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FACULDADE DE CIÊNCIAS
DEPARTAMENTO DE ENGENHARIA GEOGRÁFICA, GEOFÍSICA E ENERGIA

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100% Renewable electricity supply for Portugal and Spain

Mariana Raposo Fernandes

Dissertação de Mestrado Integrado em Engenharia da Energia e do Ambiente

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Trabalho realizado sob a supervisão de
Professor Dr. Olav Hohmeyer (Universität Flensburg)
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2014

ABSTRACT

Climate change and other questions concerning environmental issues are current topics that have been demanding several studies and investigations. The use of non-renewable energy sources is the main driver of these problems. Therefore, there is the need to seriously consider the possibility of a transition to an electricity supply system exclusively based on renewable energies sources. The goal of this dissertation is to study and develop scenarios to apply this system in Portugal and Spain, for the year 2050, and the sources considered are solar, wind and run-of-river. Results of a simulation model were used (*Renewable Energy Pathways Simulation System* - RENPASS), developed by a research team of the University of Flensburg, in Germany, and applied to that country and its surrounding countries. The scenarios development was done by defining the installation power of photovoltaic and wind, in MW. Using those defined values and the model results (which define, among others, each source potential) it is possible to calculate the electricity production coming from each source. The residual load is a factor that allowed the analysis and the evaluation of the five created scenarios, and it is calculated by subtracting the electricity production (generated by the three renewable sources mentioned above) from the electricity demand. Installation costs (investment) and electricity transmission costs were also taken into account. The three first scenarios aimed at achieving a yearly residual load approximately null, when summing up hourly values. The fourth scenario was defined by having a greatest installed power (solar and wind), which entailed high installation costs, but simultaneously lower transmission costs. As one concluded that storage using electric cars is neither feasible nor realistic, and also that transmission is the highest expenditure and therefore it should be avoided, the fifth scenario with much higher installation values was created. In any case, under any scenario, there will always be the electricity transmission need, because it is not possible to create a scenario that has a constant null residual load associated, either due to excess or lack of production.

Keywords: **100% Renewable, Electricity supply/demand, RENPASS model, Residual load**

RESUMO

As alterações climáticas e restantes questões ambientais são temas atuais que têm exigido inúmeros estudos e investigações. O uso de fontes de energia não renovável é o principal impulsionador destes problemas, e é preciso ponderar seriamente uma transição para um sistema de fornecimento de eletricidade baseado exclusivamente em fontes de energia renovável. O objetivo desta dissertação é estudar e desenvolver cenários para aplicação deste sistema em Portugal e Espanha, para o ano de 2050, sendo que as fontes consideradas foram a solar, eólica e hidroelétrica (fio de água). Foram usados os resultados de um modelo de simulação – *Renewable Energy Pathways Simulation System* (RENPASS) –, desenvolvido por uma equipa de investigação da Universidade de Flensburg, na Alemanha, e aplicado a esse país e aos seus países vizinhos. A criação de cenários é feita pela definição das potências de instalação de fotovoltaico e eólico, em MW. Através disso e dos resultados do modelo, que definem, entre outros, o potencial de cada fonte, é calculada a produção de eletricidade proveniente de cada uma. A carga residual é um fator que permitiu a análise e avaliação dos cinco cenários criados e é calculado pela subtração da produção de eletricidade das três fontes renováveis referidas acima à procura de eletricidade. Os custos de instalação (investimento) e os custos de transmissão de eletricidade também foram considerados. Os primeiros três cenários tiveram como critério atingir uma carga residual anual aproximadamente nula, quando somados os valores horários. O quarto cenário foi definido como sendo o de maior potência instalada (solar e eólica), o que implicou altos custos de instalação, mas simultaneamente muito mais baixos custos de transmissão. Como se concluiu que o armazenamento feito por baterias de carros elétricos não é viável, e que a transmissão é muito dispendiosa e deve ser evitada, foi criado o quinto cenário com valores de instalação muito superiores. Independentemente do cenário, vai ser sempre necessária a transmissão de eletricidade, porque não é possível criar um cenário em que a carga residual seja constantemente nula, seja por excesso de produção ou por defeito.

Palvras-chave: **100% Renovável, Carga residual, Fornecimento/procura de eletricidade, Modelo RENPASS**

ACKNOWLEDGMENTS

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ACRONYMS AND ABBREVIATIONS

CO_2	Carbon Dioxide
ENTSO-e	European network of transmission system operators for electricity
GHG	Greenhouse gases
HPP	Hydropower plant
IPCC	Intergovernmental Panel on Climate Change
PV	Photovoltaic
RE	Renewable energy
REE	Red Eléctrica de España
REN	Redes Energéticas Nacionais
RENPASS	Renewable Energy Pathways Simulation System
RL	Residual load
RoR	Run-of-river
SRU	Sachverständigenrat für Umweltfragen

1. INTRODUCTION

Recently, real world experiences and studies have shown that renewable energies can provide a substantial share of the energy demand. Keep on using non-renewable energy sources is not, at all, a sustainable option, given the current levels of greenhouse gas (GHG) emissions and all the environmental problems. Everything is directly or indirectly connected to these matters: the fossil sources, environmental worries, wildlife, worldwide pollution, climate changes, etc.

It is known that is extremely important to change the way we all consume and produce our energy. There are many options for lowering GHG emissions from the energy system, and meanwhile still satisfying the global demand for energy services. This need is due to the fact that GHG emissions resulting from the provision of energy services contribute significantly to the increase of atmospheric GHG concentrations.

As well as having a large potential to mitigate climate change, renewable energies can provide wider benefits. Renewable energies (RE) may, in implemented properly, contribute to the economic and social development, energy access, a secure energy supply and reduce negative impacts on the environment and health. RE involves a heterogeneous range of technologies, and various types of renewable energies can supply electricity (Intergovernmental Panel on Climate Change, 2012).

The ideal would be that we all live and work in a "low carbon society", with high levels of energetic efficiency and reduced emissions, and we would all use electric transportation. The cities would be cleaner and the air quality much higher. Many of these technologies already exist but, most of the times, it is a matter of energy policies and not only a matter of potential in terms of renewable sources.

Nonetheless, the European Union is committed to reducing the CO_2 emissions in 20% until 2050, relatively to the year 1990 (Energias de Portugal, S.A., 2012). In fact, there are three main and general goals:

1) Reduce greenhouse gas emissions in 20%;

2) Reduce total cost of energy (energy bills and total cost of electricity generation);

3) Reduce implementation difficulties (given the necessary public acceptance of the energy policies adopted).

However, the conditions for supporting renewable energies have to be enhanced both on the European and nation levels.

1.1 Motivation and goals

The need to reduce CO_2 emissions and rapidly rising energy costs has induced a growing demand for sustainable energies. Several reports and researchers have been saying this and actually, according to the SRU[1], a 100% fully renewable energy supply is possible, safe and affordable. However, the time period and costs to this system transformation have been causing controversial discussions.

Greenhouse gas emissions need to be reduced 80-95% in order to avoid a global increase of 2 Celsius degrees, and a detailed analysis of the potential of renewable energy sources for electricity production shows that energy supply only based on renewable energy sources by 2050 is a possible scenario (German Advisory Council on the Environment - SRU, 2011).

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[1] *Sachverständigenrat für Umweltfragen*

It is important to clarify that the year 2050 is really not a distant date, taking into account the level and the duration of this kind of investments and that measures taken now will have influence in 36 years. Power plants would have to be replaced next years. Based on an appropriate expansion of storage and network facilities it is possible to have the foreseeable maximum demand for electricity, so the supply can be guaranteed in spite of variations in energy production. The transition to renewables does not require a big service life extension or construction of new coal-fired power plant.

Although this study is regarding electricity supply and not energy supply in general, the important global idea to keep in mind is that the technical potential of renewable energy technologies to supply energy services exceeds current demands (Intergovernmental Panel on Climate Change, 2012).

This dissertation is about an electricity supply based 100% on renewable energies, namely photovoltaic (PV), wind and run-of-river, for 2050, for the Iberian Peninsula. RENPASS (*Renewable Energy Pathways Simulation System*), developed by a research team of the University of Flensburg, is used for this study. The mentioned model was already successfully implemented for Germany, Denmark, Sweden, Norway, Finland, Lithuania, Latvia, Estonia, Poland, Czech Republic, Austria, France, Switzerland, Belgium and Netherlands (Wingenbach, RENPASS). In the sub-chapter 'About RENPASS' the model will be fully explained.

Moreover, this dissertation intend to create several scenarios about solar and wind power installation, and the residual load is the main factor used to evaluate these scenarios. For that, the RENPASS model can provide normalized values regarding wind and solar production, for Portugal and Spain. These values are used on the scenarios development of this thesis and were calculated based on the potential of these two sources, such as solar radiation and wind speed. The residual load is defined by the difference between the electricity demand and the electricity production that the solar, wind and run-of-river energies provide.

The first task of this study is to collect all the necessary data. Measured data regarding electricity demand, and electricity production from solar, wind and run-of-river is collected, for several years, for Portugal and Spain. Afterwards, the RENPASS model is used to provide hourly values for solar and wind production. One of the goals of this study is to test the modeled data by RENPASS, comparing it to the measured real data collected from the database used, such as ENTSO-e[2], REN[3] and P.F. Bach[4].

This dissertation is divided into the following chapters: chapter 2 describes the methodology used; chapter 3 explains how the scenarios are developed and created; in chapter 4 the results are shown and discussed, and several solutions are proposed; and finally, chapter 5 presents the main conclusions and states what future work can be done regarding this topic.

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[2] European Network of Transmission System Operators for Electricity

[3] Redes Energéticas Nacionais: this is a Portuguese energy sector company which is the current concession holder of the country's two main energy infrastructure networks: the national electricity transmission grid and the national natural gas transportation grid

[4] Paul-Frederik Bach, *Consultant in Development of Energy Systems*

1.2 Renewable electricity technologies

Renewable energy technologies are definitely unique, they can be difficult to model, and they are diverse with wide-ranging characteristics. With some exceptions, renewable energy resources are location-restricted and cannot be easily stored or transported. One of the biggest barriers of this kind of alternative sources is the great difficulty of storage, and they are usually characterized by their intrinsic variability. Natural variations in weather patterns cause the output of renewable power plants to vary at all timescales. Particularly, maybe the most consequential are the annual, seasonal diurnal and sub-hourly variability of wind and solar power plants due to changing weather conditions and clouds.

Photovoltaic

The generation of electricity using PV panels is a worldwide phenomenon. Solar energy is ample and offers a significant potential for near-term (2020) and long-term (2050) climate change mitigation. There are a wide variety of solar technologies of varying maturities that can, in most regions of the world, contribute to a suite of energy services. Even though solar energy generation still only represents a small fraction of total energy consumption, markets for solar technologies are growing fast. Much of the interest of solar technology is its naturally smaller environmental 'footprint' and the opportunity it offers for positive social impacts. The actual deployment achieved will depend on the degree of continued innovation, supportive public policies and cost reductions, but there are facts that cannot be changed: solar energy is the most abundant of all energy resources, and the rate at which solar energy is intercepted by the Earth is around 10000 times greater than the rate at which human kind consumes energy (Intergovernmental Panel on Climate Change, 2012). Although not all countries are equally endowed with solar energy, Portugal and Spain have the potential to take a great part of this source.

Figure 1.1 shows a basic scheme of what happens to an illuminated solar cell.
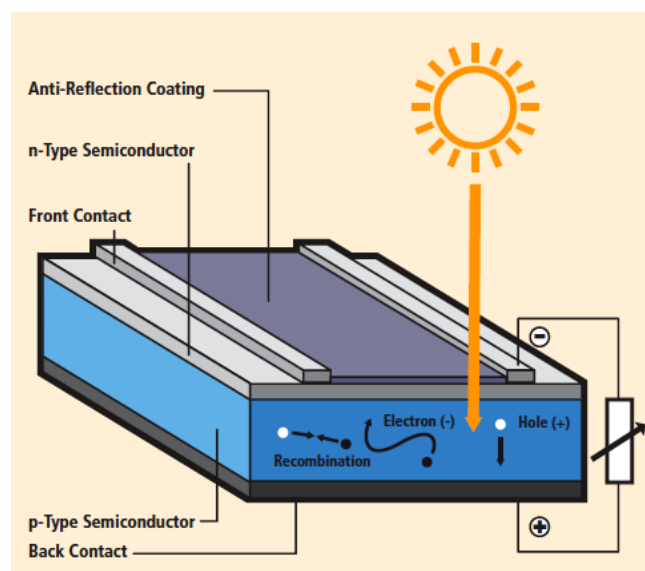
Figure 1.1- Generic schematic cross-section illustrating the operation of an illuminated solar cell (Intergovernmental Panel on Climate Change, 2012)

Photovoltaic solar technologies generate electricity by exploiting the photovoltaic effect. If the light shines on a semiconductor, such as silicon, electron-hole pairs are generated, and those are separated

by an electric field created by introducing special impurities into the mentioned semiconductor either side of an interface known as a p-n junction. This phenomenon creates negative charges on one side of the interface and positive charges on the other side. Afterwards, a voltage is created by this charge separation. If the two sides of the illuminated cell are connected to a load, current starts flowing.

Solar production is associated to a natural distribution, as it has a great potential all over the countries, especially in Portugal and Spain. An important technology to decrease the emissions of carbon dioxide caused by domestic fuel consumption is the roof-mounted photovoltaic systems, because they also help saving energy and financial costs. Therefore, today the worldwide use of solar systems is increasing. Private investors as well as local authorities have rising interest in identifying roof areas that are suitable for mounting solar systems (Kassner, Koppe, Schüttenberg, & Bareth, 2008). Large solar power plants can also have a great contribution on the fight against conventional power plants.

Figure 1.2 Figure 1.3 show a grid-connected photovoltaic power system with battery backup and an off-grid/stand-alone that incorporates large amounts of battery storage to provide power when the sun is not available.
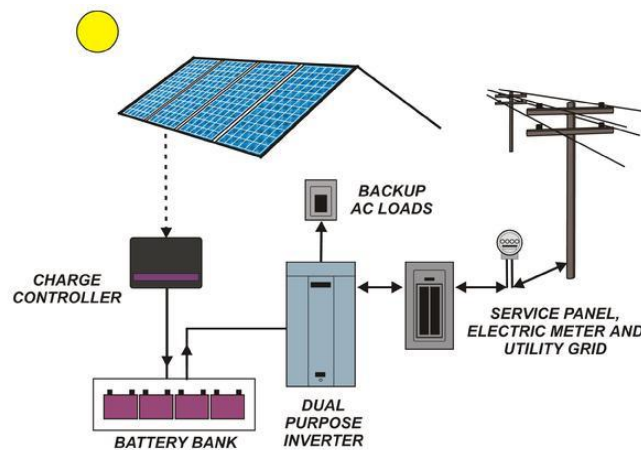
Figure 1.2 - Grid-connected PV system (Aladdin Solar, LLC., 2008)
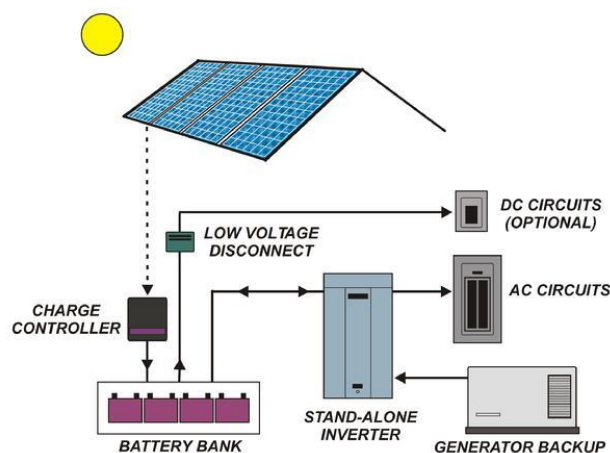
Figure 1.3 - Stand-alone PV system (Aladdin Solar, LLC., 2008)

Wind energy

Wind energy is a mature renewable energy source that has been successfully deployed in many countries. Countries such as Germany have a great potential to take energy from this source. It is technically and economically capable of substantial continued expansion and its further exploitation may be a crucial aspect of global greenhouse gases reduction strategies. Wind energy relies, indirectly on the energy of the sun. A small proportion of the solar radiation received by the Earth is converted into kinetic energy (Hubbert, 1971). The earth rotation, geographic features and temperature gradients effect the location and nature of the resulting winds (Burton, Jenkins, Sharpe, & Bossanyi, 2001).

The use of wind energy requites that the kinetic energy of moving air be converted to useful energy: electricity. As a result of this occurrence, the economics of using wind for electricity supply are highly sensitive to local wind conditions and the ability of wind turbines to reliably extract energy over a wide range of typical wind speeds.

Figure 1.4 represents the basic components of a wind turbine.
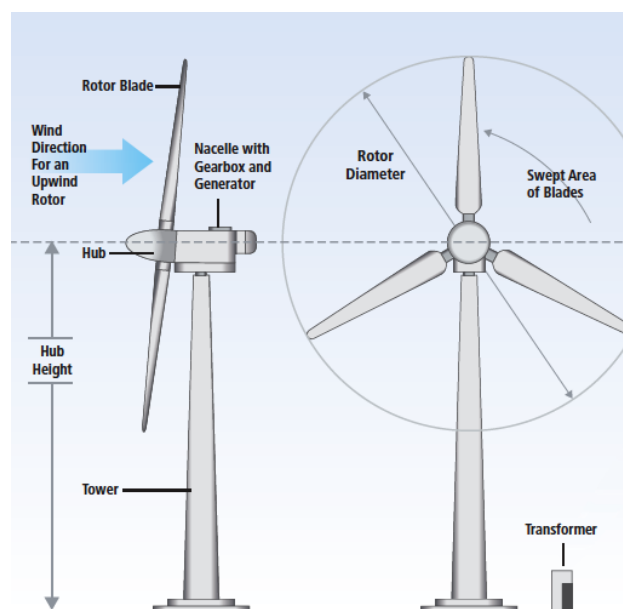
Figure 1.4 - Basic components of a modern horizontal-axis wind turbine - designed by the NREL[5] (Intergovernmental Panel on Climate Change, 2012)

Run-of-River

A RoR HPP (Run-of-River hydropower plant) draws the energy for electricity production from the available flow of the river. Such a hydropower plant may include some short-term storage (hourly, daily), allowing some adaptations to the demand profile, but the generation profile will vary depending on flow conditions. As a result, generation depends on precipitation and runoff and may have substantial daily, monthly or seasonal patterns. In this dissertation this energy is considered to be a must-run energy. When the short-term storage is not included, the RoR HPPs generate profiles that are even more variable. Since most precipitation usually falls in mountainous areas, where elevation differences are the largest, the largest potential for hydropower development is in this kind of regions, or in rivers coming from such regions.

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[5] National Renewable Energy Laboratory

In a RoR HPP, a portion of the river water might be diverted to a channel or pipeline to carry the water to a hydraulic turbine, which is connected to an electricity generator. Installations of such hydropower plants are relatively inexpensive and such facilities have, in general, lower environmental impacts than similar-sized storage hydropower plants.

Figure 1.5 shows how a run-of-river hydropower plant looks like.
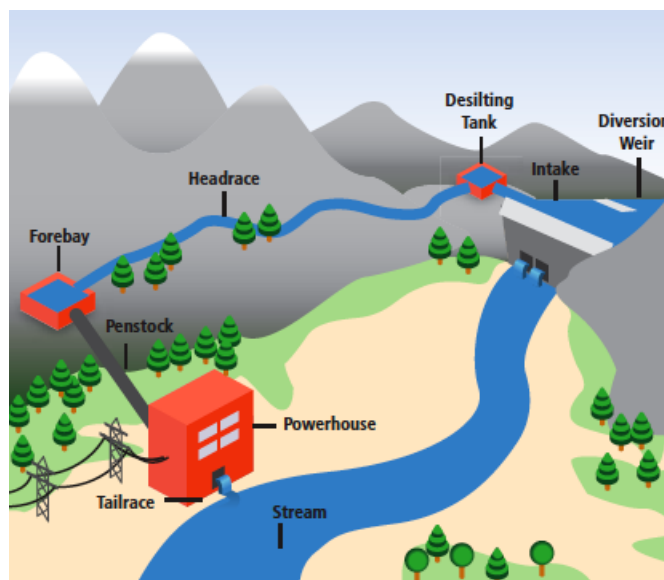
Figure 1.5 - Run-of-river hydropower plant (Intergovernmental Panel on Climate Change, 2012)

1.3 State of the art

Several studies and researches about renewable energy systems have been done along the last years. What has been implemented is depending more on the policies and not so much on the lack of information and investigation work.

