Faculdade de Engenharia da Universidade do Porto

Ramp Analysis of the Net Load Under Different Penetration Scenarios

Jorge Dias de Magalhães

FINAL VERSION

Master Thesis in Electrical and Computers Engineering in Energy

Supervisor: José Villar Collado

25-Jun-18

Resumo

Na luta contra as alterações climáticas, a União Europeia estabeleceu várias metas para reduzir as emissões de gases com efeito de estufa. Portugal, em conformidade com os objetivos europeus, continuou a desenvolver e a reformar a sua política energética, estabelecendo metas ambiciosas na quota de energias renováveis relativamente ao consumo de energia final para anos futuros. Isto significa um contínuo aumento na energia renovável variável (VRE), como eólica e solar, no sistema elétrico Português.

No entanto, vários operadores do sistema estão a alertar que os requisitos de rampas nos geradores estão a aumentar devido à VRE e exigem novos mecanismos de flexibilidade para garantir a segurança do sistema, enquanto as unidades para fornecer essa flexibilidade estão a diminuir devido à menor carga líquida a ser fornecida.

Esta dissertação estuda os impactos da energia eólica e solar em larga escala nas características da carga líquida, carga convencional menos VRE, e nas suas rampas horárias.

Cenários de carga líquida históricos e simulados são analisados a partir de uma variedade de perspetivas, como formas diárias, curvas de duração de carga e histogramas de rampas horárias.

Abstract

In the fight against climate change, the European Union set several targets to its member countries to reduce Greenhouse Gases emissions. Portugal, complying with the European framework, has continued to develop and reform its energy policy, setting ambitious targets in the share of renewables over consumption to future years. This will mean a continuous increase of variable renewable energy (VRE), like wind and solar, in the Portuguese Power System.

However, several system operators are claiming that the ramp requirements due to VRE are increasing and require new flexibility mechanisms to assure the system reliability, while the units to provide this flexibility are decreasing due to the lower net demand to be supplied.

This thesis studies the impacts of large-scale wind and solar power in the characteristics of the net load, conventional load minus VRE, and its hourly ramps.

Historical and simulated net load scenarios are analyzed from a variety of perspectives, such as daily shapes, load and net load duration curves and histograms of hourly ramps.

Acknowledgments

In this final chapter of finishing my master's in Electrical and Computers Engineering in the area of Energy, I would like to thank Dr José Collado for the guidance and demonstrated availability, assistance and patience throughout the dissertation.

I would also like to give my deepest appreciation to my parents for allowing me to have this opportunity to graduate and to provide me with all the conditions for this, as well as all the support given, motivating me to work hard and face the difficulties.

“You can’t control the wind, but you can adjust your sails”

Yiddish proverb

Table of Contents

List of Figures

List of Tables

Abbreviations

CCGT - Combined Cycle Gas Turbine
CT - Combustion Turbine
DGEG - Directorate-General for Energy and Geology
EO2017 – Energy Outlook 2017
GHG – Greenhouse Gases
NL – Net Load
PNAEE - National Energy Efficiency Action Plan
PNAER - National Renewable Energy Action Plan
RD – Ramp Downwards
REN - Gas and electricity Portuguese network operator
RES – Renewable Energy Sources
RU – Ramp Upwards
RMSA2017 - Report on the Monitoring of Supply Security in the National Electricity System 2017
VRE – Variable Renewable Energy

Chapter 1

Introduction

1.1 Motivation

In the fight against climate change, the European Union set several targets to its member countries to reduce Greenhouse Gases emissions. For that reason, the use of mainly fossil-fired plants is not a sustainable option. The European electricity system is then currently facing a major transformation, with renewable energy sources (RES) being expected to be an important part of the future generation mix. This will mean that for Portugal the significant growth of wind and solar powered electricity generation over the past decade could still continue in the coming years towards an almost renewable generation system.

