electricity is produced from these sources (less production). Only PV and wind, the two non-dispatchable technologies, were used in the simulation, because it was proved that hydro peaks of production and low electricity price during those peaks do not have a direct relation.

It was concluded that, in 2016, the 5 % of the hours with less electricity produced from wind and PV had a price of 54.53 €/MWh, 18.01 €/MWh higher than the hours with more electricity generated (from these sources). When considering the electricity produced in the whole year, this difference reflects in savings of 891.5 M€. To verify the results, APREN made available the outcomes of their model, which simulates MIBEL without the production of electricity from wind and solar. The system without electricity from wind and PV would be 21.9 €/MWh more expensive than electricity price in the year of 2016. This corresponds to total savings of 1 084 M€.

Considering the purpose of this thesis - to evaluate the growth of the cycling costs in the Portuguese thermal units due to the increase of electricity in the power system produced by intermittent technologies, and to frame these extra costs both in the renewables overcost and in the economic benefits from these sources -, with these results, it is possible to state that the extra cycling costs are irrelevant when compared both with the renewables overcosts and with the economic benefits from the RES. In 2016, these represent around 1 % of the total overcosts. Also, this outcome discredits the argument that claims that renewable energies provoke unsustainable cycling costs in the thermal units.

Another evaluation needed to be done is the comparison between the cycling costs and the total overcosts. To do so, ERSE methodology to calculate the total renewables overcost was used, in what concerns the year of 2016. The result presented overcosts of 988.3 M€, which were 96 M€ more than the savings in this year. An analysis presented in [APRE17c] also shows that the overcosts were higher in 2016 when compared to the savings, but, since 2010, the benefits have largely surpassed the overcosts. Therefore, this does not discredit the use of RES. The overcosts are driven by different reasons. When the wind and PV technologies appeared, they were not economically viable. Additionally, these entered in a market dominated by conventional thermal plants, which already had their investments paid, and only have operational costs. This led to high tariffs being paid to the RES producers to attract investment for the implementation of these solutions. As the years go by, these overcosts will tend to disappear.

It is undeniable that the RES are one of the most important solutions for a sustainable future. Obviously, like in all investments, these need to be profitable in order to capture the interest of the investors. Portugal is a role model country regarding the renewables and it should continue being so. In future works on the subject, it would be interesting to create a partnership with the owner of a thermal plant, so that these costs can be evaluated in a more detailed way. The papers in which this thesis was based have some limitations when applied to a specific system, namely the fact that a thermal plant is analysed as a whole opposed to analysing the different generation units separately. Also, there are some benefits provided by renewable energies which might not be represented by this simulation and should be analysed in the future, like the reduction of the dependency of fossil fuels, which are imported, making the country more independent in case of a world crisis, or the jobs created, both direct and indirect., which also need to be taken into consideration when the topic is being discussed.

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