There is currently a group of researchers working on a recent model that will be used for this study. The model, RENPASS, is an integrated techno-economic simulation model for the electricity supply of different European countries. Besides the fact that lots of work has been done around this transition for the 100% renewable electricity supply, this model was quite innovative. As this model was already successfully implemented for German and its surrounding countries, some master's students are developing this topic based on the model, and extending it for other countries. In this dissertation, it will be done for Portugal and Spain, and not all the model will be used, but only a part of it (the model includes a very big range of simulations and calculations about different aspects). In this specific case, the RENPASS results are obtained in a normalized values format. Afterwards, these results are multiplied by a power installation (of wind or solar, in MW), which allow us to acquire hourly values of electricity production.

By 2020 Portugal will have a share of energy from renewable sources, specifically for electricity demand, of 55,3% and Spain 40% (German Advisory Council on the Environment - SRU, 2011). The energy investments made today will determine the shape of the energy industry for a long time to come, and particularly the electricity industry. If the investments nowadays keep on being climate-unfriendly, it will not be possible to reach a long term climate policy goal of reducing greenhouse gas emissions. Investigations done about this topic also prove that transitioning to an entirely renewable

electricity supply would greatly increase the ability of the European Union to bring greenhouse gas emissions down to the requisite levels.

Right now, the electricity demand coverage for Portugal and Spain is the one represented in Figure 1.6.

| 21.2 | 21.2 | 14.6 | 14.2 | 12.5 | 9.5 | 3.1 | 2.0 | 1.7 |
| Wind | Nuclear | Coal | Hydroelectric* | Cogeneration and others** | Combined cycle | Solar photovoltaic | Renewable thermal | Solar thermoelectric |
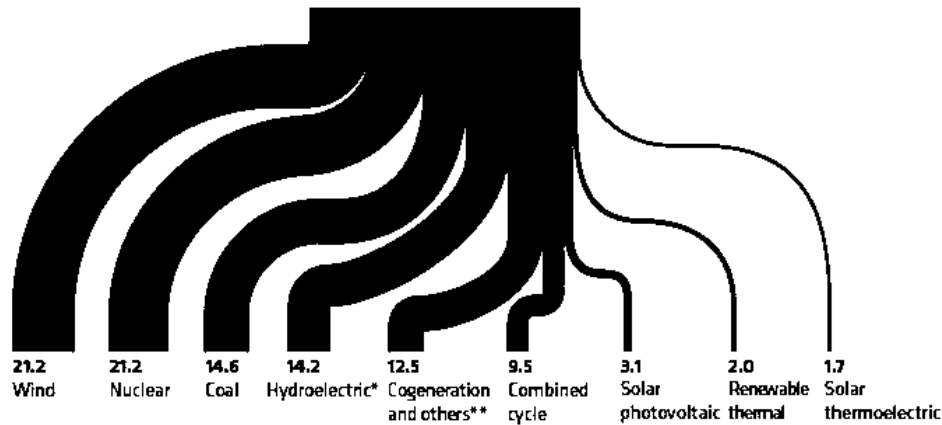
Figure 1.6 - Peninsular electricity demand coverage in 2013 (%) (Red Eléctrica de España - REE)

There are only a few fundamental technical limits to the integration of a majority share of RE, but for sure that there are areas that need development: transmission and distribution infrastructures, generation flexibility, energy storage technologies, demand management, and improvement of forecasting and operational planning methods (Intergovernmental Panel on Climate Change, 2012).

According to Connolly, Lund, Mathiesen, & Leahy, 2009, there is no energy tool that addresses all issues related to integrating renewable energy, but instead the 'ideal' energy tool is highly dependent on the specific objectives that must be fulfilled. The paper mentioned includes a review of the different computer tools that can be used to analyze the integration of renewable energy.

1.4 About RENPASS

RENPASS is a simulation model that has been developed by a research group at the University of Flensburg. Using RENPASS, different pathways of energy transition can be simulated with a high temporal and regional resolution. The model calculates on a quarter hour basis the power supply in future sustainable energy systems, thereby enabling a 100% renewable energies system. The calculations of the fluctuating electricity supply are always depending on the weather influence, and there is the need to ensure a matching of supply and demand for every point in time, so also controllable components, like hydro pump storage, biomass or compressed air storages could be used in the electricity system. The model provides, among others, quarterly-hour results about the individual generating plants, reservoir levels, power flow between the model regions and resulting prices (Wiese, Renewable Energy Pathway Simulation System - Manual, 2013). For this dissertation, not all these components were calculated. Only the normalized values for wind and solar were obtained from the model and used to calculate production, depending on the installations that were set up for the different scenarios (Wingenbach, Adaption of wind turbine and photovoltaic simulation algorithms of RENPASS to Portugal and Spain, 2014). These scenarios were defined manually according to some criteria.

The goal of the energy transition is to achieve a 100% renewable energy supply. One of the main and more important questions that can be studied using the model is how production and demand can be provided in such a flexible system and what contributions can different shares of certain technologies

make. This different energy transition phases are comparable in a transparent way and, in order to achieve this real transparency, RENPASS is based exclusively on open source software (Wiese & Bökenkamp, Renewable Energy Pathways Simulation System, 2014).

RENPASS allows the simulation of different scenarios that combine different pathways in the areas demand, renewable expansion, thermal power plants, storage development, grid development, economic parameters and exchange algorithms. Before simulating an energy system there are an enormous number of parameters that have to be set. The installed capacities and expansion pathways of the different energy sources are set exogenously for the period to be analyzed. For each time step, the production of wind, solar and run-of-river electricity is subtracted from the demand. The so-called residual load, defined before, is then supposed to be supplied by the least expensive combination of the fully controllable production plants, storage units and grid utilization (Wiese, Renewable Energy Pathway Simulation System - Manual, 2013).

Licenses for open source software are designed to guarantee the freedom to share and change all versions of a program and to make sure it remains free software for all its users. If changed copies of the software are distributed, the distributor has to make sure that the recipients can also get the source code and that they get to know which rights they have. The GNU – General Public License is a free copy left license for software and other kinds of works, and RENPASS will be published under GNU GPL 3. According to this license, everybody can use RENPASS and adjust it to their needs, and this is important to keep the model open (Wiese, Renewable Energy Pathway Simulation System - Manual, 2013).

The aims of this model are: to be a techno-economic simulation of 100% renewable energy systems and pathways; comparability, transparency and reliability of assumptions for credibility; dependency of the active participation of the users; retrievability of mistakes in the calculation and data; making gaps in data availability obvious and modular setting to combine expert knowledge of different areas. For this dissertation, not all the areas of the model were taken in consideration (Wingenbach, RENPASS).

2. METHODOLOGY

In this chapter, the methodology used for this thesis is explained in detail, mapping out the methods that were used throughout the work. It also summarizes the important values that will be used later on the project, and which components will be studied. A big part of this chapter is about data collection and therefore all databases will be mentioned. Charts and tables were created to provide a better overall view of the three energy sources that were taken into consideration, and also regarding electricity demand. After that, an explanation will be provided as to why these data were collected, how they take part of the study, and how they will be manipulated. A data interpretation is also done, along with the RENPASS results. The RENPASS results are included in this chapter, since they are part of the methodology. Modeled data and measured data are compared during this chapter, in order to validate results.

2.1 Data collection and processing

The first step was to collect real measured data from consistent sources to be used as the basis of the current work and hypothesis. Data about demand, wind and solar potential and also about the run-of-rivers' energy were collected. These non-modeled data were mainly collected from ENTSO-e, but also from other sources that will be referenced below.

One of the purposes of data collection was to compare it with modeled data. As it was already referred, this work is based on modeled data provided by the RENPASS model. This model was already tested for Germany (Wingenbach, RENPASS). Therefore, another goal of this study was to test if the model could be applied to Portugal and Spain. Thus, in order to rely on these modeled data, it is useful to compare it with data that can be collected from databases.

After data collection, several scenarios regarding demand, generating capacity and production can be created. For instance, after obtaining demand data, a factor value is set up to multiple the demand values for that factor. Moreover, if a scenario considers a 10% demand increase by 2050, regarding 2012, the factor would be 1.1. This will also work for the generating capacity: with a small range of calculations one can get the energy production from each source, just by setting up a value for the installation of the sources that will be taken into consideration.

As a result, the residual load can be calculated based on demand and energy production scenarios. Moreover, this calculation of residual load, for Portugal and Spain, can later help in making a better analysis.

The model was developed for common years. As 2012 was a leap year, the last day of the year (31st December) was not considered for practical purposes (Wingenbach, Adaption of wind turbine and photovoltaic simulation algorithms of RENPASS to Portugal and Spain, 2014). Without this step, calculations would not be possible.

It is important to mention that all the procedures made in this work were exactly the same for Portugal and Spain, with the exception of some data format and preparation.

2.1.1 Demand

The hourly load values [MW] were collected for Portugal and Spain, for the years of 2012 and 2013. These values correspond to the hourly average active power absorbed by all installations connected to the transmission network or to the distribution network, excluding pumps of pumped-storage stations and the consumption of generating auxiliaries. However, network losses are included. In the database[6] it is possible to download the hourly load values for a specific country and for a specific month.

The initial idea was to collect demand data for Portugal and Spain for 2013 (latest year). However, given the fact that other required data were only available for the year of 2012, demand data for this

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[6] ENTSO-e

year were also collected. This was done in order to maintain consistency throughout the whole study. Several charts were created, for both countries, in order to evaluate the monthly demand characterization (that leads to energy consumption). These data was obtained from ENTSO-e.
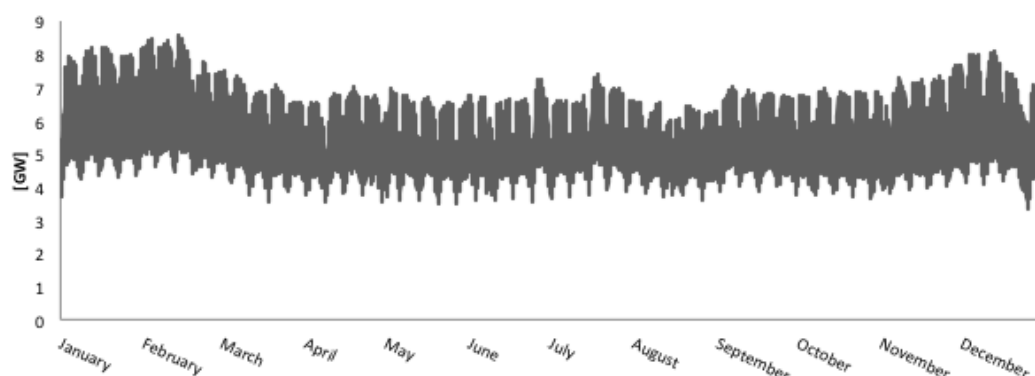
Figure 2.1 - Load hourly values, Portugal, 2012, ENTSO-e
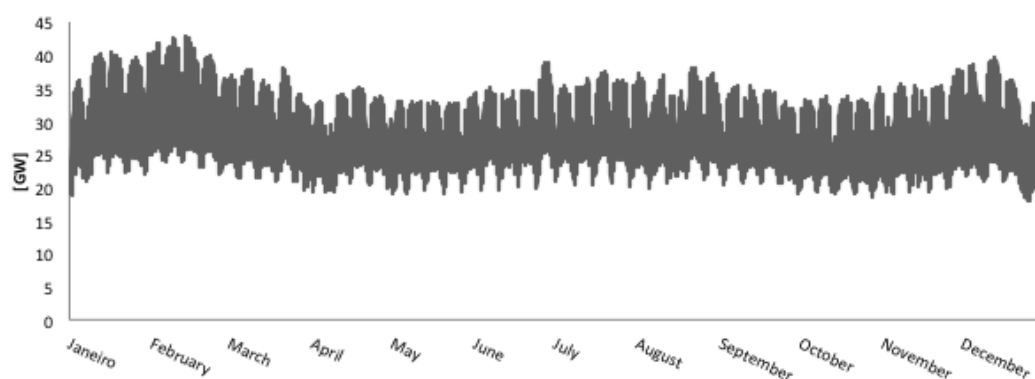
Figure 2.2 – Load hourly values, Spain, 2012, ENTSO-e

It is important to point out that consumption should not be confused with load. Load is always a snapshot of one single moment (power, with units of GW), while consumption describes a time period (energy, with units of GWh). Moreover, load is calculated as an average value for every hour and therefore consumption can be calculated based on a load integral.

2.1.2 Generating capacity

The net generating capacity of a power station is the maximum electrical net active power it can produce continuously throughout a long period of operation in normal conditions, where 'net' means the difference between the gross generating capacity of the alternators and the auxiliary equipments' load and the losses in the main transformer of the power station. The net generating capacity of a country is the sum of the individual net generating capacities of all power stations connected to either the transmission grid or to the distribution grid.

Data collection was done regarding years 2010 to 2013, to be able to have an idea of the installed power (in MW) during this period. However, the needed data to study the *status quo* refer only to 2012 and were specified for each kind of renewable energy. These data were collected from ENTSO-e. The following table shows what data were needed for this work, as a reference. However, data about the run of the rivers were not available.

Table 2.1 - Generating Capacity [MW], ENTSO-e

	Portugal	Spain	
Solar (PV)	122	4,104	2010
	155	4,916	2011
	220	6,444	**2012**
	282	6,894	2013
Wind	3,705	19,821	2010
	4,080	20,729	2011
	4,194	22,534	**2012**
	4,368	22,768	2013

2.1.3   Production

From the ENTSO-e database it is also possible to collect data regarding the detailed monthly production of Portugal and Spain. This data collection was made for the years 2010 to 2013. However, unlike demand data, production data were only available in monthly values. There were also collected data from REN, and from Paul-Frederik Bach, in a quarter-hour basis and in an hour basis, respectively.

Although data were collected for the past four years, only data for 2012 were considered for the present study, because that is the most recent year with the most reliable and updated data. Energy production mainly depends on the installed power of wind, solar, run of the rivers, and also on renewable sources offer during these years (like wind speed, radiation, and precipitation levels). This production values analysis worked as a comparison tool, in order to check the applicability of RENPASS's modeled data to Portugal and Spain. The latest kind of renewable energy was the run-of-rivers, as it was noticed that it could be very useful, mainly because this is also a dispatchable energy source. Table 2.2 summarizes the measured data sources.

Table 2.2 - Databases

	Portugal	Spain
Solar (PV)	**ENTSO-e**	**ENTSO-e**
Wind	**ENTSO-e**	**ENTSO-e**
		P. F. Bach
Run of River	**REN***	**REN**[7]
	ENTSO-e	**ENTSO-e**

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[7] This data was calculated based on the one for Portugal(*): normalized according to the yearly electricity production of both countries, since it was not possible to find reliable data

Table 2.3 - Yearly electricity production [GWh]

	Portugal	Spain	
Solar (PV)	-	-	2010
	-	-	2011
	357	11,615	**2012**
	447	13,135	2013
Wind	9,023	43,357	2010
	9,002	42,105	2011
	10,011	48,471	**2012**
	11,751	55,356	2013
Run of River	-	-	2010
	-	-	2011
	3,669	6,544	**2012**
	6,986	9,606	2013

No data regarding solar energy and run of river energy was available for the years 2010 and 2011.

2.1.3.1   Solar

Electricity production resulting from solar energy both in Portugal and Spain mainly depends on solar energy power plants. As the potential is quite substantial, the electricity production does not depend that much on that potential. By analyzing the monthly values, it is possible to notice that there is a higher offer from this kind of renewable energy during the summer. However, this source of energy is still profitable during winter (Figure 2.3).
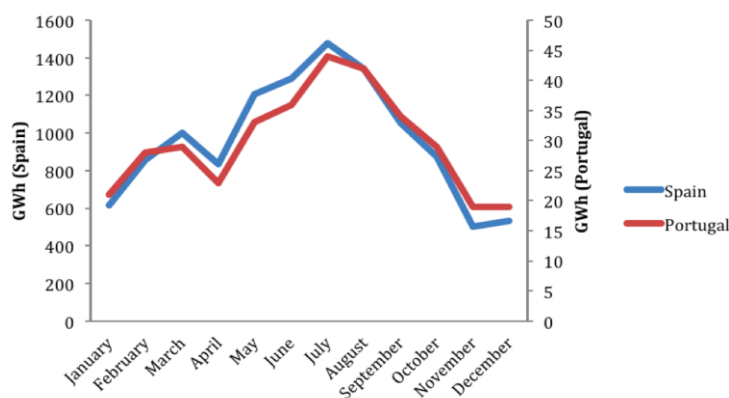
Figure 2.3 - Solar production in 2012, ENTSO-e

2.1.3.2   Wind

Given the fact that the wind power installation on both countries is the same during the year of 2012, production variations are mainly caused by weather conditions. As can be seen, production patterns in Portugal are not that different from those of Spain. The main disparity concerns the power installation, which makes sudden variations in the Spanish wind production when wind conditions change and smoother variations in Portugal when weather conditions change. Apart from this, a significant

uncertainty in the estimate of energy from a wind plant is the interannual and interseasonal variation in energy output (Baker, Walker, & Wade, 1990).
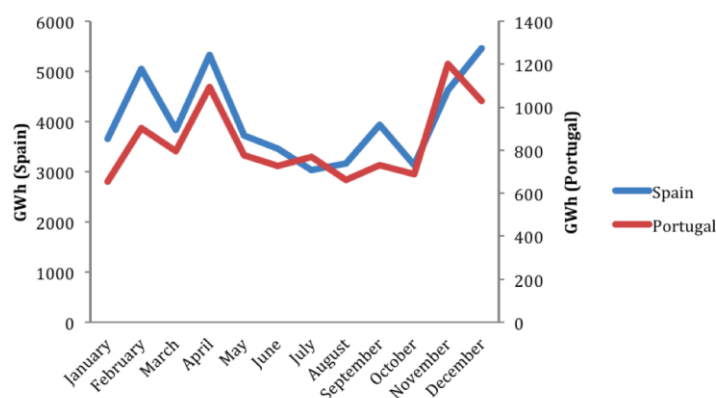
Figure 2.4 - Wind production in 2012, ENTSO-e

2.1.3.3   Run-of-River

The electricity produced from the run-of-rivers was considered later on the present study. These data were not available for the years of 2010 and 2011. For 2012 and 2013, only monthly values were available from ENTSO-e. Later on, data in a quarter-hour basis for 2013, for Portugal, were possible to obtain, unlike data about wind and solar production. Data for 2013 were collected from REN, after thorough research and after contacting some researchers on this field. Though, as these data were only available in a quarter-hour basis, raw data has gone through a process: every four values were summed up so that one could get hourly data. As there were no data about this type of energy production for Spain, data were normalized for Spain, according to yearly electricity production of both countries (ENTSO-e), as pointed out before.

Figure 2.5 shows how this source offer is changing throughout the year.
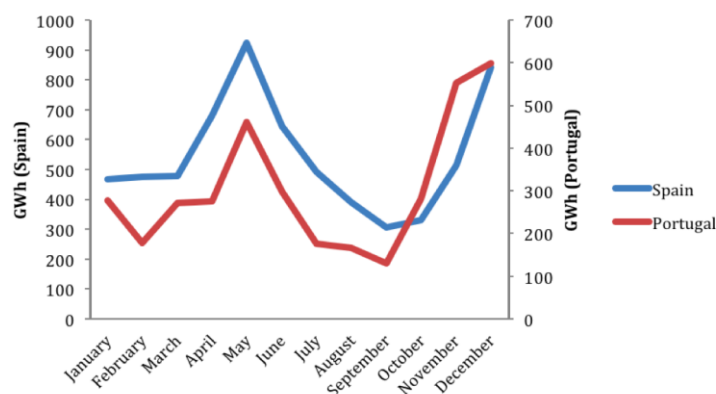
Figure 2.5 – Run-of-river production, 2012, ENTSO-e

As the run-of-river potential is still not clear and studies do not provide any concrete information about it, it was assumed that the energy taken from this renewable source in 2013 would at least be the same as in 2050.
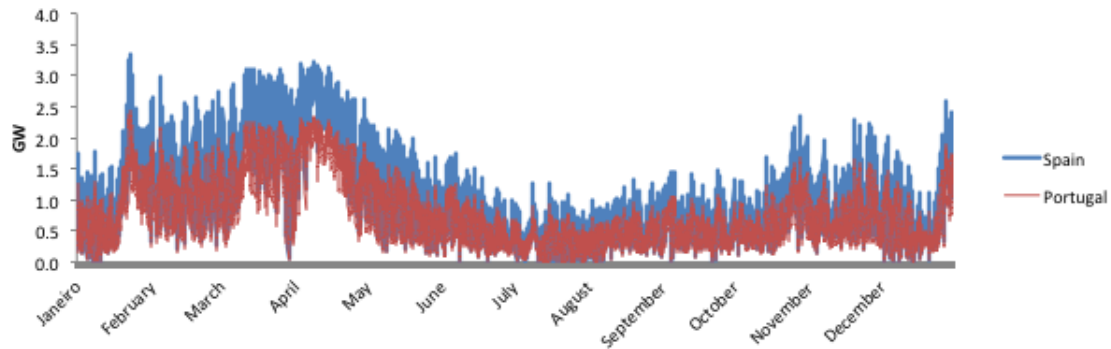
Figure 2.6 – Run-of-river production, 2013, REN

2.2 Data interpretation

First of all, one can notice that electricity consumption increases substantially, in both countries, during the warm and the cold seasons. This means that both countries have two relatively extreme seasons, which require heating/cooling during winter and during summer. Spring and autumn are periods that apparently have comfortable climate conditions. Unlike Germany, Portugal and Spain have high needs for cooling power during summer.