The problem is that large scale integration of variable renewable energy (VRE), like sun and wind, poses substantial technical challenges to the power systems operation procedures mainly due to its variable and hard-to-predict nature. Net load, which is the load minus non-dispatchable generation, mainly wind and solar, would significantly diverge from load as the penetration level increases.

This thesis focuses on the consequence characteristics of the net load and its hourly variations in the Portuguese Power System when a large amount of wind and solar power generation is integrated into the grid.

1.2 Objetives

The research of this thesis is centered around the impact that large penetrations of VRE could have in the net load and its ramps. In this perspective, we present the following topics that summarize the objectives to be achieved in this dissertation:

- definition of a set of future scenarios of interest in terms of renewable generation penetration, according to the environmental European and Portuguese energy strategies.
- Computation of the net load and its ramps for the period 2008-2017 and for the future scenarios proposed.
- Analysis of the flexibility requirements of large-scale penetration of both wind and solar and take some conclusions.

1.3 Structure

The present dissertation is divided in 5 chapters.

In Chapter 1, a brief introduction is made on the subject under study, as well as the motivation of study and its main objectives.

In Chapter 2, the political and environmental motivations that lead to the rise of renewable energy in the Portuguese power system are discussed, as well as some of the problems that this significant increase may cause in the power system operation. One of these problems is the potential increase of the net demand ramps, whose analysis is the main objective of this theses, which is in addition accompanied by a decrease of firm or dispatchable generation,

In Chapter 3, the methodology to design the scenarios for the proposed analysis and the metrics used to quantify the ramps are explained.

In Chapter 4, the results of the simulations are presented and analyzed to quantify the potential problems associated to the ramps of the net demand.

Finally, chapter 5 presents the conclusions and proposals for future work.

Chapter 2

Contextualization

2.1 Decarbonization Policies

2.1.1 Europe

Strong drivers like climate change, the scarcity of fossil resources and technological improvements are leading to a transformation of the power system in many world regions.

The Paris Agreement, reached at the XXI United Nations Climate Change Conference (COP 21) of the United Nations Framework Convention on Climate Change, included the commitment to achieve greenhouse gas (GHG) emissions neutrality between 2050 and 2100 in order to limit global warming to well below 2°C above the pre-industrial temperature.[1].

As part of its strategy to become a low-carbon region the EU has already set ambitious targets to reduce GHG emissions so that by 2050 its economy does not depend, or does so to a lesser extent, on energy produced from GHG-emitting sources. This target sets a GHG emission reduction of between 80% and 95% by 2050 compared to 1990 emissions.

To achieve this objective, the EU has developed a set of benchmark policies and intermediate milestones for decarbonization. In particular:

- The 2020 Climate and Energy package, adopted in 2007 by the European Council, laid the foundations for fulfilling the commitments on climate change and energy, with a set of 2020 targets, such as reducing GHG emissions by at least 20% from 1990 levels, producing 20% of final energy consumption with renewable energy and reducing the consumption of primary energy by 20%.[2]
- The 2030 Framework, adopted in 2014 as a continuation of the previous Energy and Climate Change Package, included a binding target of reducing GHG emissions by 40% compared to 1990 levels. In addition, the Framework proposed another binding target of increasing renewable energy "by at least 27%", although this objective would not be translated into legally binding targets for EU Member States. An energy efficiency target of 27%[3] was also set but was eventually revised in 2016 setting a binding target of 30% by 2030[4].

- Roadmap 2050, presented in 2011, which states that by 2050 the EU must reduce its emissions to between 80% and 95% below 1990 levels, yet not mentioning specific subobjectives like the other packages .[5]

2.1.2 Portugal

Portugal, along with other EU Member States, is actively involved in the fight against climate change through the annual meetings of the Conference of the Parties of the United Nations Framework Convention on Climate Change [6].

Currently, the Portuguese government's policy for the energy sector is set out in the National Plan of Action for Energy Efficiency 2017–2020 (PNAEE) and in the National Plan of Action for Renewable Energies 2013–2020 (PNAER), both approved by Ministers' Council Resolution No. 20/2013 of 10 April [7] and both contingent on European directives. In 2015 the Council of Ministers Resolution n.º 56/2015, of July 30, established the main national policy instruments in the areas of mitigation and adaptation to climate change - the National Program for Climate Change (PNAC 2020/2030)[8]. All these strategic documents are intended to be tools for a better energy strategy by defining the means of achieving international goals and commitments in matters of energy efficiency and the use of renewable resources.

These Plans of Action have the following major objectives for 2020:

- 20% greenhouse gas (GHG) reduction target compared to a 1% increase permitted under the EU-Effort Sharing Decision vs 2005.
- A share of renewables of 31% in final gross energy consumption and 10% for energy consumption in transport.
- new energy savings targets of a 25% reduction of primary energy consumption nationally and a 30% reduction of energy consumption in the state-owned sector

The emissions recorded in 2016 confirm a trajectory of compliance with the national and European emission reduction targets for 2020. Total emissions, representing a reduction of around 21% over 2005 levels, are within the PNAC target range for 2020. In renewables, since 2004, the highest growth has been recorded by electricity from a share of 28% to 53%, followed by transport, which went from 0% to 7% in a decade. Regarding energy efficiency, primary energy consumption is below the target for 2020, but to be accomplished it will be necessary to continue to implement the measures envisaged under the PNAEE.

In terms of sectoral contribution, electricity is the sector with the largest contribution to the final share of renewables, accounting for 66% of the total RES increase between 2005 and 2020 to meet the 31% target.

In 2015 the Coalition for Green Growth, a consultative body whose mission is to advise the Portuguese government on the implementation of policies to endorse green growth, shaped the strategic document Compromise to Green Growth (CCV), approved by Ministers' Council Resolution No. 28/2015 of 30 April to promote the participation and coordination of the interventions of public and private entities with relevant attributions in this field.

CCV document sets quantified targets for 2020 and 2030 and "lays the groundwork for a commitment to policies and objectives that foster a development model capable of reconciling the indispensable economic growth with a lower consumption of natural resources, without interfering with social justice and quality of populations"[9].

The 2020 targets proposed in CCV document were in compliance to PNAER and PNAEE, while for 2030 the major key energy policies proposals were:

- Reduction of GHG emissions between 30% and 40% in 2030 vs. 2005.
- Share of renewables of 40% in final gross energy consumption.
- 30% reduction on energy baseline by 2030.

In table 2.1 we can see all the information compiled and is interesting to see that most of the targets for Portugal are the same except in renewables where the increase is in proportion of renewable energy sources in the energy mix of the European Union (EU) by an equal percentage.

Table 2.1- Analysis of EU and Portugal environmental targets: 2020, 2030 and 2050

	2020		2030		2050
GHG emissions	-20% (vs 1990)	-18% to -23% (vs 2005)	-40% (vs 1990)	-30% to -40% (vs 2005)	-80% to - 95% (vs 1990)
Share of renewables over final consumption	20%	31%	27%	40%	N/A
Energy efficency	20%	25%	30%	30%	N/A

2.2 Evolution of Renewables in Portugal's Energy System

The decarbonization of the economy and the reduction of energy dependence in Portugal over the last two decades was largely the result of changes in the electricity sector and the gradual increase in renewable electricity generation.

Between 2000 and 2017, installed power in the renewable power plants increased from 3.9 GW to 13.7 GW (Figure 2.1), with an average annual growth rate of around 8%. The increase in renewable power is especially notable between 2004 and 2011 with the start-up of several wind farms, consequently fossil power has been declining since 2011.

From 2016 to 2017 the installed capacity increased 260 MW, standing out the new Foz-Tua hydroelectric power plant with 261 MW, equipped with 2 reversible groups. In the remaining technologies there were few changes with the entry into service of 20 MW in wind farms, 30 MW in photovoltaics and reduction of 50 MW in cogeneration.