From November to February, electricity consumption is also higher than during the warmer seasons. Higher artificial lighting and cooling needs can be considered as a reason for this fact.

Many users using a lot of electricity at the same time cause periods of peak demand. For example, on a hot day many households and offices will turn up their air-conditioning, causing a sharp increase in electricity demand. There could be other explanations, such as holidays, companies' production peaks, heat waves, cold waves (increases heating needs), etc.

As figure 2.7 shows, Spain's electricity demand is five times higher than Portugal's. This is due to obvious differences in population and country size.
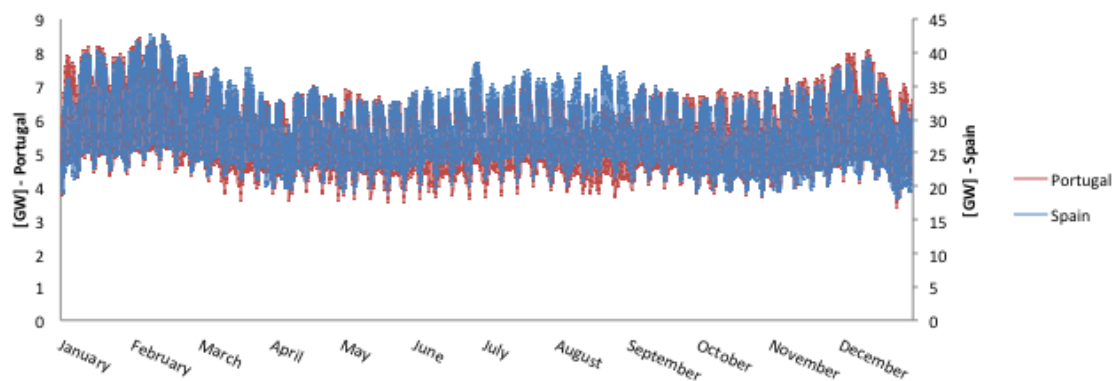
Figure 2.7 - Electricity consumption, Iberian Peninsula, 2012 (normalized)

A more detailed study regarding electricity consumption was also done, in order to verify how the daily characterization would be.
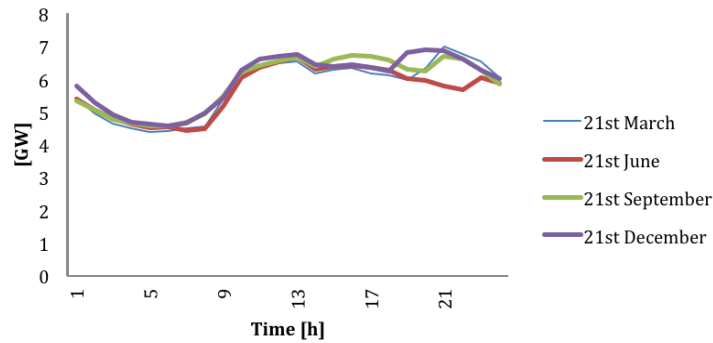
Figure 2.8 - Electricity consumption for 4 different season days, Portugal, 2012
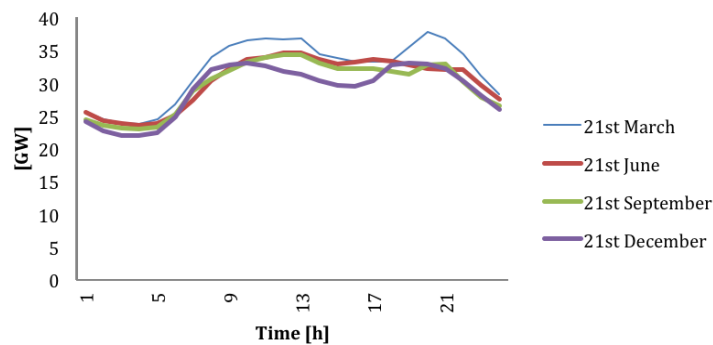
Figure 2.9 - Electricity consumption for 4 different season days, Spain, 2012

Even in different seasons of the year, one can realize that there is a daily demand pattern, present throughout the year. However, it is interesting to consider that a possible change in demand peaks will show up in 2050. The main change will probably be on daily demand, due to different life styles and tariffs.

According to figure 2.3, Spain has a greater potential for solar energy production than Portugal. As both countries have approximately the same weather conditions and, for this reason, roughly the same amount of solar radiation, this figure makes it very clear that it is just a matter of installed power - and subsequently, energy policies – than a matter of potential and energy offer. Despite this, it is clearly shown the natural structure of this chart: a much higher solar production between April and October, which is typical of a North Hemisphere country that has not a very usual cloudy weather.

If we look to figures 2.5 and 2.6, it is possible to verify that there is a lower rate of precipitation during the warm season, around summer and autumn, and a much higher increase during winter and especially during spring. This influences directly, as one can see, the run of the rivers electricity production, which means this source has the power to be a great contribution to satisfy the demand needs during this period.

2.3 RENPASS Results

The RENPASS results were obtained in hourly values, according and based on wind speed, radiation, etc. and those were the values where this work relied on. These RENPASS results were hourly normalized values for: wind and solar in Spain and wind and solar in Portugal. These four RENPASS results were obtained in a .csv format and they were worked on until they could be usefully evaluated.

Although these were values in an hourly basis, they were transformed in monthly values in order to be easily analyzed. Figures 2.10 and 2.11 provide us a general overview of comparison between these two sources in Portugal and Spain.
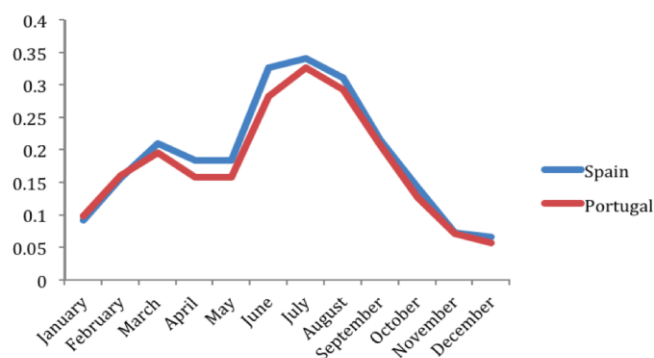
Figure 2.10 - Solar results, RENPASS Model (Normalized values)
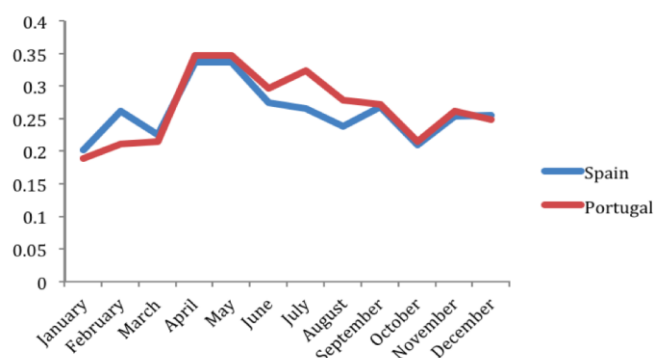
Figure 2.11 - Wind results, RENPASS Model (Normalized values)

As the model considers mainly weather conditions, apart the installations of wind turbines and solar panels, it is easily noticeable that both countries have quite the same potential, concerning wind and solar energies. It is possible to confirm this fact if one compares figures 2.3 and 2.10. The same works for wind: it is very useful to compare Figure 2.4.

2.4 Comparison between modeled data and measured data: validating RENPASS results

In general, data quality is never as high as we need it but still, obviously, measured data is always better and more reliable than modeled data. It is viable to use modeled data if, for example, it is not possible to get reliable measured data or if one of the goals is to test the model in use. In that case, a comparison is a way to verify whether the model is working properly or not. In this specific situation, the model was already implemented to Germany and to its surrounding countries and one of the objectives is to verify if some parts of the model (those required for this work) can be adapted, if they are working properly, and also if the model itself can really be extended and implemented for Portugal and Spain. This process makes part of the results validation.

In order to build a method of comparison, between modeled and measured data, the modeled data obtained from the RENPASS model, which was taken for solar and wind in Portugal and solar and wind in Spain, was multiplied by the generating capacity [MW] of each corresponding energy. For example, the 3760 normalized hourly values of solar in Portugal in 2012 were multiplied by the installed solar power of that year (220 MW). Subsequently, one obtained 3760 values in MW, and they were summed up in order to get monthly values so, afterwards, the result is twelve monthly values in GWh. From then on, these values could already be compared with the ENTSO-e measured data, which could only be collected in a monthly format.

The same procedure was done for the other data, except for wind in Spain. In this case, in addiction to this process, as it was possible to get hourly values, from P. F. Bach (mentioned above), a deeper evaluation was feasible. Besides the analysis based on the ENTSO-e data, the modeled data could also be compared with this other source (P. F. Bach), on an hourly basis. Unfortunately, this could not be done for the data for Portugal and solar for Spain.

Despite the fact that it is much more useful and precise to have hourly values, they can only be comparable with ENTSO-e data if they are also converted in monthly values. The ideal would be to have measured hourly data, from ENTSO-e or another database, for all the sources.

Figures 2.12 and 2.13 show how this comparison was taken into consideration.
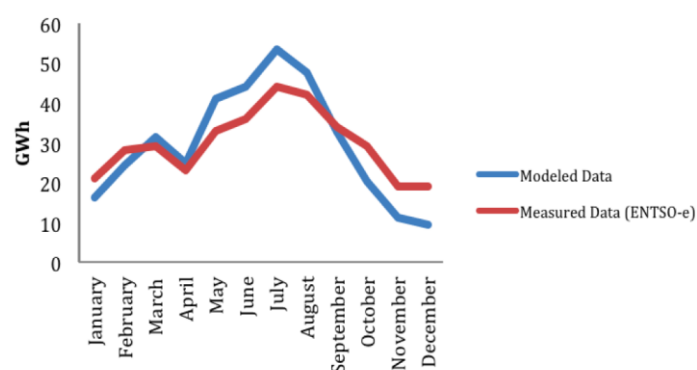
Figure 2.12 - Solar production, Portugal, 2012: Comparing modeled and measured data
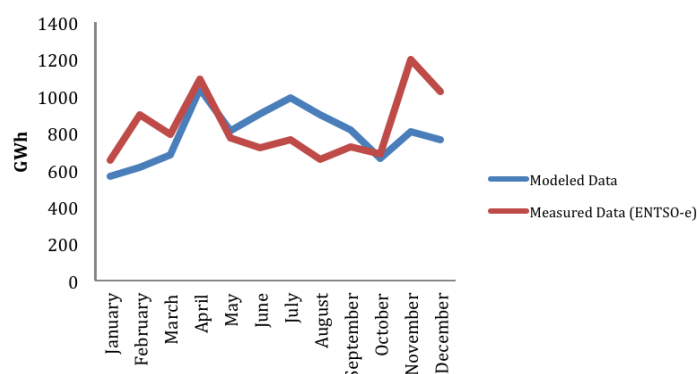
Figure 2.13 - Wind production, Portugal, 2012: Comparing modeled and measured data

For the solar production in Portugal, the yearly deviation between the modeled data and the measured data is -0.1%, based on the ENTSO-e data (measured). On the other hand, the yearly deviation for wind production in Portugal is higher: 4.8% (Figures 2.12 and 2.13).
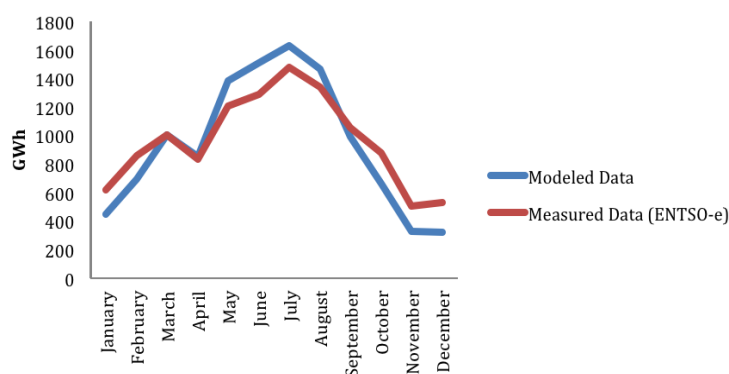
Figure 2.14 - Solar production, Spain, 2012: Comparing modeled and measured data
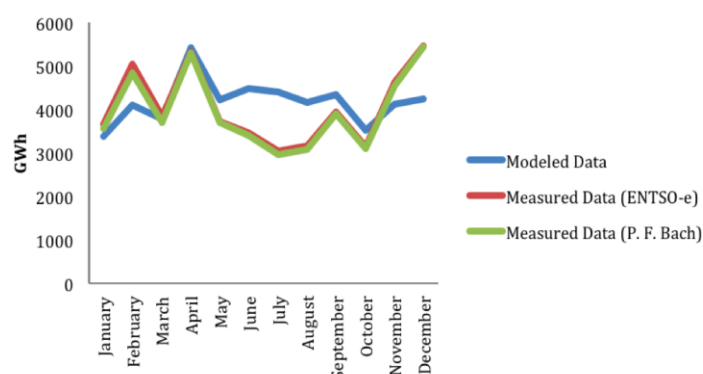
Figure 2.15 - Wind production, Spain, 2012: Comparing modeled and measured data

For the solar production in Spain, the yearly deviation between the modeled and the measured data is 2.5%, based on the ENTSO-e data (measured). For the wind production in Spain, there is in addiction the P. F. Bach measured data, which could be collected in a hourly basis, but it was summed up to be comparable with the ENTSO-e data. This time, the yearly deviation based on ENTSO-e is 3.5%, and the deviation based on P. F. Bach is 5.3%.

According to figure 2.15, it is easy to realize that both measured data are matching reasonably well, which is a sign that both data are reliable and trustworthy.

Table 2.4 summarizes the yearly deviations between the modeled and the measured data, for both countries and for both energy sources.

Table 2.4 - Yearly deviations between modeled and measured data: in yellow, based on ENTSO-e; in blue, based on P. F. Bach

	Solar	Wind	
Portugal	-0.1 %	4.8 %	
Spain	2.5 %	3.5 %	5.3 %

2.5 Residual load calculation

In this specific case, residual load is calculated by subtracting hourly values of wind, photovoltaic and run of the river generation from hourly demand data. These have to be must-run requirements. If residual load is then sorted in descending order, a load-duration curve is created.

After obtaining the RENPASS results, the 8760 values (24 x 365), for wind and solar, in Portugal and Spain, columns of normalized values are built. Afterwards, these columns multiplied by any value for solar and wind installation would create another column for electricity production.

Table 2.5 schematically describes how the calculation of this factor is done.

Table 2.5 - Residual load calculation scheme

Values	Demand	–	Wind	–	Solar	–	Run-of-river	=	Residual Load
1	d_1	–	w_1	–	s_1	–	r_1	=	RL_1
2	d_2	–	w_2	–	s_2	–	r_2	=	RL_2
3	d_3	–	w_3	–	s_3	–	r_3	=	RL_3
…	$d_{...}$	–	$w_{...}$	–	$s_{...}$	–	$r_{...}$	=	$RL_{...}$
3760	d_{3760}	–	w_{3760}	–	s_{3760}	–	r_{3760}	=	RL_{3760}

The three columns in the middle (**demand**, **wind**, **solar**) have calculated values, which can change if the factors mentioned above are changed. These columns calculations are:

$$Demand = Demand\ in\ 2012\ \times\ demand\ factor \qquad \text{Eq. 1}$$

$$Wind = Normalized\ wind\ values\ [RENPASS] \times\ wind\ factor\ [MW] \qquad \text{Eq. 2}$$

$$Solar = Normalized\ solar\ values\ [RENPASS]\ \times\ solar\ factor\ [MW] \qquad \text{Eq. 3}$$

$$Run-of-river = Run-of-river's\ production\ in\ 2013 \qquad \text{Eq. 4}$$

$$Residual\ Load = Demand - Wind - Solar - Run-of-river \qquad \text{Eq. 5}$$

A null residual load represents the ideal overall scenario, since it means that all the demand would be satisfied by the production that comes from solar, wind and run-of-river energy. This is, for an hourly or daily basis, unreal. The instantaneous residual load for electricity varies continuously, and supply must exactly meet demand at all times in a power system in order to maintain the system's stability, which means that generation should also ramps up and down continuously with demand. If $\sum_{i=1}^{8760} RL_i < 0$, it means that the yearly electricity production coming from a given renewable energy source, in total, is higher that the electricity consumption.

The calculation of the residual load allows an analyzing procedure that can help us to be critical when evaluating a scenario. It shows if, with a specific scenario, a big need of storage would be required or if transmission of electricity from neighboring countries/grids should be considered.

3. SCENARIOS DEVELOPMENT

The scenarios development is a process that demands an analysis of several factors. The calculation of the residual load is the basis to evaluate the scenario creation. An excel sheet was created in order to have all the elements that influence the residual load characterization of a specific scenario. Everything that will be described was done for Portugal and Spain.

The demand data of 2012 and the solar and wind normalized values, obtained from the RENPASS model build fixed columns:

Hour	2012 GW Demand	Normalized Values Solar	Wind
1	5.404	0	0.047
2	5.196	0	0.049
3	4.954	0	0.058
4	4.573	0	0.061
5	4.277	0	0.071
6	4.102	1.41E-11	0.088
7	4.009	3.38E-10	0.106
8	3.958	3.40E-10	0.125
	3.702	0.00141598	0.146

Figure 3.1 - Fixed values

The next step was to create cells that are changeable: the demand factor, the solar factor and the wind factor. These three values define how demand will increase/decrease and which installation of solar and wind will be in 2050:

Demand Factor, d.f.	1	INCREASE RATE
Solar Factor, s.f.	1000	GENERATING CAPACITY [MW]
Wind Factor, w.f.	2000	

Figure 3.2 - Changeable cells

Next, three other columns were created: demand of 2012 × demand factor; solar normalized values × solar installation and wind-normalized values × wind installation (Table 2.5).

If we define the demand factor at 1, it means that the column regarding demand in 2050 will be equal to the column about demand in 2012:

Figure 3.3 - Changing electricity demand and wind and solar production

If we write, in the cell about the solar installation, the number 1000, it means that the column regarding solar production (2050) will be the column of the normalized values of solar x 1000; and exactly the same works for wind production.

After this procedure, the run-of-river production was also added, as shown on figure 3.3, with no calculations associated. These values were collected about the year 2013. As it was mentioned before, it was assumed that this production would be, in 2050, at least the same as in 2013.

Finally, the residual load could be calculated, by subtracting the solar, wind and run-of-river electricity production from the electricity demand. Several charts were created, in order to be possible to make a

deep analyze. Based on this analyze, it is possible to be critical and to decide if the scenarios are viable.

3.1 Changing the Demand factor and the Generating capacity

Five charts were created to allow an analysis of the residual load. Some macros in excel were created in order to recalculate all the values after changing the factors. One shows the residual load in a hourly basis, with 3760 values; another shows a duration curve of the residual load – this one requires a descending reorder of the values of the residual load; another one shows a monthly residual load, in TWh, which is very useful as it is able to show that, in some months, production is not enough to meet the demand and some others have over-production. The other two charts are relative to a day/night analysis: one shows the total day/night residual load, and the other displays the day/night residual load, according to the four seasons.

3.2 Costs in 2050: Initial investment

Another very important factor that should be evaluated in this study is the installation cost. Therefore, a calculation regarding costs was done. This costs, calculated for solar and wind, include investment and fixed operation costs, which is a percentage of the investment. According to the Scenario a3, the fixed costs for 2050 are as follows (German Advisory Council on the Environment - SRU, 2011):

Table 3.1 - Costs for 2050 [c€/kWh]

	Portugal	Spain
Solar (PV)	5.83	5.83
Wind	6.74	6.33

Every time that one of the three "changeable cells" is changed, everything changes: the calculation of the residual load is automatically re-done and the charts associated to the residual load, just mentioned, take a new shape. Macros were created and used. As of course, different installations result in different costs, different analysis about the investment also has to be done.