Since wind and hydro have already some expressive capacity in the power system, the technology that is going to grow more in the future is solar. By 2021, 31 new solar photovoltaic plants will be expected in Portugal, with a total of more than 1,000 MW of licenses that the government has already approved in the market regime.[10]

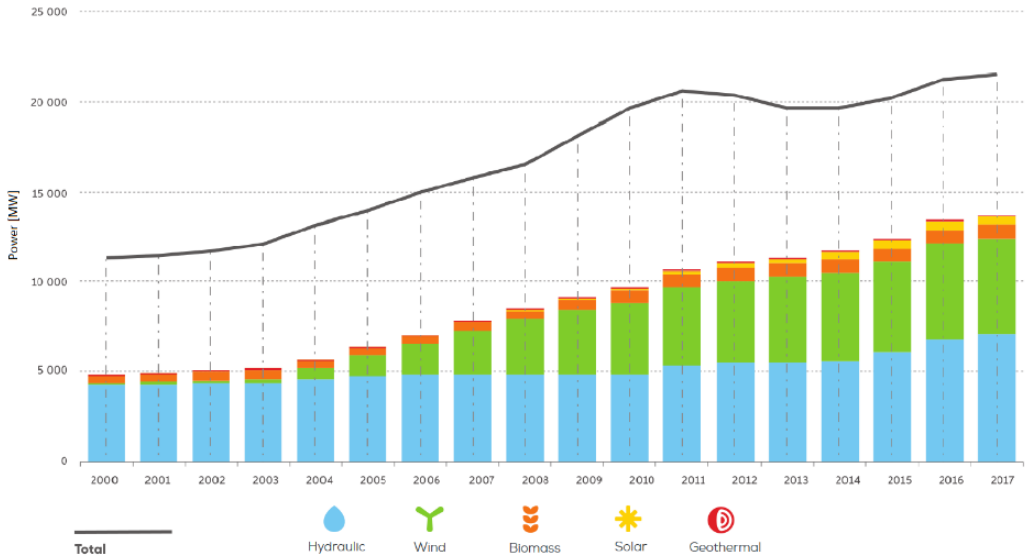

Figure 2.1 - Evolution of Installed Power in the Portuguese Power System**[11]**

Now focusing on the year 2017, which is going to be the reference for the scenarios, the consumption of electricity supplied from the public network totaled 49.6 TWh the highest since 2010. Renewable power plants generated 23.5 TWh, equivalent to 42% of Portugal's total electricity production mix the lowest figure since 2012.

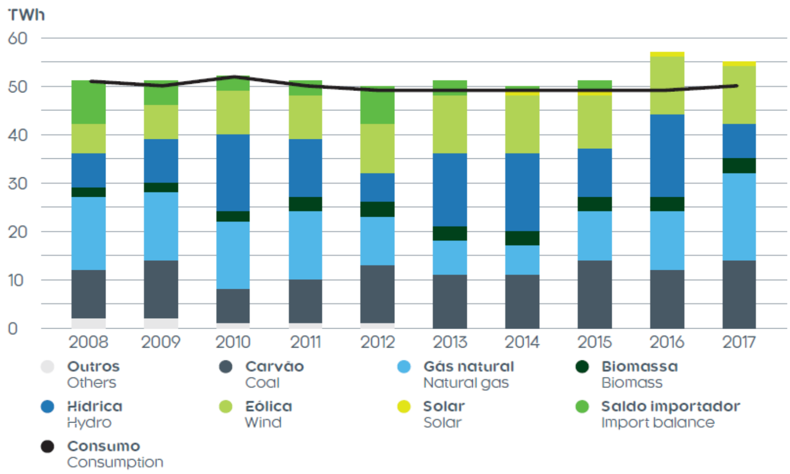

Figure 2.2 - Evolution of Supply in the Portuguese Power System **[12]**

As it can be seen in figure 2.2, hydroproduction this year was under very unfavorable conditions supplying only 10.5 % of consumption, comparing to last year, where exceptional conditions were recorded, supplying 28% of consumption Wind production, slightly below the average, with a productivity index of 0.97, supplied 23% of consumption. In the remaining renewables, biomass supplied 5% of consumption and photovoltaic 1.6%. In non-renewable production coal accounted for 26% of consumption and natural gas, combined cycle and cogeneration, 34%. In foreign trade, the balance was exporter for the second consecutive year, equivalent to 5% of national consumption.

2017 was also marked by an export balance of 2.7 GWh, the second highest value ever. This value was only surpassed by the export balance for 2016, which was 5.1 TWh.

Concerning energy dependency its index, % of net imports in gross domestic energy consumption and in bunkers, based on tonnes of oil equivalents, reached one of the highest values in recent years, 79%.

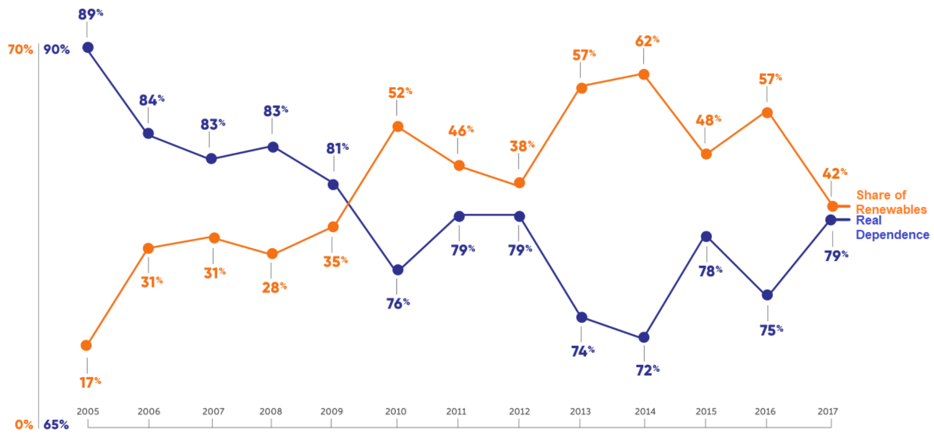

Figure 2.3 - Evolution of Energy Dependence and Renewables Quota in Electric Production **[11]**

In Figure 2.3 can be observed the significant correlation between energy dependence and the hydrological regime, and consequently the share of renewables in the production of electricity.

The increase in renewable energy penetration has produced multiple benefits such as less dependence on imported fossil fuels and declining carbon dioxide emissions in the electricity sector. Renewable electricity generation with a priority dispatch has reduced wholesale electricity market prices by displacing the most expensive fossil fuel- fired generation.

2.3 Flexibility

According to [13], a power system is flexible when it can deal with uncertainty and variability in demand and generation and maintain the system reliability at reasonable costs.

All power systems have some inherent level of flexibility to balance supply and demand at all times and are expected to deal with variables such as uncertainty and variability in load changes. Traditionally different combinations of hydro and thermal generation are used to manage variability and satisfy demand and must have some level of flexibility. Daily and weekly patterns of system demand help forecasting and understanding the time horizon over which significant ramps take place (e.g. the morning increase), enabling operators to plan and implement effective strategies for flexibility.

However with the integration of high shares of variable renewable energy (VRE) that are non-dispatchable (that cannot be regulated to match changes in demand and/or system requirements like wind and solar), poses significant additional challenges to the electrical power system and makes the balance harder to attain.

Both wind and solar generation output vary significantly over the course of hours to days, sometimes in an expectable way, but often imperfectly forecasted.