The goal when trying several values for the generating capacity for solar and wind was to find a combination of these two sources that would generate a total residual load approximately equal to zero, when summing up the 3760 of residual load.

3.3 Full load hours

The capacity factor is a measure of how often an electric generator runs for a specific period of time. It is useful to compare how much electricity a generator actually produces with the maximum it could produce at a continuous full power operation during the same period. For instance, if a 5 MW generator produced 25000 MWh over a year, its capacity factor would be 0,57, because $\frac{25000\ MWh}{8760\ h \times 5\ MW} = 57\%$.

The concept of full-load hours is an especially useful term for dispatchable generators, which can be switched on and off (Morris & Pehnt, 2013). There are 8760 in a normal year, and the number of full-load hours can be used as an indication of how many hours a particular generator needs to run each

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year to be profitable. For example, if a power plant needs 4000 full-load hours of operation to be profitable, that is equivalent to a capacity factor of $\frac{4000}{8760} = 45.7\%$.

$$FLH_{Wind} \; [Time, h] = \frac{Yearly \; Production \; [Energy, MWh]}{Generating \; Capacity \; [Power, MW]} \qquad \text{Eq. 6}$$

$$FLH_{Solar} \; [Time, h] = \frac{Yearly \; Production \; [Energy, MWh]}{Generating \; Capacity \; [Power, MW]} \qquad \text{Eq. 7}$$

This calculation depends on two factors that are deeply connected: if the generating capacity increases, the yearly production increases. The full-load hours is a fixed value.

Table 3.2 states how many hours would be needed to produce the year production, if the generators work all the time in their maximum power capacity.

Table 3.2 - Full load hours [h]

	Portugal	**Spain**
Solar (PV)	1,624	1,755
Wind	2,266	2,221

3.4 *Status Quo* of Portugal and Spain

The *Status Quo* of a country is the actual situation related to the subject in study. This analysis is helpful to compare the current situation of Portugal and Spain with the scenarios for 2050 that were created and that will be shown in the next chapter. In this case, it was assumed that the *Status Quo* is related not to the last year but to the year 2012. The reason for this choice is that, as stated before, the RENPASS results were related to the year 2012 due to the data for this year be better updated and more reliable than the one for the year 2013, which is still not very clear for being so recent. Towards a coherent study, the study is all done based on the year 2012.

The residual load analysis was done with different perspectives. For that, there was the need to make some definitions.

For calculation purposes, and with a deviation of around 10 days, it was practical to assume that:

Winter	January	February	March
Spring	April	May	June
Summer	July	August	September
Autumn	October	November	December

and also:

Day period	8h – 20h
Night period	20h – 8h

The values for both countries in 2012 about solar and wind installations are described in table 3.3:

Table 3.3 - Iberian Peninsula - Generating capacities, 2012, [MW]

	Portugal	Spain
Solar (PV)	220	6,444
Wind	4,194	22,534

There was no information available regarding the run-of-river generating capacity, neither for Portugal nor Spain, but only the production in 2013.

After studying the *Status Quo* of both countries, it is easier to analyze the residual load characterization, in order to be realistic and to make comparisons.

Portugal in 2012

The next charts show different points of view regarding the residual load of the country, and are supposed to give some sensitivity so that a critical analysis can be done about the several scenarios. On one hand, a positive residual load means that the renewable sources production is not meeting the electricity demand. On the other hand, a negative residual load means that electricity demand is being satisfied by the renewables production.

Figure 3.4 – Yearly residual load, Portugal 2012

The maximum hourly value of the yearly residual load is around 7 TWh, and it occurred during winter. There is already a period of time when the residual load is negative, which means that the electricity production coming from renewable energies is temporarily higher than the electricity demand. This happened during the springtime due to the high rate of precipitation. As might be expected, the rest of the time is characterized by a general positive residual load, which means that there is still a great amount of electricity that is not satisfied by renewable sources.
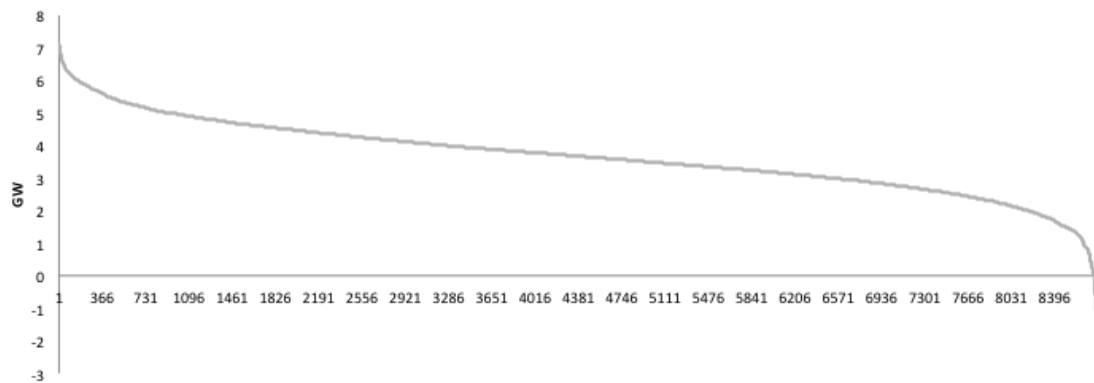
Figure 3.5 - Duration curve of the yearly residual load, Portugal 2012

The duration curve presented on the figure 3.5 shows that there are only 32 hours per year when the residual load is negative, i.e., when the electricity demand is totally covered by the electricity production. Most of the time, as would be expected, the electricity demand is much higher than the electricity production coming from renewable sources.
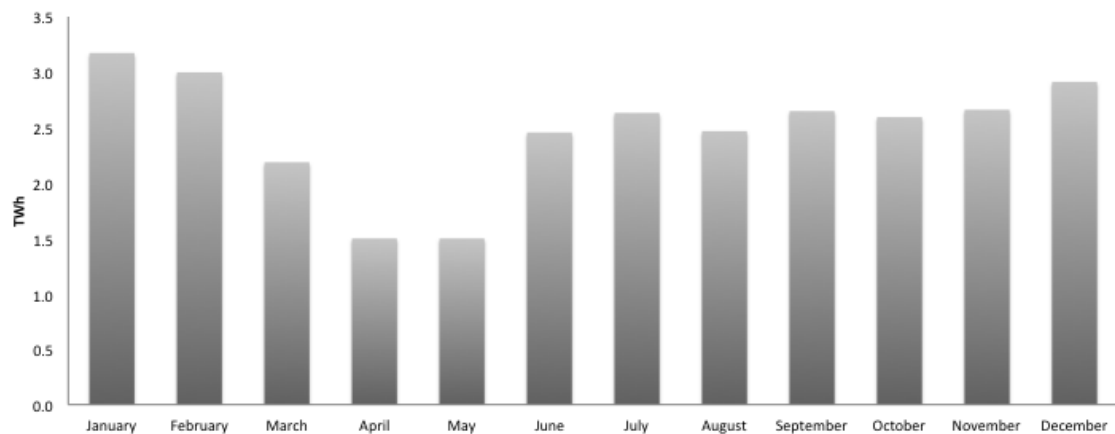
Figure 3.6 - Monthly residual road, Portugal 2012

The monthly residual load (figure 3.6) is useful to notice that there is a typical seasonal characterization, which shows a decrease on the months that have a greater precipitation frequency. It is helpful to realize if a seasonal storage could be considered, for any scenario that is set up.

The maximum production deficit, in January 2012, was 3.2 TWh in Portugal. This high value is supposed to decrease substantially, as soon as the new scenarios are created in this study.

Figure 3.7 let us understand if the rate between the demand needs and the electricity supply coming from renewable sources is higher during the day or during the night, and what is the difference between seasons. In fact, there is not a big difference between the day and night periods. Although the electricity demand is obviously higher during the day, the residual load is still usually lower than during the night, since during the night there is no solar production and the wind production is lower than during the day. In any case, it is just a difference of 0.4 TWh.
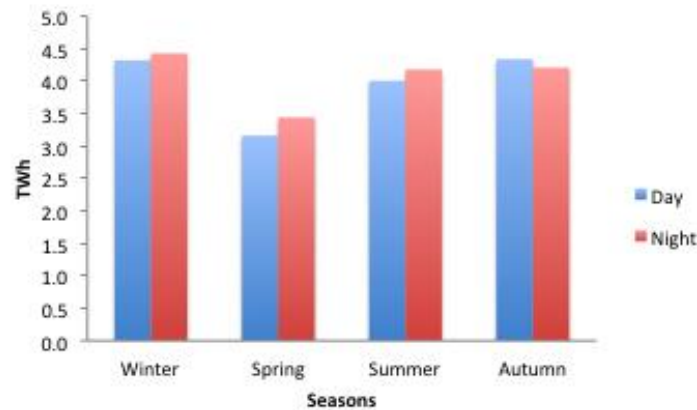
Figure 3.7 - Yearly residual load according to the 4 seasons and to the time period, Portugal 2012

One can notice that during spring, the residual load is a bit lower. This is due to the run-of-the-river production of electricity. Winter is the season in which the residual load is higher, and this fact might be justified by the higher needs of electricity during the cold season: cooling/heating, lighting needs, etc. are reasonable explanations for this statistic. It is also visible that most of the time the residual load is lower during the day, except for autumn.

Spain in 2012

As it was done for Portugal, the residual load was also analyzed for Spain, for the year 2012. The Spanish residual load characterization is quite similar for Portugal but the scale, which is higher.
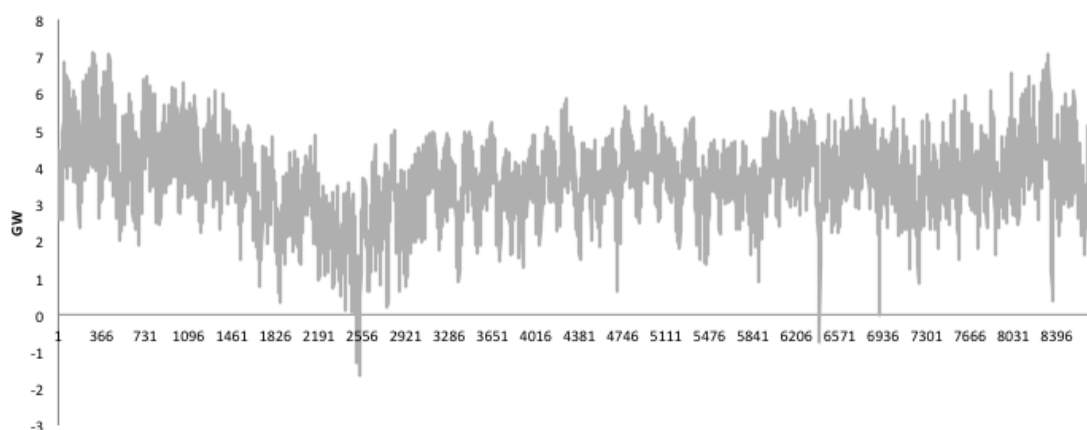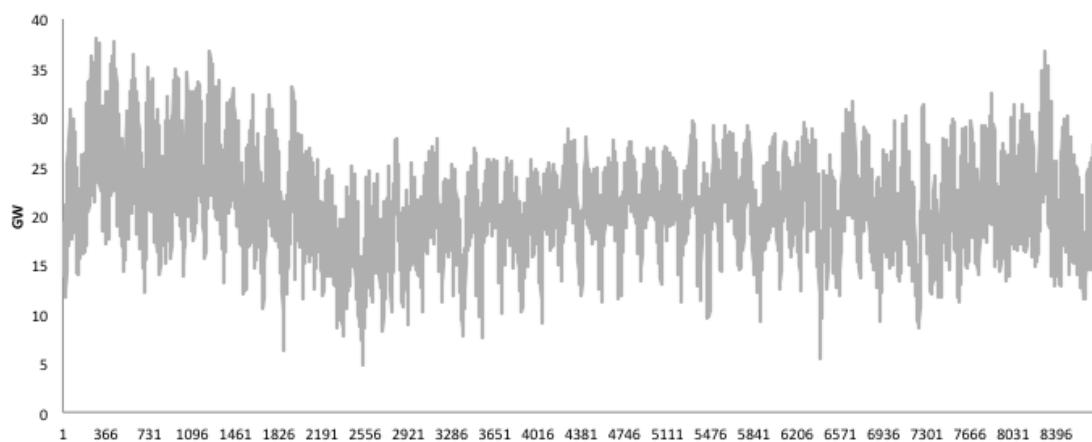

Figure 3.8 - Yearly residual load, Spain 2012

The maximum hourly value of the yearly residual load is around 38 TWh, and it happened during winter. Right now, the residual load is always positive, which means that the electricity production coming from renewable energies is always lower than the electricity demand.
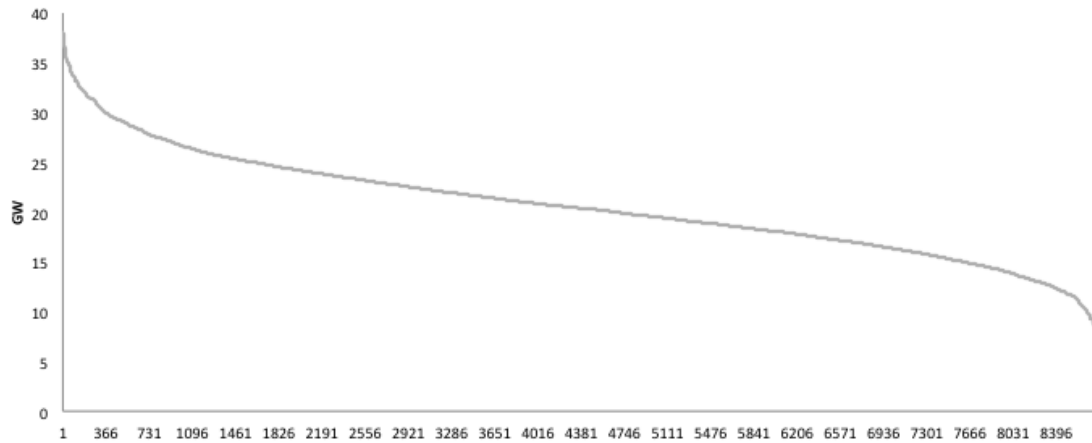
Figure 3.9 - Duration curve of the yearly residual load, Spain 2012

The duration curve (Figure 3.9) of the yearly residual load confirms that there are no negative values for the residual load in this time series. The lowest value that the residual load in Spain could achieve was 4,6 TWh: slightly lower than the maximum achieved in Portugal.
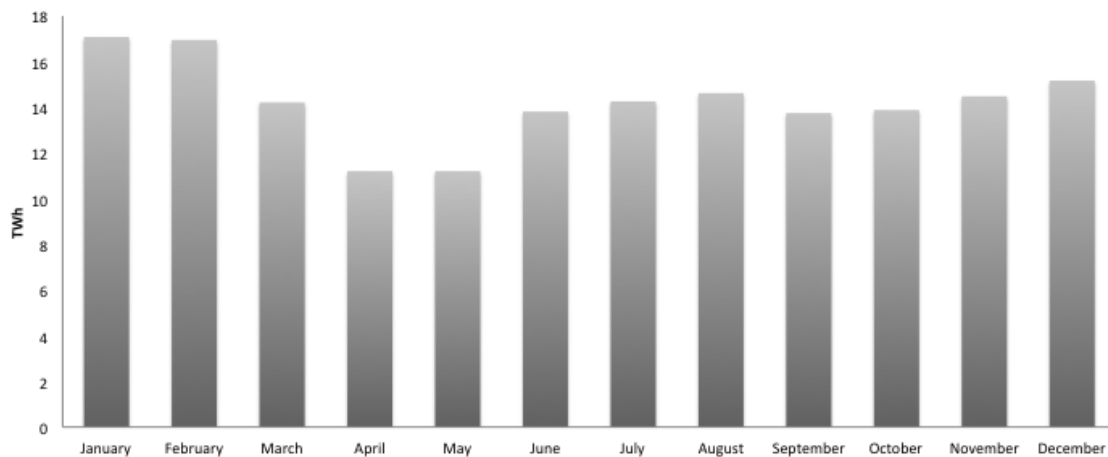
Figure 3.10 - Monthly residual load, Spain 2012

There is again, as we could see for Portugal, a seasonal pattern. The residual load is usually lower during spring and higher during the summer and winter, i.e., during both 'extreme' seasons. This can be explained by the obvious higher needs for heating/cooling during the cold and the warm seasons.

When analyzing both *Status Quo* it is easy to see that the most differences are between the seasons and that they are not mostly about the period of the time day/night.

Besides the values, it is noticeable that the patterns are the same in Portugal and Spain; undoubtedly because both countries have the same kind of climate and renewable sources potential.
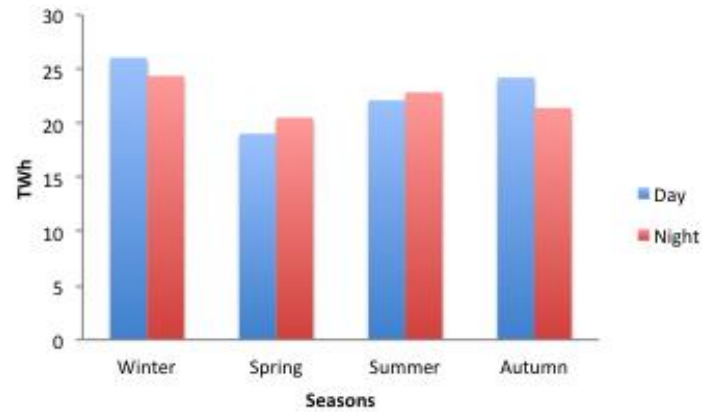
Figure 3.11 - Yearly residual load according to the 4 seasons and to the time period, Spain 2012

In Portugal, around 35% of the electricity demand is satisfied for these three renewable sources electricity production: wind, solar and run-of-river. For Spain, this value is 28%.

Besides this statistics, what come in the next chapter are scenarios of electricity production for 2050, i.e., a study regarding the electricity production and consumption in 36 years. This is why it is useful to make a study about the current situation of both countries, so that there are values we can rely on, and also results one can compare to. The method will be the same: analyzing the residual load from different perspectives in order to find out what is the best solution. The next chapter is not about predictions or simulations; it is about scenarios. In the next chapter the results will be shown, and afterwards, a deeper consideration regarding the scenarios is taken in concern. A deeper costs study will also be done.

4. RESULTS AND DISCUSSION

The scenarios development leads to the results. When defining the solar and the wind factors (installations) and the demand factor, a scenario for 2050 is created. This was done for Portugal and Spain. As there is a large number of possible combinations, not all the scenarios that were tried will be shown, but only the most relevant ones. In this chapter, several scenarios of 100% renewable electricity supply for Portugal and Spain in 2050 are presented. They were essentially based on the goal of trying to get a null yearly residual load, when summing up the 8760 values. The residual load from different points of view and the costs are analyzed in this chapter for each created scenario.

The way the installation values were chosen will also be described. In each subchapter, the chart regarding yearly residual load will be shown. After that, the monthly residual loads, the duration curves, the residual load according to the time period and to the seasons and also the costs will be shown for the four scenarios. These scenarios will be presented all together, so that a deeper and easier analysis can be done. The comparison allows an easier and more reliable evaluation of the different scenarios. Table 4.1 and 4.2 summarize the installation power for each scenario, for Portugal and Spain.

Table 4.1 - Scenarios for 2050: Portugal [MW]

Scenario	PV	Wind
4.1 'Solar and Wind 50-50%'	13,000	9,250
4.2 'Less Solar, More Wind'	6,000	14,100
4.3 'Lower Costs'	15,000	7,750
4.4 'Total residual load < 0'	6,000	16,900

Table 4.2 - Scenarios for 2050: Spain [MW]

Scenario	PV	Wind
4.1 'Solar and Wind 50-50%'	68,950	54,450
4.2 'Less Solar, More Wind'	48,000	71,000
4.3 'Lower Costs'	80,000	46,000
4.4 'Total residual load < 0'	48,000	85,200

After evaluating the residual load from different perspectives, and after selecting the most advantageous scenarios, the flexibility possibilities will also be study. These possibilities include storage and electricity transmission. This has to be taken into consideration, since it is not possible to achieve a constant null residual load, among the year.

Furthermore, the demand factor was defined at 1 for all the scenarios created, which means that it was assumed that the electricity demand remains the same as nowadays. This assumption is based on the high possibility of the population increase will be combined with energy efficiency decrease. This decrease can be justified by the fact that the more efficient the processes are the more the consumer uses them (Sorrell, 2008). For instance, if gasoline gets cheaper, people will tend to abuse of this source.

4.1 'Solar and Wind 50-50%' Scenario

To begin with, the electricity demand was summed up and a scenario with half of the electricity produced by wind and the other half by solar was created, which leads to different solar and wind power installations.

The main goal was to generate a yearly residual load, for 2050, approximately null. This was a simple scenario that worked as a baseline, since it gave some sensitivity to what can be done next and what can be changed in order to improve the residual load characterization and costs. The demand factor was set up at 1, as mentioned before, which means this scenario considers that in 2050 the population electricity demand is the same as now.

In this scenario, the run-of-river production was subtracted from the electricity demand and the rest of the electricity that needed to be satisfied was divided by solar and wind productions. As the full load hours are different for both energy sources, it resulted in different values for the installation of wind and solar. Those power installations are:

Table 4.3 – 'S. and W. 50%-50%' Scenario for 2050, [MW]

	Portugal	Spain
Solar Factor	13,000	68,950
Wind Factor	9,250	54,450

Portugal in 2050

Unlike the residual load in 2012, this residual load scenario for 2050 is very low. However, it is not possible to create a scenario that is null during all the 8760 hours of the year, because electricity demand is always changing as well as the renewable sources production.
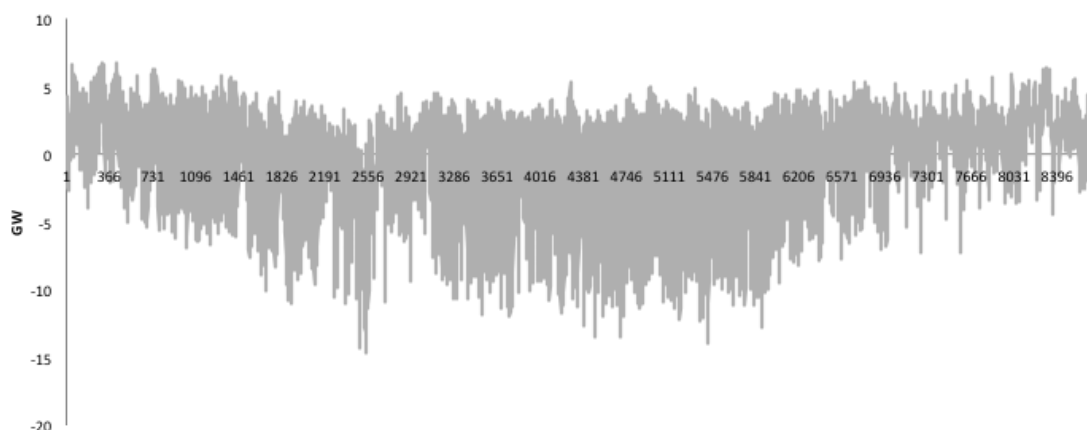
Figure 4.1 – 'S. and W. 50%-50%' Scenario for 2050: Yearly RL (Portugal)

If we compare figure 4.1 with figure 3.4 it is possible to notice a large difference between the real residual load of 2012 and the one created for this scenario, for 2050. Not only the values, but also the characterization itself obtained a new shape. There is a long period of time when the residual load is, on average, below zero – the warmer seasons. This is because of the substantial solar potential, whereas the wind potential is quite the same during winter and during summer. Since high power installations were considered in this scenario, the production of electricity is greater than nowadays.

Spain in 2050

The same method was used to calculate the yearly residual load for Spain, and the same residual load characterization is presented on the next chart (Figure 4.2). The values, however, are obviously different. The main goal is to create a time series that is as much as possible and as often as possible close to zero, which is not realistic because electricity production cannot meet electricity demand at every point.
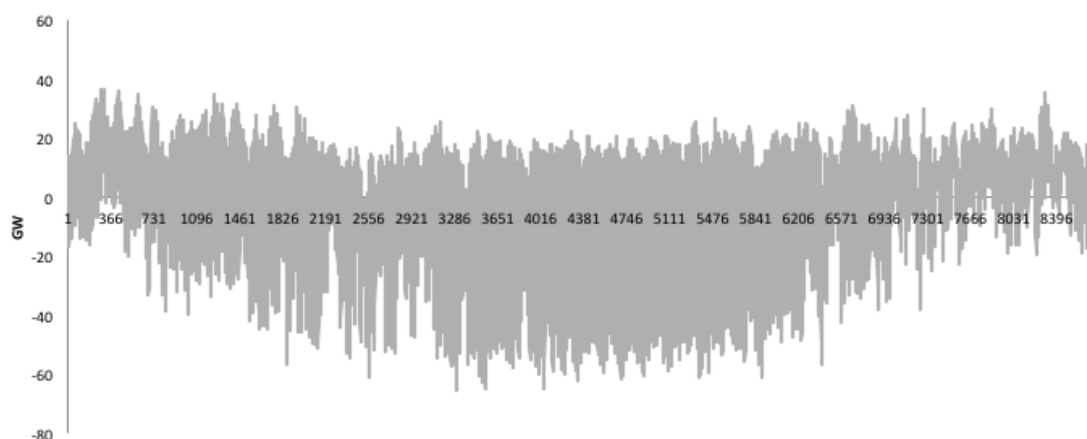
Figure 4.2 - 'S. and W. 50%-50%' Scenario for 2050: Yearly RL (Spain)

4.2 'Less solar, more wind' Scenario

The creation of this scenario was based on the first scenario (above). The very low and negative residual load associated to the warm seasons mentioned before allowed the thought about the possibility that the solar factor is too big for what is needed. During spring and summer there is great solar production, due to the big potential of this renewable source in the two countries in study: Portugal and Spain. Also, the warmer seasons are connected to an even greater potential of solar production.

The option, then, was to verify the results, setting up a lower solar factor and a higher wind factor, in order to still be possible to keep a null yearly residual load when summing up the hourly values.

Table 4.4 – 'Less S., More W.' Scenario for 2050, [MW]

	Portugal	Spain
Solar Factor	6,000 ↓	48,000 ↓
Wind Factor	14,100 ↑	71,000 ↑

Portugal in 2050

These new solar and wind factors are clearly connected to a considerable residual load characterization change. It took a new shape, and the strong fluctuations do not happen as often as in the chart presented on Figure 4.1. However, there are still some unavoidable peaks and the variations are evident, especially during spring and summer. Anyway, the values are in general getting closer to null, which is one of the main goals, in order to decrease the possible needs of storage and electricity transmission costs.
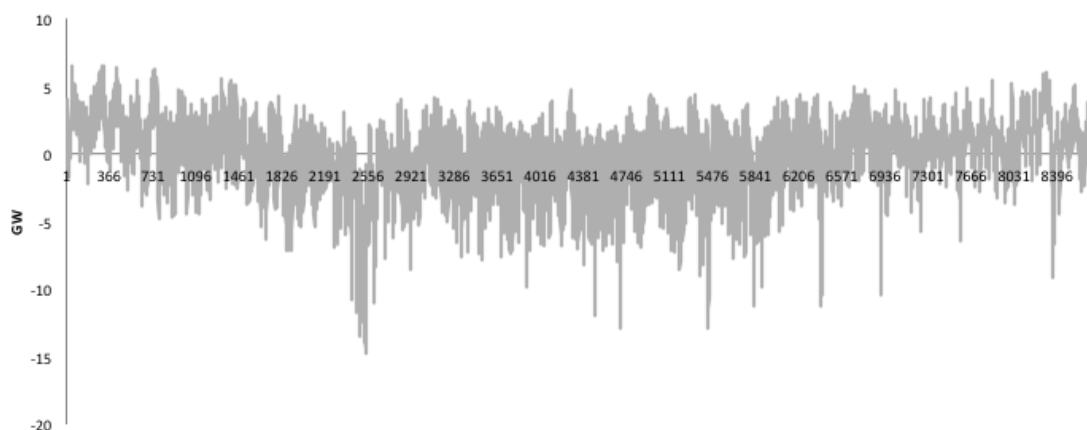
Figure 4.3 - 'Less S., More W.' Scenario for 2050: Yearly RL (Portugal)

Spain in 2050

The shape of the yearly residual load for Spain reached, for this scenario, a very similar one to the previous scenario. However, the values are, in general, closer to zero. This chart is useful to have an overall yearly view, but it is not very enlightening. It is possible to realize that around the warmer seasons the low residual load values remains.
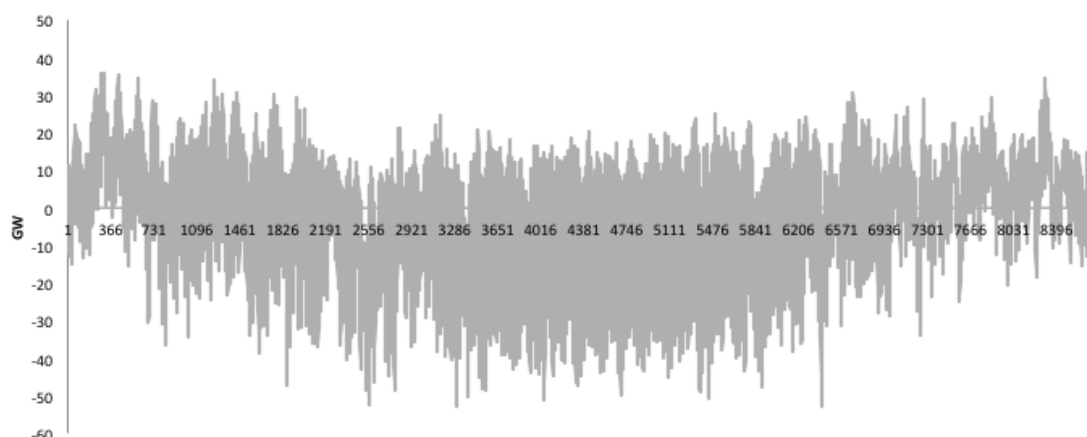
Figure 4.4 - 'Less S., More W.' Scenario for 2050: Yearly RL (Spain)

Some peaks show us some examples of immediate need of heating or cooling or higher production, as well as variations in the energy sources themselves, considering the quick weather changes (solar radiation and wind speed, for example). Besides these facts, it is possible to verify that the hourly values moved towards the X-axis, including the negative values. This means that there is also not so much waste in terms of solar and wind production. The over-production is not desirable, and, indeed, it is useful to remember that not only the lack of production will have to get a solution but also the over-production. This scenario shows a lower discrepancy between the seasons. It is important to highlight the fact that the run-of-river's overall production increases during spring, due to the higher levels of precipitation.

Observing the residual load characterization, one can verify that this scenario allowed better results than the previous one, both for Portugal and Spain.

4.3 'Lower Costs' Scenario

The previous scenario's main goal was to minimize the differences between the residual load during the warmer seasons and the colder seasons, since the first scenario (4.1) result had a very high solar production, and consequently a very low residual load during spring and summer. Decreasing the solar production and increasing the wind production was a way to minimize these differences, although the costs have increased a little.

In this scenario, the goal was also to keep a null yearly residual load when summing up the 8,760 values, but it was focused on reducing the installation costs. Since wind is expected to have higher costs than solar in 2050, the goal was to increase in 15% the solar installation [MW] for Portugal and 16% for Spain, and to decrease in 16% the wind installation for Portugal and 15.5% for Spain, in order to get lower investment expenditures.

As it has already been done, in the end of the analysis of each scenario, a consideration is done in order to understand if there was an improvement or not. If not, coming back to the previous scenario is a good way to find the approach for the best option.

Table 4.5 shows which solar and wind factor were set up and which were the increases and decreases in terms of solar and wind power installations.

Table 4.5 – 'Lower Costs' Scenario for 2050, [MW]

	Portugal	Spain
Solar Factor	15,000 ↑	80,000 ↑
Wind Factor	7,750 ↓	46,000 ↓

Portugal in 2050

Comparing with the scenario created in the previous chapter, the yearly residual load has now a much more irregular shape. While Figure 4.3 shows that the yearly values are much more focused around 0 GW, the 'Lower Costs' scenario presents as a result a worst structure. Meanwhile, this chart only gives us an overall view on the residual load over the year, but it does not allow a very specific analysis. It shows, as usual, that during summer the renewable sources production meets the demand very often, leading very often to an over-production. It is also very common that during winter the residual load increases, which means that the lack of production is very frequent during this period.
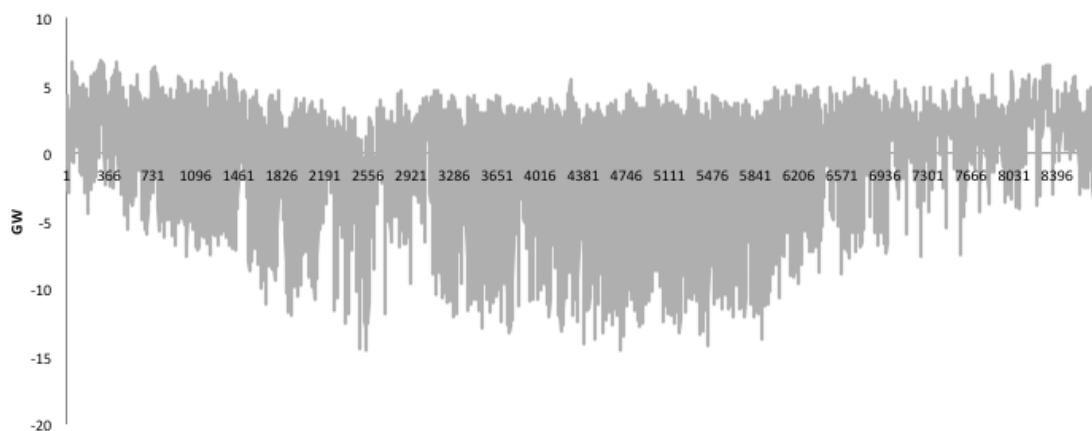
Figure 4.5 - 'Lower Costs' Scenario for 2050: Yearly RL (Portugal)

This last chart does not look like this scenario is going towards what is been looking for, unlike the "Less Solar, More Wind" scenario. The ideal would be that the time series would get thinner around the X-axis. This could be expected since, the solar factor was set up at higher value than on the scenario above, and the wind factor was set up at a lower value. It remains to be seen, however, if the whished lower prices offset these results. It is important to keep in mind that, even if this scenario shows better results in terms of installation costs, it does not mean that in general this is a "cheaper" scenario, because storage and electricity transmission still have to be taken into account.

Spain in 2050

In Figure 4.6 one can observe a different type of shape, based on the values for solar and wind factors of the yearly residual load in Spain, for the year 2050. It looks now that there is a long period, around spring and summer, where the residual load is more often low. Instead of reaching a shape closer to zero, there was a range of hours during which the residual load got inconveniently negative, as the solar factor increased a lot. Ideally, this chart would be as thinner as possible around the X-axis. While the maximum does not reach 40 GW in any hour, during the negative 'moments' it can get close to -80 GW, which is not very balanced.
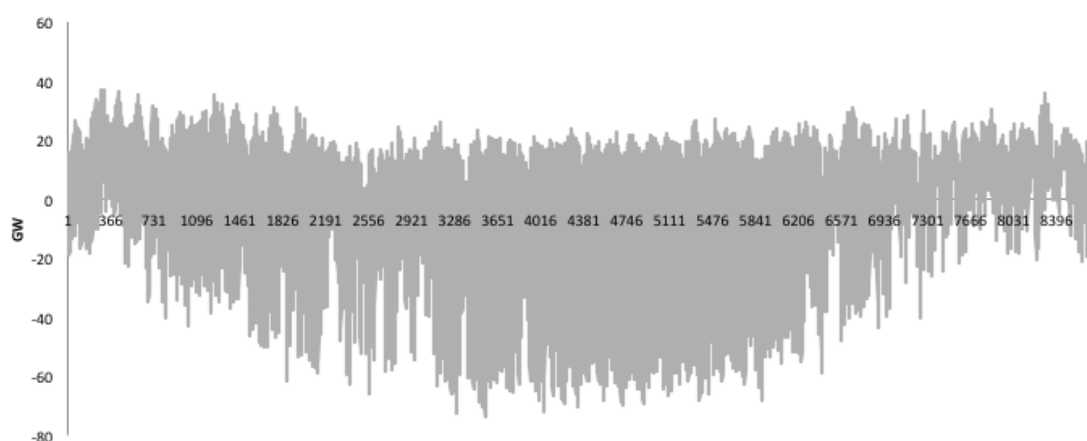
Figure 4.6 - 'Lower Costs' Scenario for 2050: Yearly RL (Spain)

Apparently, there are no obvious benefits in choosing this scenario to the detriment of the 'Less Solar, More Wind' scenario, apart from the installation costs that will still be studied.

As these sources (solar and wind) have different structures and potential according to the time period and to the seasons, they must be adapted so the combination gives us a result we need. For example, even with lower costs associated, increasing the solar factor in a country that does not have a big potential of solar production is probably not a good decision. In the case of the Iberian Peninsula, this increase would give a big profit during summer and spring (the sunniest seasons) but the residual load during these seasons would be too small, which is also not the goal.

Since the second scenario was the one that displayed better results so far, the idea now was to create a fourth scenario which is suppose to be an improvement, based on the 'Less Solar, More Wind' scenario.

This time, a greater production and a "higher supply" will be tried, which means that, unlike for scenario 4.1, 4.2 and 4.3, now the sum of the hourly values of the yearly residual load will be negative.

4.4 'Total Residual Load < 0' Scenario

Given the fact that the previous scenario (4.3) showed less interesting results in terms of residual load, this fourth scenario will be based on the second one. Besides the lower installation costs associated to scenario 4.3, storage and electricity transmission costs will still have to be calculated and studied, in order to conclude if these lower installation costs are profitable or not. The fact is that they probably do not justify the much higher and inconvenient seasonal residual load variations.

A 'total residual load' slightly lower than zero was tried this time. This total is referred to the yearly 8,760 values, all summed up. The solar and wind factors were based on the second scenario presented in chapter 0: the solar factor, for both countries, was set up at the same value as in the 'Less Solar, More Wind' scenario and the wind factor, also for both countries, was set up at 20% higher than in the 'Less Solar, More Wind' scenario, which means 16,900 MW in Portugal and 85,200 MW in Spain. The goal was to emphasize the effect of the scenario mentioned, since that showed to be the most viable one until now. Increasing wind power installation does not completely guarantee the supply, (that would mean that the residual load is never positive), but it would result in a higher rate of electricity supply and, subsequently, the yearly residual load would get slightly more negative. In the beginning, this scenario was about to be set up at an increase of 10%, for both solar and wind, also related to the second scenario. Afterwards, a deeper analysis allowed concluding that there was no need for increasing solar production, but instead, it suggested that a higher wind production would be more advantageous.

Table 4.6 - 'Total Residual Load < 0' Scenario for 2050, [MW]

	Portugal	Spain
Solar Factor	6,000 =	48,000 =
Wind Factor	16,900 ↑	85,200 ↑[8]

Portugal in 2050

Figure 4.7 shows the first result of this scenario. It is very similar to the one of scenario 4.2. This time, the solar factor remained the same as in the scenario mentioned, and the wind factor increased by 20% relatively to that scenario. The yearly residual load has a much thinner shape around the X-axis, as it was desirable. There is a time period around spring when the residual load is very often negative; this is again due to the high rate of precipitation, typical of this season. Apart from that, the hourly residual load not often is higher than 5 GW. Apart from the peaks, it is almost never lower than -10 GW.

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[8] Both increases are related to scenario 4.2 ('Less Solar, More Wind' scenario)
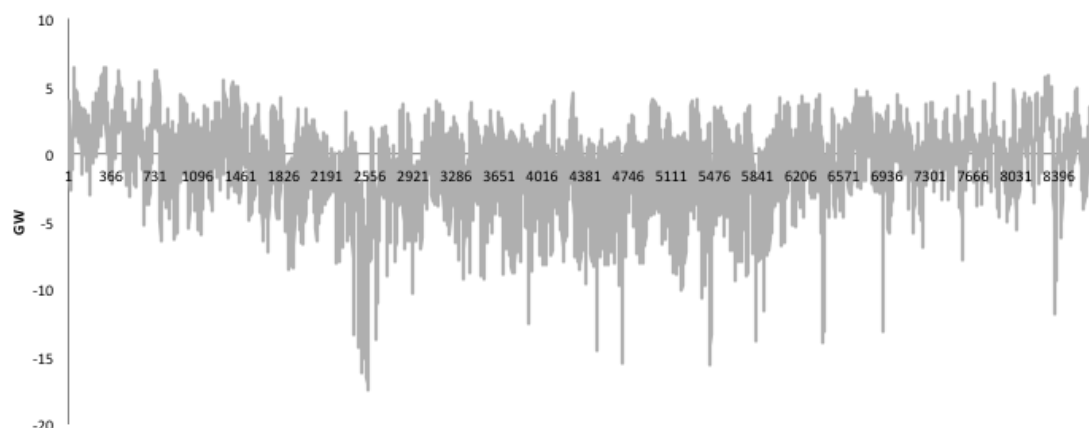
Figure 4.7 - 'Total RL < 0' Scenario for 2050: Yearly RL (Portugal)

Spain in 2050

The shape of the next chart, representing the yearly residual load for Spain in 2050, does not appear as ideal as the one for Portugal in this scenario; nevertheless, it is the best residual load structure found for Spain so far.