For example, much of the variation in solar energy during the day and year is very predictable since the movement of the sun is well understood, but an additional, less predictable source of variability is the presence of clouds that can travel over solar power plants, limiting generation for short periods of time. Cloud cover can lead to very rapid changes in the performance of individual PV systems, but the impact on the grid will be minimized if solar projects are distributed geographically so that they are not simultaneously affected by clouds. In this way, the variability from a large number of systems is smoothed out.

Compared to solar, wind energy is less predictable but still subject to daily and seasonal weather conditions. Wind energy is often available in winter or at night when the wind blows more strongly, which can be a challenge in some cases when output is lower load levels [14].

The level of uncertainty of VRE power production is reflected in wind and solar forecasting errors. Although uncertainty is a natural feature of power systems, the uncertainty of VRE can make extra impact in the power system operation.

VRE forecasts can contribute to reducing the uncertainty of variable renewable energies. The use of forecasts helps grid operators to commit or de-commit generators more efficiently to take account of changes in wind and solar power generation and to prepare for extreme events where renewable power production is abnormally high or low. Including renewable energy forecasts in the unit commitment and dispatch can improve the scheduling of other generators to reduce reserves, fuel consumption as well as operating and maintenance costs [15].

Sometimes wind or solar generation increases when the load increases, but in cases where VRE output increases when the load falls (or vice versa), additional measures are required to balance the system. System operators must ensure that they have sufficient resources to accommodate significant upward or downward ramps during VRE's generation to keep the system in balance.

Figure 2.4 shows an example of the flexibility required for a high penetration of wind and solar energy. The use of all VRE's requires that conventional dispatchable generators meet the net load, defined as demand minus wind and solar energy.

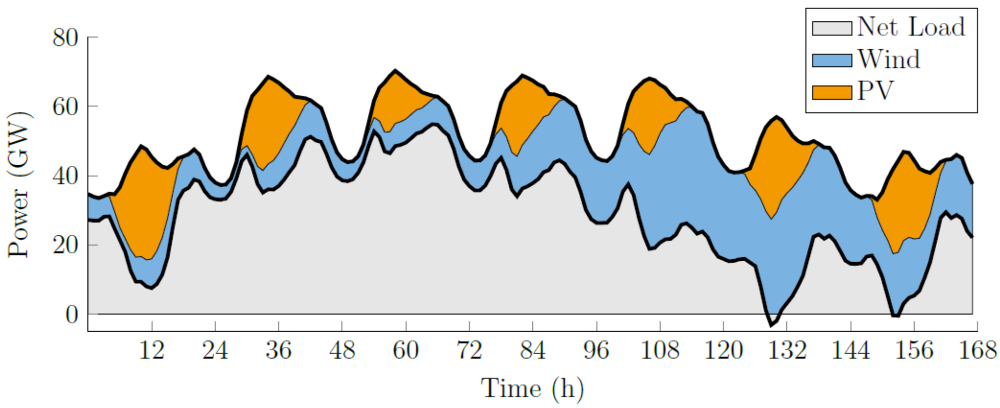

Figure 2.4 - Sample week of load and net load with high VRE penetrations.**[16]**

The graph shows the load and net load for a sample week. It can be seen that the output level of the remaining generators must change more quickly and be turned to a lower level with wind and solar energy in the system, causing the appearance of some incidents as:

- ramping events, that refer to the rate of increase or decrease of the dispatchable generation to follow changes in demand;
- higher turn downs, meaning that dispatchable generators, because of high VRE generation, must decrease their output to low levels but remain available to rise again quickly.
- shorter peaks, peaks are shorter in duration, which leads to fewer operating hours for dispatchable plants, affecting cost recovery and long-term security of supply [17].

The presence of additional wind and solar energy in electricity grids can result in coal or natural gas power plants being switched on and off more frequently or their output changing more frequently to take account of changes in VRE. This type of cycling of fossil fuel generators can lead to an increase in wear and tear of the units and to a reduction in efficiency, in particular due to thermal stresses on the equipment due to output changes [18].