Now, the 8,760 residual load values are much closer to the X-axis and, besides the peaks, the variations are not that significant. It is possible to notice that, as always, the residual load is slightly more constant and balanced during the cold seasons. In the beginning and in the end of the year there is also a longer period of time when the residual load is positive, but it never gets as negative as in the warmer seasons, probably because of the lack of solar production, since wind characterization is usually more constant along the year.
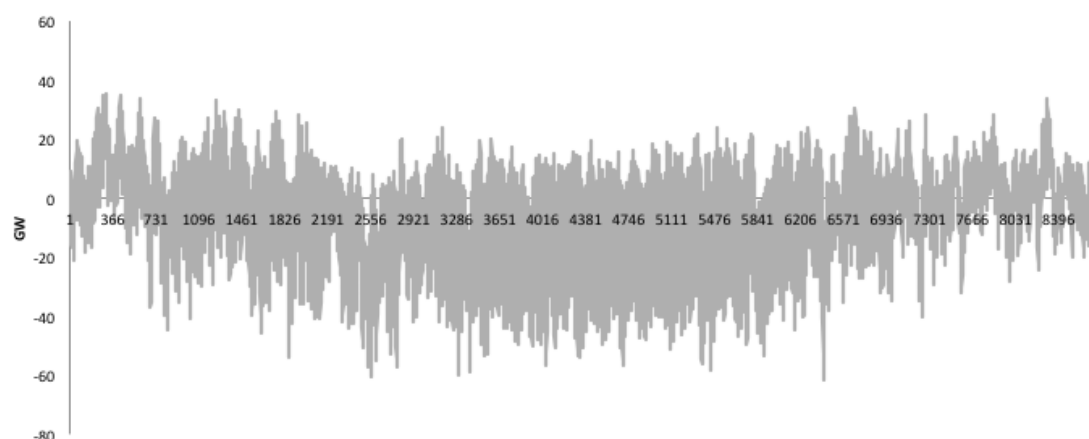
Figure 4.8 - 'Total RL < 0' Scenario for 2050: Yearly RL (Spain)

The values defined for this scenario, in terms of wind and solar factor, decreased a lot the residual load. This means that there is a huge amount of time when the residual load is negative; a lot more than the periods with positive residual load. But this scenario still has two usual problems: the over electricity production that is not needed and requires dispatch, and also the time periods when the electricity production is not enough to meet the electricity demand.

The solution for these problems (under and over-production) is a flexibility system. This flexibility can be tried using <u>storage</u> or <u>electricity transmission</u>, so after analyzing the four created scenarios (sub-chapter 4.5), the best scenarios in terms of residual load will be selected in order to study the storage possibility; if this option ends up showing not to be feasible or if it has very high expenditures associated, then it will be study the electricity transmission possibility, including costs.

For an easier evaluation of the scenarios, the comparison is the useful tool one can use to understand the ideal conditions. Towards that deeper study, the scenarios were placed together, so it is easier to make a strong analysis, which will be shown in the next sub-chapter.

4.5 Deep analysis of the four scenarios – Monthly residual load, duration curves, day/night residual load and costs

The next charts show the four scenarios together. The monthly residual load characterization is able to show if there is a seasonal pattern and how the electricity demand and electricity production behave together in each month of the year; while the duration curve just reorders the 8,760 yearly values of residual load, it allows a perception of the time period during which the production is higher/lower than the demand; the day/night residual load shows if there is a big difference between the day period and the night period; and the day/night residual load according to the seasons shows this daily pattern together with the 4 seasons of the year; finally, the costs are calculated in the end and placed together, so it is possible to summarize them and compare the four scenarios.

Portugal

In Figure 4.9, one can observe two clear seasons in terms of residual load: from October until February, and from March until September. This happens for all the scenarios. This is probably due to the high solar production. It is easy to realize that the scenario in purple (4.4) is always the lowest one when the monthly residual load is positive, but it is also the highest (in terms of absolute value during the warmer months, from March until September). This scenario is connected to a low residual load, when compared to the other three scenarios. A negative total residual load was the goal of this scenario, and that is very present on the next chart. Next, the 'Less Solar, More Wind' scenario (in red), is the one that shows results closer to the X-axis, i.e., for the "positive" months, from October until February, it is usually the scenario that shows lower values, except for February. This means that the difference between the electricity demand and the electricity production is, in general, lower than for the other two scenarios. If we look for the months when the residual load is typically negative, between March and September, this scenario is still the one that shows better results, excluding April and May. This is probably because of the high precipitation rate that happens during this period. It is useful to remember that the 'Solar and Wind 50-50%' scenario is not a very extreme one if we look to the results, and that it actually worked as a first experiment. From this scenario, the others were created as a try for an improvement when related to the past one. The 'Lower Costs' scenario shows to be, at least during the colder months, the more extreme one, since the residual load is always higher than for the other scenarios. This means that there is a big gap between the needs and the supply by renewable sources, which is not desirable.

March and September are the months when the residual load is closer to what is ideal, no matter the scenario. This is probably because of the lower needs of electricity (there is probably not so much need for cooling/heating because these are medium months in terms of temperature) and maybe because of the lower solar production as well, when compared with the other months.
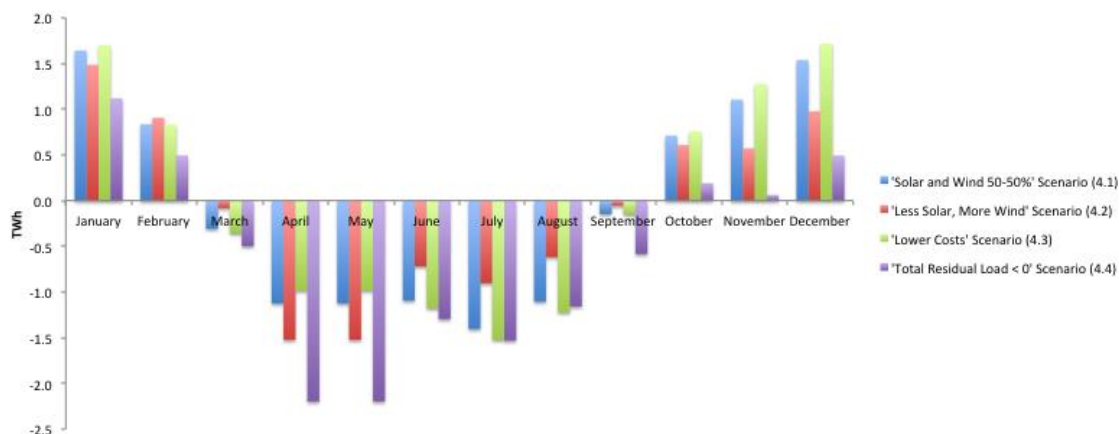
Figure 4.9 - Monthly residual load: four scenarios for 2050 (Portugal)

Figure 4.10 shows that, for 'Solar and Wind 50-50%' Scenario (4.1), only around 5,600 hours of the year are interrelated to a positive residual load, which means that during the rest 3,160 hours the electricity production is higher than the electricity demand. This is the scenario that shows a longer period connected to a positive residual load. Scenario 4.3 is quite similar to this one, and it is possible to observe that both scenarios have a more extreme characterization when compared to the other two scenarios, which means that they are both associated to higher values of residual load during the range of hours when it is positive, and much lower values for the hours when the residual load is negative. Additionally, scenario 4.2 is the one that looks more balanced, since it shows lower positive values and higher negative values. Scenario 4.4 does not show a very different duration curve, but it is very extreme when it gets to the negative values of residual load, though (purple series).

It is important to keep in mind that the X-axis is about a number of hours, and not precisely about the time of the year itself: the residual load values were reordered, which means that if one sees when the series cross the X-axis, it is possible to see how many hours of positive/negative residual load there are for each scenario.

The ideal for this chart would be a series as horizontal as possible, because that would indicate a very balanced scenario.

Although all the scenarios show a quite similar duration curve, the more balanced seems to be scenario 4.2. Scenario 4.4 also looks a good option if one decides to go for a "higher supply scenario", since it better supplies the needs.
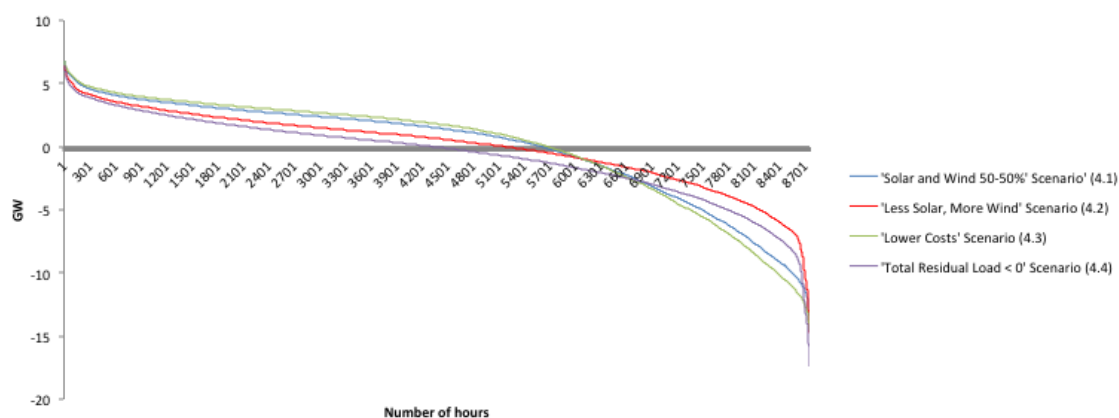
Figure 4.10 - Duration curve of the yearly residual load: four scenarios for 2050 (Portugal)

Evaluating the day/night residual load (Figure 4.11) can also be helpful to confirm what has been said so far. This was calculated summing up all the yearly residual load values between 8 a.m. and 8 p.m. (day period) and the values between 8 p.m. and 8 a.m. (night period), which means that for each calculation $\frac{8760}{2}$ values were summed up.

For all the four studied scenarios, the day period is usually connected to a negative residual load, which does not necessarily mean that the residual load is always negative during the day: it just means that if the 4380 values are summed up, the total is negative. The same works for the night period. By observing Figure 4.11, it is possible to see that after the first scenario (4.1), it was created the 'Less Solar, More Wind' scenario (4.2), which was a try to decrease the difference between the day and the night period. The residual load according to the time period improved a lot. After that, a 'cheap' scenario was tried: the result was a big increase of the residual load, both to the day and night period, and that was expectable but not desirable. Afterwards, the last scenario to be created was supposed to be a scenario where the electricity supply is higher than for the other previous scenarios, as mentioned before, and as it was based on the second scenario (because that showed the best results), the residual load characterization improved, and it showed the lowest residual load for the night period.
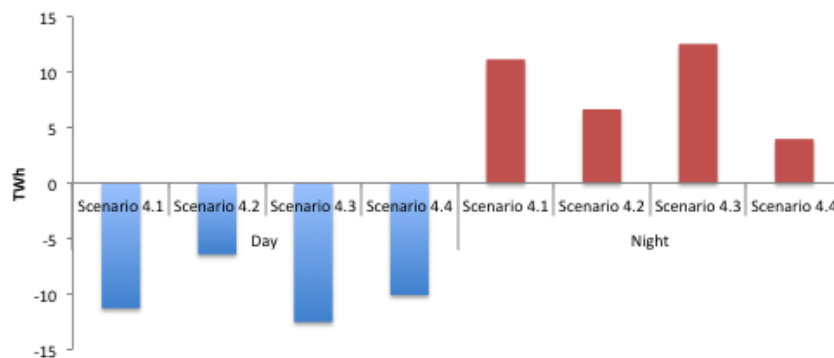
Figure 4.11 - Yearly residual load according to the time period: 4 scenarios for 2050 (Portugal)

Figure 4.12 shows the seasonal patterns, together with the day/night effect. It presents the two yearly seasons that were mentioned before, since spring and summer have quite the same structure, and so autumn and winter. It allows the idea that in case of using storage, there are these two big seasons, and we would need to recharge the batteries during spring and summer, to satisfy the needs during autumn and winter. Scenarios 4.2 and 4.4 show the best results, seasonally and even in terms of day/night residual load.
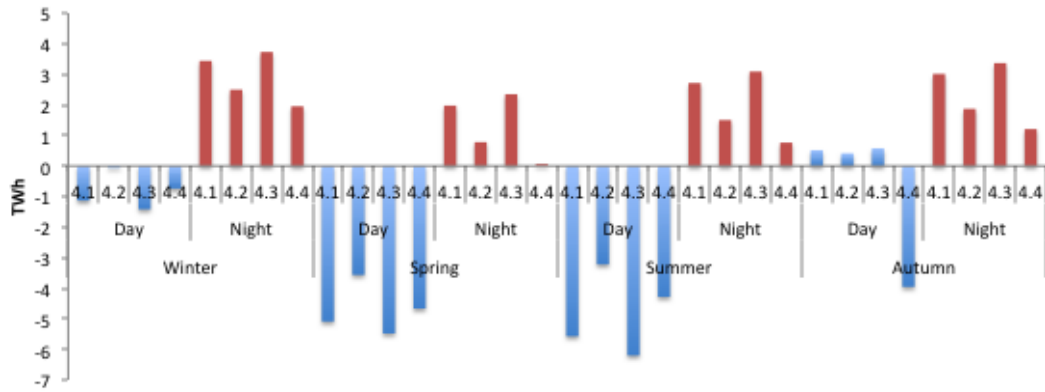
Figure 4.12 - Yearly residual load according to the 4 seasons and to the time period: 4 scenarios for Portugal in 2050

The costs calculations include investment and fixed operation costs, which depends on the percentage of the investment. Although these are values that should be taken into consideration, it is important to remember that probably more relevant than these costs are the storage and transmission costs that must take part of the study.

Table 4.7 shows that the last scenario created (4.4) is the most expensive one, since it also presents greater solar and wind installations.

Table 4.7 - Costs for Portugal: four scenarios for 2050 [M€]

Scenarios	PV	Wind	Total Installation Costs
4.1	1,230	1,413	2,643
4.2	568	2,154	2,722
4.3	1,420	1,184	2,604
4.4	568	2,582	3,150

Figure 4.13 shows what Table 4.7 indicates. It is easier to see now the expenses for each scenario. It is possible to see that even with different solar and wind costs, the first three scenarios present quite the same total installation expenses.
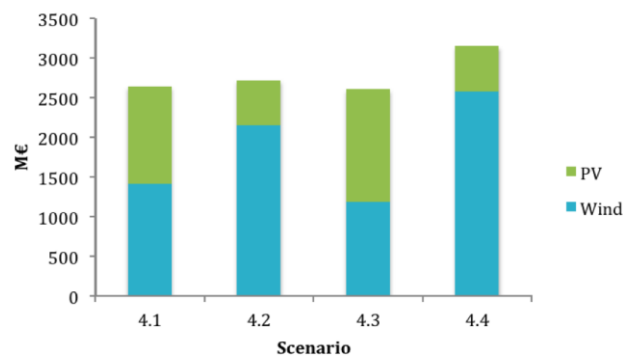
Figure 4.13 - Costs for Portugal: four scenarios for 2050

Spain

For calculating the monthly residual load, the hourly values were summed up for each month. What comes next is similar to the equivalent one for Portugal (Figure 4.9), except the scale due to the country's size.
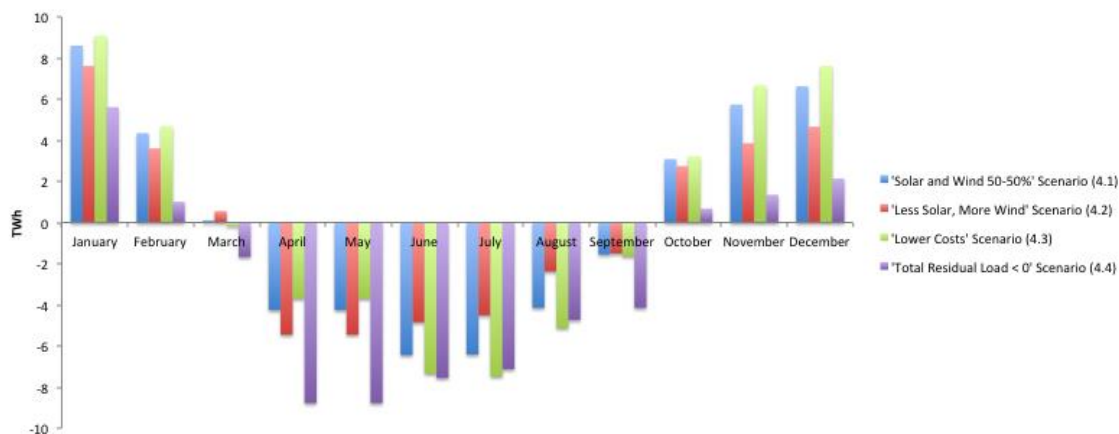
Figure 4.14 - Monthly residual load: four scenarios for 2050 (Spain)

By observing figure 4.14, it is visible that the 'Lower Costs' scenario is for most of the months the scenario that has the worst results: from October until February, the residual load is always higher than for the other scenarios (green bars). For the months when the residual load is, as always, negative (from April until September) this 'cheap' scenario also shows something that is not the goal: high absolute values of residual load, except for April and May. In any case, March is usually a month when, independently of the scenario chosen, the residual load is closer to null, which is the ideal situation: the electricity production coming from renewable sources is close to satisfy the electricity demand, without lack of production or over-production. Looking at the months when the residual load is usually positive (during the colder seasons), scenario 4.4 is the one that shows the lowest values, but observing the months when the residual load is negative, it is easy to understand that we are looking to a scenario that was created in order to have, in total, higher electricity production than electricity demand. These "warmer months" are characterized by very low residual load. The most balanced scenario is again the 0, because the bars show to be closer to the null value (red scenario).

The months between March and September show a period during which the monthly production is higher than the electricity demand, while the other five months of the year still have a positive residual load associated, for every scenario.

As a general rule, if a scenario shows to have better results for Portugal, it will also probably be the best for Spain.
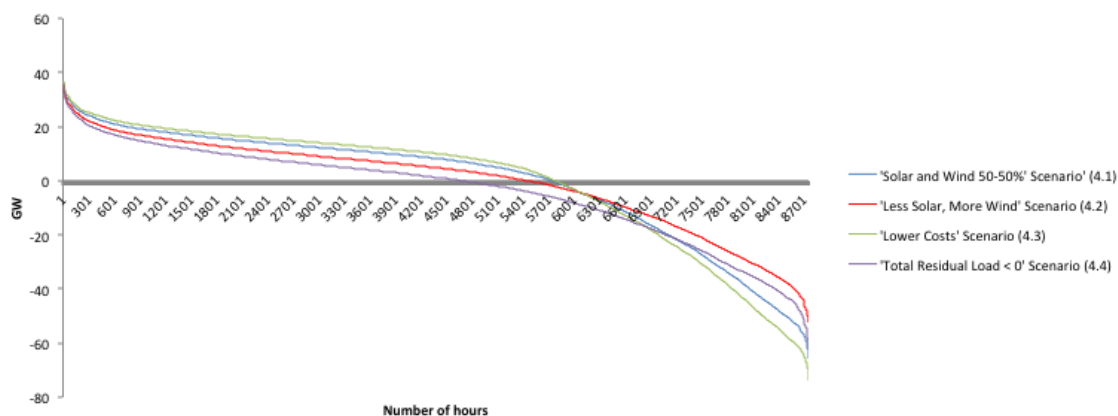
Figure 4.15 - Duration curve of the yearly residual load: four scenarios for 2050 (Spain)

The duration curves for all the scenarios are quite similar to the ones for Portugal. The 'Lower Costs' scenario, 4.3, (in green) shows to have greater amplitude between the positive values and the negative values of residual load. Reordering the values of residual load it is possible to see what is the number of hours when this is positive or negative.

The duration curves for the residual load show that it is never higher than 35 GW but from the point they turn negative all the duration curves decrease much faster and they reach very high negative values, mainly for the 'Lower Costs' scenario.

For the 'Solar and Wind 50%-50%' scenario, only around 5,750 hours of the year are interrelated to a positive residual load, which means that during the rest 3,010 hours the electricity production is higher than the electricity demand. Scenario 4.3 is quite the same. This is just a matter of amount of hours; it is not directly connected to the values of residual load.

The ideal would be to avoid a big difference between the positive and the negative values of residual load and to bring these time series as close to zero as possible, which would result in a horizontal chart.

Daily speaking, the yearly residual load according to the time period had, in 2012, a lower value for the period of the day when comparing with the night period, but still positive. Thus, for all the scenarios created for 2050, the period of the day is associated to a negative residual load, while the night period is connected to a positive value, which means that between 8 p.m. and 8 a.m. the electricity production is still lower than the electricity demand, and the opposite for the day period: the electricity production cannot meet the electricity demand. It is important to highlight that each of these residual loads is a summing up of the all day values and of the all night yearly values (4380 + 4380).

Figures 4.16 and 4.17 show an improvement from the first scenario to the second, since there is a decrease of residual load. The same did not happen from the second scenario to the third one: the 'lower costs' scenario shows to have as a result a higher values, both for day and night period. Afterwards, when comparing scenario 4.3 and 4.4, given the fact that the solar factor was decreased and the wind factor was defined at a considerably higher value, the residual load characterization improved. The same was done between the first and the second scenario: the solar factor decreased and the wind factor was set up at a higher value. Basically, the scenarios that show better results are the ones that have lower solar factors (48,000 MW) and higher wind factors (71,000 MW and 85,200 MW). Increasing the distance between these two bars (day and night) is not the goal, because it means that the needs are not being supplied and that during the night there is, in general, lack of production taking into consideration the demand needs, and during the day there is the opposite problem. The excess of production is preferable but not ideal.
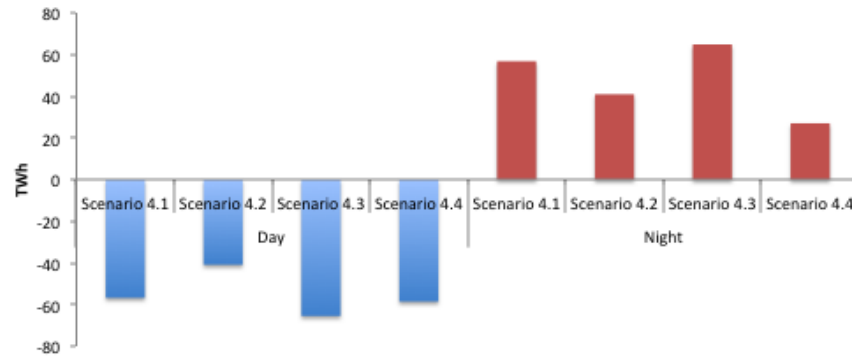
Figure 4.16 - Yearly residual load according to the time period: four scenarios for 2050 (Spain)
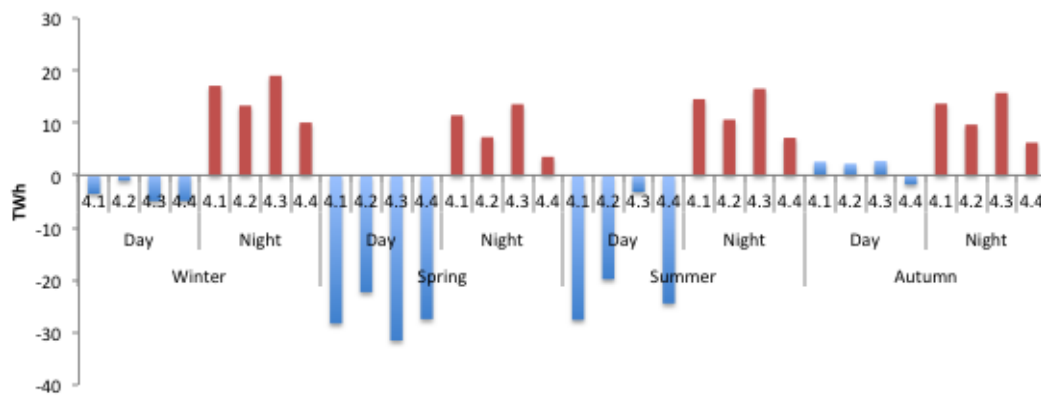
Figure 4.17 - Yearly residual load according to the 4 seasons and to the time period: 4 scenarios for Spain in 2050

The installation costs for Spain are obviously much higher than for Portugal, taking into consideration the size, the population and the needs of the country. It is possible to verify that, since the scenarios were built the same way for Portugal and for Spain, the cheapest scenario in terms of investment is the same for both countries and the most expensive too (Table 4.8 and Figure 4.18).

Table 4.8 - Costs for Spain: four scenarios for 2050 [M€]

Scenarios	PV	Wind	Total Installation Costs
4.1	7,054	7,654	14,708
4.2	4,911	9,981	14,892
4.3	8,185	6,467	14,652
4.4	4,911	11,977	16,888
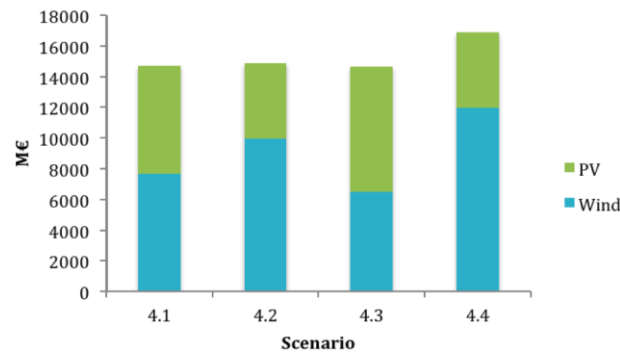
Figure 4.18 - Costs for Spain: four scenarios for 2050

Four scenarios were created and studied for solar and wind installations in Portugal and Spain, and each corresponding residual load was analyzed. There is an infinite number of solar and wind factors combinations that could have been tried, but only a limited number of installations could be shown and analyzed in this study.

After analyzing these four scenarios, it is possible to verify that in terms of residual load, the scenarios that show better results are the 4.2 and the 4.4. Scenario 4.4 is financially not ideal, but there are still some other costs that need to be studied. Anyway, it is possible to understand that no matter the scenario for 2050 is, there is the need of flexibility, which means that storage/transmission will have to be taken into consideration.

To begin with, storage will be studied.

4.6 Seasonal storage

As the several analysis of the residual load (mainly the chart that shows the monthly residual load) proved that there are two major situations during the year – one when the residual load is mainly positive and another when the residual load is negative -, a seasonal storage could be a good option to solve this lack/over-production problem. Electric cars batteries will be considered. This storage will be, at first, calculated for scenario 4.2 as that showed the best results, for Portugal and Spain. Figure 4.19 and 4.20 show a cumulative effect when summing up the hourly residual load values along the year, for Portugal, for the second scenario. Calculating the integral of the positive curve, it is possible to obtain the amount of electricity that needs to be stored, as it represents the positive residual load – associated to the period when the electricity production is not enough to meet the demand. The negative curve of the chart shows the amount of electricity that can be stored, and used when the residual load is positive, i.e., when the electricity production is not enough to satisfy the electricity demand. As the goal of this scenario was to create a null residual load when summing up the hourly values, the two areas of this chart are about the same.
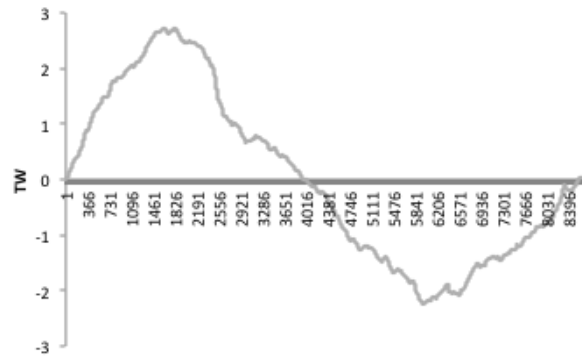
Figure 4.19 - Storage need: scenario 4.2 for Portugal [TWh]

The positive curve represents 5,700 TWh, and that is the amount of electricity that needs to be stored, since it represents the positive residual load.

Figure 4.20 shows exactly the same for Spain, also for the second scenario.

For Spain, the positive curve represents around 29,500 TWh, and that would be the electricity amount that would need to be stored to solve the yearly period that is associated to a positive residual load.
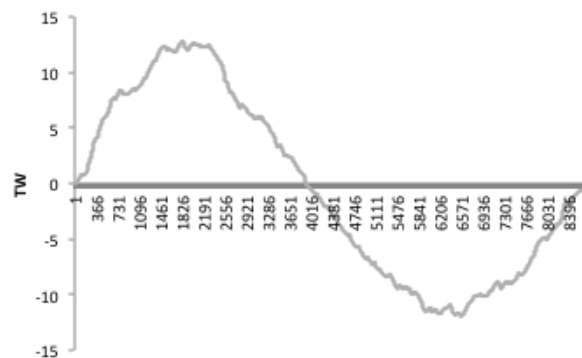
Figure 4.20 - Storage need: scenario 4.2 for Spain [TWh]

As this storage will be considered using electric cars' batteries, we need to know the batteries' capacity in 2050: 53,4 kWh (Kampman, van Essen, Braat, Grünig, Kantamaneni, & Gabel, Impacts of Electric Vehicles - Assessment of electric vehicle and battery technology, 2011).

If we divide the yearly amount of electricity, for Portugal, that needs to be stored, by each electric car battery, we have $\frac{5,700 \times 10^9 kWh}{53,4\ kWh} = 1.1 \times 10^{11} cars$.

For Spain: $\frac{29,500 \times 10^9 kWh}{53,4\ kWh} = 5.5 \times 10^{11} cars$.

The result is, obviously, a very big number of cars, since it would indicate nowadays around 9,000 cars per inhabitant for Portugal, and around 12,000 for Spain. This simple calculation clearly shows that this seasonal storage option is neither real nor feasible. Even if this calculation was done only for scenario 4.2, the unviable results would also happen for the other scenarios, so there is no need for making the calculations for the other three scenarios.

This study just ruled out the storage possibility, and so electricity transmission should be considered. For that, the German residual load will be studied, and the Iberian Peninsula residual load will be calculated. Therefore, it is possible to verify if they can match in terms of electricity needs: if the

German residual load is high enough so that electricity transmission is advantageous. Then electricity transmission costs will have to be taken into account.

These calculations regarding transmission costs will have then an important role on the decision: is the investment in more expensive scenario in terms of renewable sources worth it, if it means that both countries can have greater electricity independence and can avoid transmission?

4.7 The German and the Iberian residual loads for 2050

As mentioned before, it was decided to study the German residual load, for transmission purposes between Germany (as a representative of a Central European electricity grid) and the Iberian Peninsula. This residual load was calculated by the RENPASS model (Figure 4.21), in an hour-basis and turned into a monthly structure so that it is possible to compare it with the monthly Portuguese and Spanish residual loads.

Observing the German residual load, one can see that there are basically no time periods when the residual load is positive, which means that the needs are all supposed to be satisfied in terms of electricity supply by 2050 in Germany. For Portugal and Spain, the scenarios created during this study did not have the goal of having this 'electrical independence'. Instead, for scenario 0 for example, the sum of the monthly residual loads is around zero TWh, which means that if we sum up the 'bars' for Portugal and Spain we would get a value close to null. That is visible in Figure 4.22. As there is no electrical independence for the Iberian Peninsula, according to the scenarios created (both 4.2 and 4.4), the electricity transmission can be considered a good idea. The complete lack of electricity transmission necessity, for supplying the demand needs, defines this 'electrical independence' term for a country/peninsula.
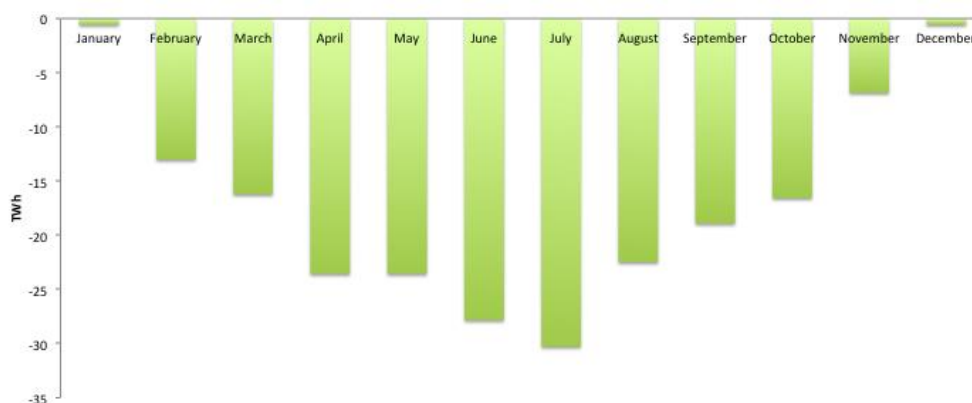
Figure 4.21 - German residual load for 2050 (RENPASS model)

The scenarios that showed to have better results in terms of residual load characterization, both for Portugal and Spain, were the 4.2 and 4.4. Given the fact that is not possible to conduct a deeper analysis to all the scenarios created, 4.2 and 4.4 were selected. As mentioned before, the first scenario was based on the idea that the electricity production that needed to be supplied was divided between the solar and the energy sources, which results in different solar and wind factors. Therefore, the scenario 0 was based on the first one. The total residual load remained null: the solar factor was decreased and the wind factor was increased, in order to improve the residual load characterization. As this scenario showed good results, it is interesting to study the Portuguese and the Spanish residual loads together for this scenario (Figure 4.22). Later on, scenario 4.4 was created based on the second scenario: the solar factor remained the same and the wind factor was increased by 20%. As a

comparison, the same will be done for the scenario 4.4, also because this one showed to have good results in terms of residual load (Figure 4.23).

Summing up the positive monthly residual load values, i.e., the positive bars, there is a total of 27.6 TWh and for the negative bars -29.5 TWh, which means that there is a balance between the 'positive' and the 'negative' months. For scenario 4.4, these values are, respectively, 13.1 TWh and -52.2 TWh, which confirm the goal of this scenario: negative total residual load. This was a try to have a higher electricity supply.
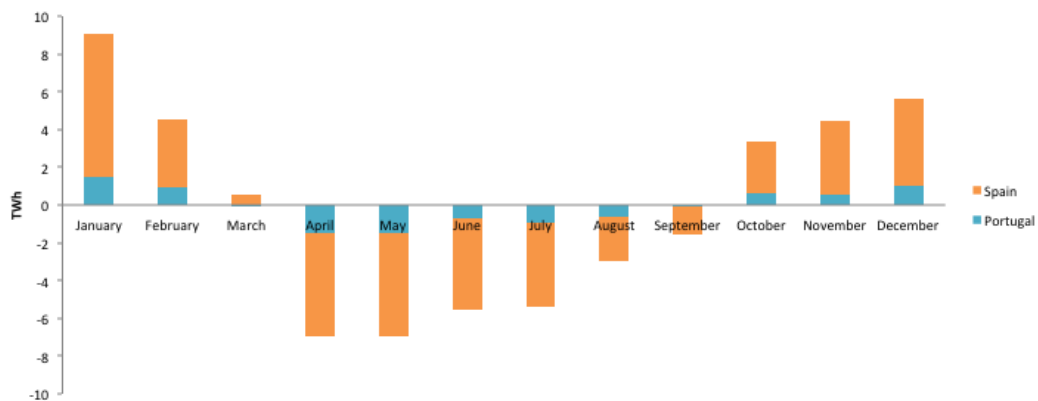
Figure 4.22 - Iberian residual load for 2050 - Scenario 4.2
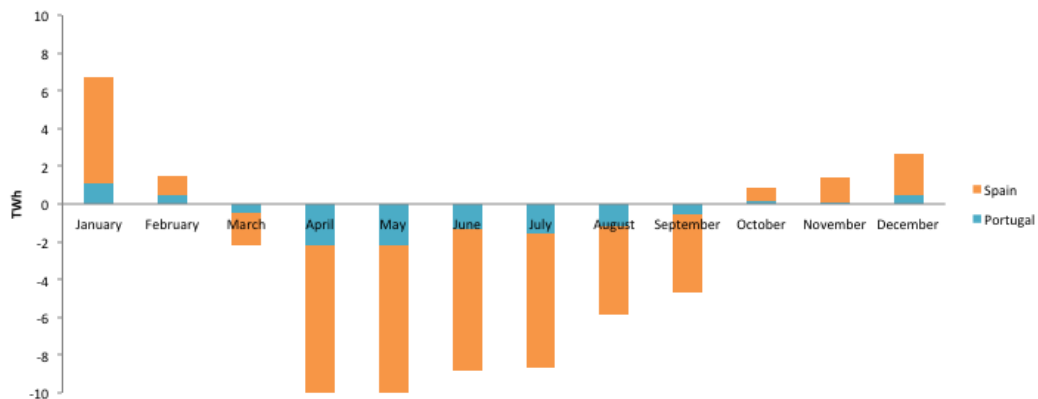
Figure 4.23 - Iberian residual load for 2050 - Scenario 4.4

For both studied scenarios, there are months when the electricity production coming from renewable sources is not enough to meet the electricity demand and months when there is over electricity production. Because of that, electricity transmission will always have to be taken in consideration. Therefore, the next step is to analyze the renewable energies costs calculated in the sub-chapters 4.2 and 4.4 composed with the transmission costs. After this approach, it is possible to conclude what is the best option between these two in terms of total costs. Besides this, there is still a problem that needs to be solved regarding the months when the electricity production is higher than the demand and it needs to be dispatched, which happens from March/April until September. The option of selling electricity to neighbor countries is always a possible decision that needs to be taken into account.

Figure 4.24Figure 4.25 allow a study of the Portuguese and the Spanish residual loads together. The blue marker denotes the result for the 'Iberian Peninsula', and the German residual load calculated by RENPASS is in green. As long as the bars for Germany are longer than the bars that characterize the Iberian Peninsula, it means that it is possible to make electricity transmission. The negative residual load that Germany shows characterizes the electricity that this country has to dispatch. During the

months when the Iberian residual load is positive, i.e., from October to February, electricity has to be imported, and Germany can export that amount of electricity. However, during January and December, for both scenarios 4.2 and 4.4, the residual load is higher, in terms of absolute value, for the Iberian Peninsula than for Germany. This means that during these two months, Germany does not have enough over-production to export the electricity that the Iberian Peninsula needs at this time. Nevertheless, the option could be to consider electricity exportation from another relatively close country to Portugal and Spain, since the whole Central Europe is very strongly connected in terms of electricity grid.
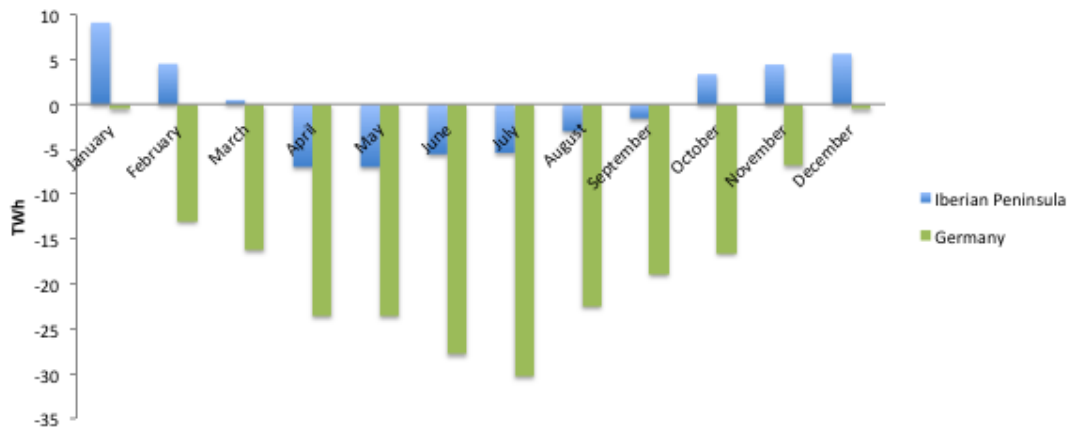
Figure 4.24 - Monthly residual load: Germany and Scenario 4.2 for the Iberian Peninsula for 2050
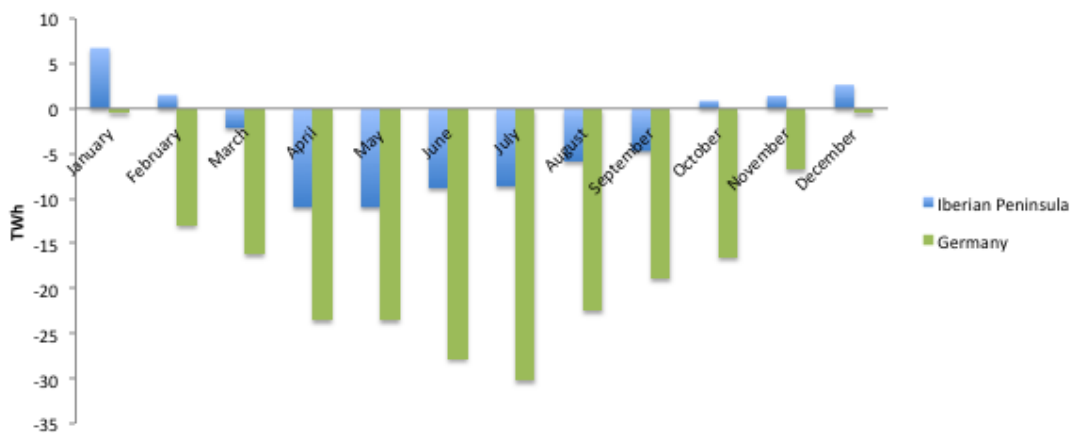
Figure 4.25 - Monthly residual load: Germany and Scenario 4.4 for the Iberian Peninsula for 2050

After observing the last two charts it is possible to verify that if electricity transmissions will have to exist anyway, then the best option is to calculate the transmission costs for both scenarios and keep in mind what are the costs, for both scenarios, in terms of renewable energies also for both countries (calculated above). Then, adding up *renewable energies costs (installation) + transmission costs*, for each scenario, allows making an overall view of the expenditures.