Flexibility can come from conventional generation intended to have more flexible characteristics, including:

- Ramp rate
- Operating range, including minimum generating level
- Start-up/shut-down times
- Minimum up and down times

Manufacturers are already developing units that have higher ramp rates and cycle capabilities, while coping with the potential maintenance costs associated with cycling.

A more flexible conventional fleet will also require traditional base load units, such as coal-fired and nuclear power plants, which have lower minimum operating levels and increased cycling capability [18].

Although simple-running natural gas plants, which can be designed to rapidly change performance, are often regarded as natural combination with VRE, there are already other sources of flexibility in the electricity system which will be described briefly below.

Two essential components for the system operation are unit commitment and dispatch. Unit commitment is the scheduling of generators available, usually day-ahead. Dispatch is the method by which system operators choose from available generators to supply power at least operating costs.

For example, if generators have fixed schedules for longer periods, such as one hour, they are committed to their fixed schedules and are unable to balance the system in the event of schedule deviations. With faster dispatch, the load and generation stages can be more closely coordinated, which reduces the need for expensive control reserves. This allows the most economical resources within the system to be balanced and used more efficiently.

Changes in system operating practices and markets may provide access to significant existing flexibility, often at a lower economic cost than options that require new sources of physical flexibility [19]. For example, the creation of short-term market products for flexible generation can help to ensure that the available physical flexibility is available when needed.

California Independent System Operator (CAISO) and Midcontinent Independent System Operator (MISO) proposed flexible ramping provision [20][21], that are capable of providing specific incentives that make resources more flexible when flexibility in system operations is required. The flexible ramping product includes the adaptation of a new short-term energy market, which serves to change energy supply or demand within minutes. This ramp market tries to send sufficient price signals to generators and encourage them to bid their real ramp capacity. When designing a market for ramp services, several remuneration schemes may be considered, like having generators provide a fixed price for the ramp capacity together with their energy bid or a ramp offer curve [22].

Demand response technologies can also be relevant. Increasing the responsiveness of electricity demand to operator controls and/or price signals will increase flexibility by allowing consumers, particularly in the industrial and commercial sector, to change their demand because of system events or economic circumstances [23]. Demand-response mechanisms consist of automated load control by the system operator, real-time prices and tariffs for the duration of use. A typical response time for an automated response on demand is seconds to minutes. Demand response can be cost-effective, but requires new regulations on response time, minimum magnitude, reliability and verifiability of demand side resources [24].

In addition, energy storage technologies, including pumped hydropower, compressed air, heat storage and batteries are also valuable with high penetrations of variable VRE. Storage can absorb energy when its value is low, reduce VRE curtailment and offer additional operational flexibility due to its fast response time. Many storage technologies (e.g. batteries, flywheels, supercapacitors) have fast response times (seconds to minutes) that are available over a short period of time. Other storage technologies such as pumped storage power plants and compressed air reservoirs are better suited to offer flexibility in the time horizon from hours to days. Several heat storage technologies can also offer flexibility, such as thermal storage or concentration of solar energy, which uses highly efficient heat storage and can become an dispatchable resource of high capacity [25]. Many available storage technologies have higher capital costs compared to other flexibility options currently available, and most power systems require further technological improvements to make storage competitive against other flexibility options.

Transmission capacity is frequently though of an essential part of system flexibility, as it provides an alternative to local VRE generation. Instead, interconnections allows VRE to be transmitted to other regions where it can be used. In addition, the improvement of connections to adjacent transmission networks, including the expansion of existing lines, provides the power supply system with improved access to a range of balancing resources [19]. The combination of all generation assets by such connections improves both flexibility and net demand throughout the power system. Weather patterns become less correlated in larger areas, which smoothes the output profiles of wind and solar energy [26].

The fitting combination of flexibility options for a particular energy system will be specific to that system and will depend on the relative economy of the options available, among other factors. In a network integration study, planners can evaluate the relative costs and benefits for different options by systematically testing and evaluating different combinations of new operating practices and other sources of flexibility.