Only after analyzing the costs associated to the electricity transmission it will be possible to conclude if the installation costs that have been calculated are relevant or if one should go for an expensive scenario if that means having a more convenient residual load structure all year, avoiding transmission. The residual load is directly connected to a storage system need or to the possibility of Portugal and Spain being electrically dependent from their surrounding countries, including Germany.

Since after studying the storage possibility, one could say that is not a viable option, only after studying the transmission costs, in the next chapter, one can probably conclude what is the way to avoid: the expenditures directly related to the renewable energies (installation, etc.) or the electricity transmission costs.

4.8 Electricity transmission: Energy and Costs - Two Scenarios

Transmission costs will be calculated for scenarios 0 and 4.4. Although it is interesting to study the Portuguese and the Spanish residual loads together and create charts with two series where one can see the Iberian Peninsula and the German residual loads, as it was done in the previous sub-chapter, for calculation purposes it is necessary to make a study for Portugal and Spain separately. The transmission calculations (in terms of energy) and costs have to be calculated separately: for Portugal and Germany for both scenarios and for Spain and Germany also for both scenarios. Whereas the last charts show the monthly residual load, the electricity transmission was calculated in an hourly-basis.

The hourly transmission values were calculated with a range of conditions. This process was done four times: for Portugal and Spain, for scenario 0 and 4.4. The calculation of the 8760 values was based in a triple-if formula:

- If the hourly residual load value of Germany is positive, then the transmission value is immediately zero;

- If it is negative, which means that Germany is having over-production an can export to Portugal, then there is another condition:

    - If the Portuguese/Spanish residual load value is negative, the transmission is also immediately null, because it means there is over-production in Portugal/Spain and so there is no need for electricity transmission;

    - But if it is positive, then the transmission value is the absolute value of the German residual load:

        - If that absolute value is lower than the one for Portugal/Spain (this means that Germany does not have enough over production to supply all the needs of Portugal/Spain, but it will export all the electricity exceeding the needs of Germany);

        - If Germany has an absolute value higher than the one for Portugal/Spain, then the transmission is the exact amount of electricity that Portugal/Spain needs to meet the demand.

After calculating the yearly values for Portugal and Spain in terms of transmission needs, for both scenarios, the all values were summed up and the total transmission needs are showed in Table 4.9.

Table 4.9 - Total yearly electricity transmission for 2050 imported from Germany [TWh]

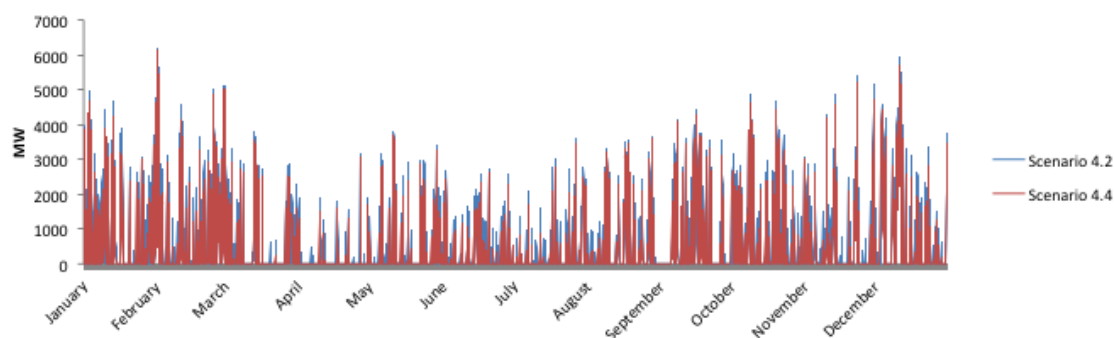|	Portugal	Spain
Scenario **4.2**	4.14	19.14
Scenario **4.4**	3.20	14.79

Figure 4.26 - Electricity transmission scenarios: from Germany to **Portugal** in 2050
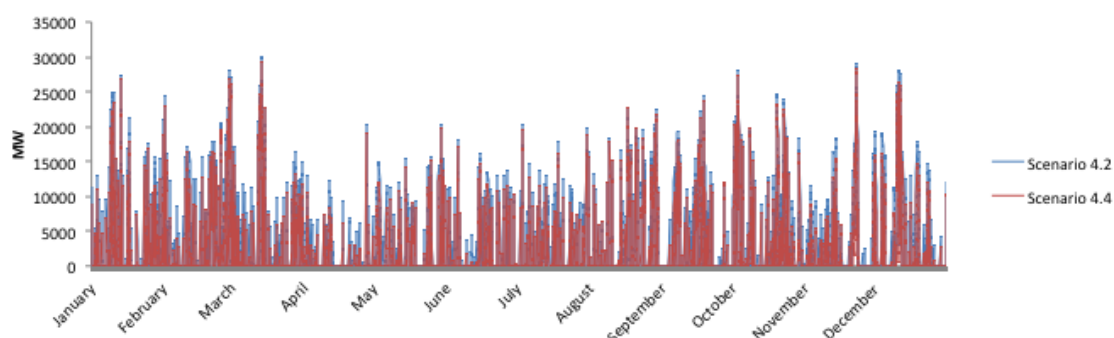
Figure 4.27 - Electricity transmission scenarios: from Germany to **Spain** in 2050

As it should be expected, the transmission needs for scenario 4.4 are lower than for scenario 4.2, precisely because for this last one lower installation values for solar and wind were defined.

The previous charts show the hourly electricity transmission from Germany to Portugal and from Germany to Spain, for both scenarios created for 2050 (4.2 and 4.4) for Portugal and Spain, and in case the German residual load for 2050 is the one calculated by RENPASS and presented on this study (Figure 4.21). The values in TWh, presented on Table 4.9, of the total yearly electricity transmissions for 2050 were obtained by summing the 8,760 values.

The transmission costs are 0.91c€/kWh.km. These costs include capital costs of line, land and tower, capital costs of station equipment and capital costs of transmission system. This quantity is calculated for comparison with estimates of total transmission-system capital cost in other studies (Jacobson & Delucchi, 2010).

The transmission costs calculation depends on two different variables: the number of kilometers in a straight line between the Iberian Peninsula geographical center, (centroid), and the German centroid and the total amount of energy that Portugal and Spain need to import from Germany [kWh], to ensure that supply reliably matches demand. The Iberian Peninsula centroid is Madrid and the German centroid is Kassel. The distance between these two points is 1,580 kilometers. The total amounts of electricity that has to be used for these calculations are presented on Table 4.9 (above).

In fact, it is important to note that talking about the German centroid (Kassel) does not necessarily means that the electricity is being exported only from Germany, since the Central Europe system is highly connected.

Figure 4.28 - European map: Iberian Peninsula centroid (Madrid) and German centroid (Kassel)

The calculation for the electricity transmission costs is:

$$
\begin{aligned}
Electricity\ &Transmissions\ [\text{€}] \\
= Transmission\ Costs\ &\left[\frac{\text{€}}{kWh.km}\right]^9 \times\ Imported\ Electricity\ [kWh] \\
&\times\ Distance\ from\ Kassel\ to\ Madrid\ [km]
\end{aligned}
$$
<div style="text-align:right">Eq. 8</div>

Table 4.10 - Total yearly electricity transmission costs for 2050 imported from Germany [M€]

	Portugal	Spain
Scenario **4.2**	60,279	278,697
Scenario **4.4**	46,638	215,311

Different scenarios involve different wind and solar installations, which results in different renewable energies costs; and different wind and solar installations also result in different residual loads characterizations and, subsequently, different electricity transmission needs. So for every scenario there are two associated costs: the ones related to the solar and wind installations and the transmission costs.

Both for Portugal and Spain, there is a decrease of 23% of the yearly transmission costs from scenario 4.2 to 4.4 (Table 4.10). This clearly shows that if wind and solar factors are greater, then the needs of electricity transmission are much lower, which results in lower total yearly electricity transmission costs. What was still about to be found is that if that lower transmission costs would offset the higher costs related to the investment.

Table 4.11 shows that transmission costs are associated with much higher values than the costs related to the installation/investment costs, calculated before. This table summarizes what are the costs associated to scenarios 4.2 and 4.4, for Portugal and Spain.

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[9] 0,91c€/kWh.km

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Table 4.11 - Summary of costs [M€]

Costs	Scenario 4.2	Scenario 4.4	
Transmission	60,279	46,638	
Initial investment (Installation, etc.)	2,722	3,150	**Portugal**
Total	63,001	49,788	
Transmission	278,697	215,311	
Initial investment (Installation, etc.)	14,892	16,888	**Spain**
Total	293,589	232,199	

Table 4.11 shows that the scenario that seemed in the beginning of the study to be the most expensive (4.4), because of its high investments costs is, in fact, the cheapest because of its much lower electricity transmission needs. This immediately proves also that from the four scenarios studied in the beginning of this chapter, scenario 4.4 would have the lowest total costs. If scenarios 4.1, 4.2 and 4.3 have lower solar and wind factors associated, then they also have much higher transmission needs and they would definitely end up being more expensive. In fact, the 'Lower Costs' scenario was actually not the one that would have lower total costs, but only lower installation costs.

As just noted, transmission cost is the main financial concern. So the idea of creating a scenario where there is no need of electricity transmission (as done for Germany) arose. This would be a scenario where Portugal and Spain are electrically independent from any other country. However, creating this scenario will have other associated problems: over-production will be an issue.

4.9 The Fifth Scenario: Independence Scenario for the Iberian Peninsula

The fifth scenario was created based on the last one (4.4), increasing by 50% and 46% the solar factor, for Portugal and Spain, respectively, and by 48% and 41% the wind factor. This scenario will have a much lower residual load characterization, since it is suppose to supply the demand needs without the necessity of importing electricity from any country. However, in practical terms, it remains to be studied if this installation values are realistic and achievable.

Table 4.12 - 'No electricity transmission' Scenario for 2050, [MW]

	Portugal	**Spain**
Solar Factor	9,000	70,000
Wind Factor	25,000	120,000

The electricity dispatching will still be a problem because of the over-production. Selling electricity to a neighbor country is always an option to take into consideration. Storage and hydro pumps can also be a way to solve this issue. Figure 4.29 represents the monthly residual load for this scenario, for Portugal and Spain together. It can now be compared with the German monthly residual load calculated by the RENPASS model (Figure 4.21).
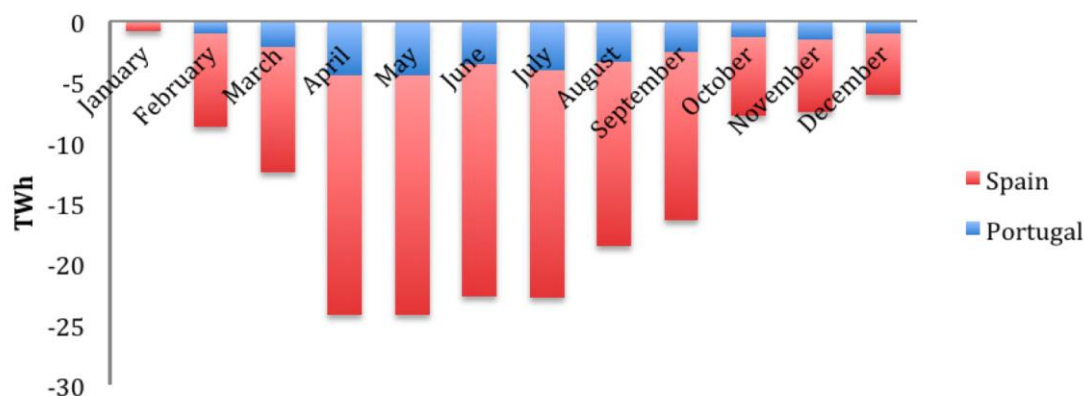
Figure 4.29 - Monthly residual load: the 5th scenario for 2050

The costs associated to the investment, for this scenario, are displayed in Figure 4.30 andFigure 4.31. The total costs for Portugal are 4,671 M€ and for Spain are 24,031 M€, which corresponds to, respectively, 48% and 42% more expensive than for the scenario 4.4. Although the costs are much higher for this scenario, one must remember that for this one there are no needs of electricity transmission.
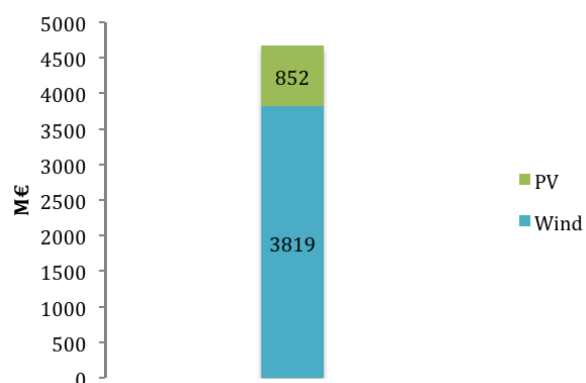
Figure 4.30 - The 5th scenario for 2050: Costs for Portugal
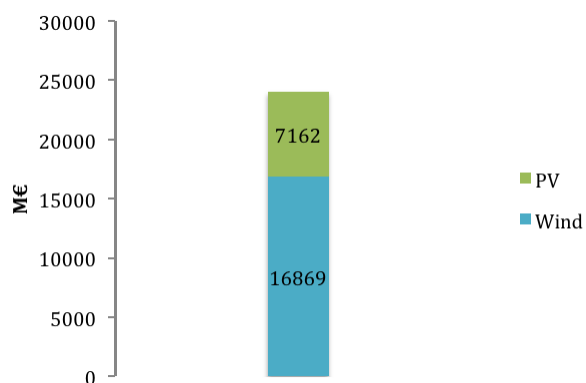
Figure 4.31 - The 5th scenario for 2050: Costs for Spain

At first, the four scenarios were created and then after evaluating their residual load characterization and costs, the two best scenarios, not in financial but in residual load terms, were chosen. Choosing scenarios 4.2 and 4.4 that were created allowed us to make a study regarding their transmission costs, because that was also a relevant concern.

For the four first scenarios presented, and even for the ones that showed to have better results (4.2 and 4.4) there would be the need of solving the problem of underproduction, because demand has to be satisfied all the time and for none of them the residual load is always negative. Comparing with the fifth scenario, on one hand, since these scenarios have lower solar and wind factors (installations) they are also cheaper in terms of investment but, on the other hand, these scenarios need electricity transmission, which is very expensive, and they still have a problem with over-production. This means that there is an amount of electricity that has to be dispatched, in any case (scenario 4.2 or 4.4). In order to solve the problem associated to the large amount of expenditures related to the transmission costs, the fifth scenario was created. This scenario was defined by its greater solar and wind factors, and also by not requiring electricity transmission. Nevertheless, the need of electricity dispatch is still a problem. One can always consider, in any case, exporting electricity to a surrounding country, but that would also require other kind of studies.

These calculations for the different scenarios are not supposed to be considered as predictions. It is useful to remember that the *Status Quo* study was also done so that it is possible to compare the current situation and the several possible scenarios for 2050, for both Portugal and Spain. Without the current situation of the countries, it is almost useless to make studies about scenarios for 2050. These scenarios development allow us to have a perception of what can happen in terms of residual load and costs if the solar and wind installations are, at least, around these defined values.

Relying on the model used, RENPASS, it is possible to have an overall view of the situation of these two countries, Portugal and Spain, in terms of electricity supply and demand, by defining the solar and wind installation, in MW, and the demand factor (the factor that defines how would the demand increase/decrease).

5. CONCLUSION AND FUTURE WORK

This dissertation proves, as done before in some other studies, using a different tool, that Portugal and Spain have a great potential in terms of renewable energies, namely solar and wind.

It was possible to conclude that the model is ready to be used for these two countries in study. Modeled data showed to be reliable. As P. F. Bach and the ENTSO-e sources had quite the same data, it also proves that both are reliable measured data.

It was possible to conclude that, when the RENPASS results are taken into the study and scenarios are created, Portugal and Spain have quite the same residual load characterization. This is regarding to their similar solar and wind potential, undoubtedly because both countries have the same kind of climate.

Another conclusion is that the full load hours, for both Portugal and Spain, is greater for the wind energy than for solar energy.

In terms of residual load, it was noticeable that the period between 8 a.m. and 8 p.m., corresponding to the day period, has in general lower values associated. This means that during the day, the electricity production is usually higher than the electricity demand, no matter the installations that are set up. It was possible to observe that according to solar and the wind factors, the residual load characterization changes considerably. If solar is a greater component in a scenario, during summer the electricity production will increase, and so during the day; if, for example, while creating a scenario, one notices that the problem is related to the residual load during the night, then the solar factor will not influence that much. This is why it was decided to create a baseline scenario and from that one on, the goal was to improve the residual load characterization. During this process, it was possible to conclude that it is never possible to make that electricity production meets electricity demand at all time, during the 8,760 hours of the year. Thus, over-production and underproduction were always two main problems during this study. In terms of monthly residual load, it is perceptible that there are basically two seasons: the cold season from October until February, when the residual load is mostly positive, which means that the electricity demand is not satisfied by the production coming from renewable sources; and the warm season, presented from March until September, when the residual load mostly shows negative values, telling us that the production is more than enough to supply the demand and there is actually over-production. This might happen because of the higher potential/offer from the sources in study during this period of the year.

When creating and evaluating the four first scenarios, it was possible to conclude that they have different associated installation costs, and specifically the last one showed to be the most expensive. However, these costs did not include the transmission costs (and all of them would need electricity transmission). When the transmission costs were calculated for all the scenarios, one could finally understand that those costs are the most relevant ones, because those are the really big expenditures. So, no matter what are the solar and winds installations of a scenario, the most important element to think regarding financial terms is the transmission costs. Setting up a big solar and wind factors require significant investments, but as that avoids electricity transmission, it can be considered as a useful and profitable investment. That investment is denoted in the creation of the fifth scenario. In this situation, the monthly residual load, for Portugal and Spain, is already quite similar to the one calculated by RENPASS for Germany in 2050.

During the winter, the monthly values get closer to zero and during the warm season these values are very low. Therefore, we can conclude that no matter the scenario and the country, during summer the residual load is always lower than during winter.

Moreover, it is possible to conclude that creating a scenario that needs no electricity importation from another country always ends up being less expensive, since the electricity transmission is the most expensive element of the system. Nevertheless, it is important to keep in mind that dispatch of electricity has to be taken into consideration. It was possible to conclude that electric cars batteries are not a possible and feasible option, since it would require an unrealistic number of cars.

For future work, it remains to be studied the electricity transmission system and dispatch operation. The period when the residual load is negative is also a topic that should be researched: a study regarding electricity exportation could be a possibility. Additionally, different storage options can also be studied. Furthermore, the potential of the run-of-river in 2050 can also be studied, as in this study it was assumed that one could count with, at least, the same production there was in 2012. An environmental impact study can also be performed, taking into account solar, wind and run-of-river, according to each installation, in order to complete the scenarios cases.

The location and implementation of solar panels and wind turbines should also be studied for the scenarios created, also in order to check the feasibility of the installation values.

Since in this whole study the demand factor was defined at 1, another study for different electricity demands' characterizations could be established. Studies regarding electricity demand are also very important because it changes the whole study.

Given the rather complexity of the transition for the 100% renewable electricity supply, a huge number of questions still have to be explored and a large number of studies can be further researched regarding this topic. Besides this fact, it will always be a matter of energy policies and political decisions. However, it is important to continue the studies regarding this subject, so that the issues associated to the use of non-renewable energies become a problem that can realistically be avoided.

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