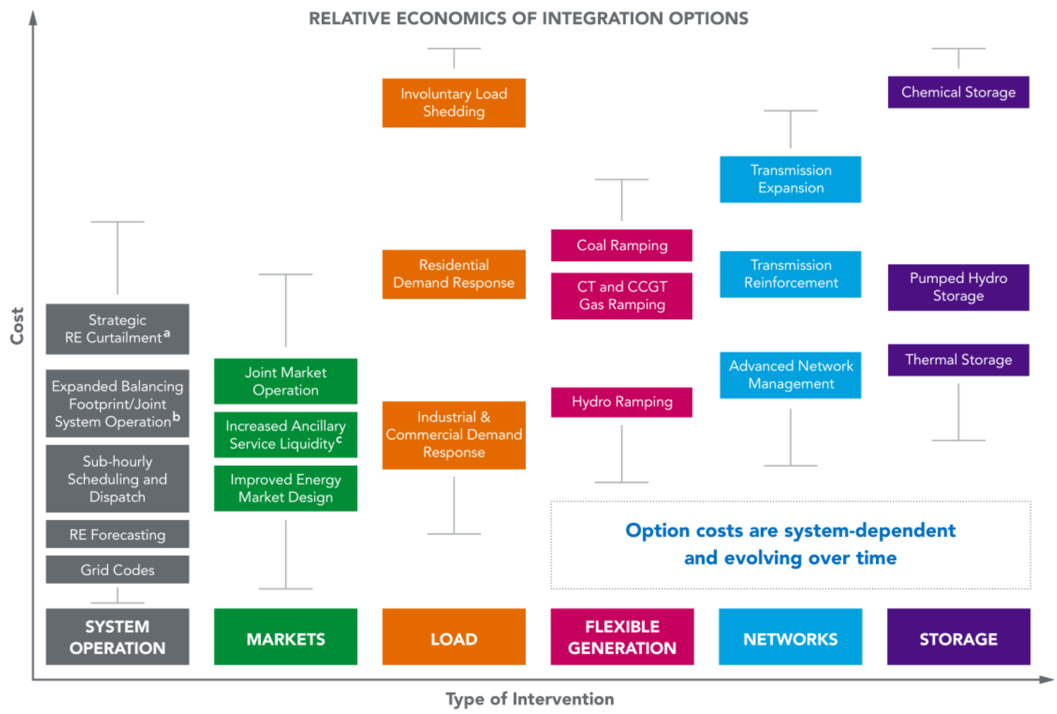

Figure 2.5 - Example of flexible integration options. Spanning from physical (storage, transmission), operational (cycling thermal fleets, forecast integration), to institutional (new market designs, integration of demand response).**[27]**

By adopting many of the integration best practices in figure 2.5, utilities in many regions have successfully incorporated large amounts of variable renewable energy.

Chapter 3

Methodology

3.1 Scenario Development

The objective of this step is the definition of a set of future scenarios of interest in terms of renewable generation penetration, according to the environmental European and Portuguese energy strategies, but also according to existing Portuguese economic constraints and expected evolution. For these scenarios the net demand will be computed, and its up and down ramps analysed following the next steps proposed in this methodology.

The scenarios have been designed by performing a literature review of the most relevant reports, and a summary in the subsections below has been presented for each, for 2030 and 2050 that correspond to significant dates in the EU energy and environmental strategies.

Using the above information, a final set of scenarios to be considered has been designed to perform the ramp analysis of the net load.

The main data that are needed to define these scenarios are:

- Demand
- Solar installed capacity
- Wind installed capacity

Several important assumptions will be needed to compute the net demand from the scenario definitions:

- Demand profile does not change: this may be contradictory with some of the assumptions of the original scenarios of the reports, since it is expected the increasing active participation of final customers in controlling their demand and additional electrification of the energy system. Thus limiting the real accuracy of the results.
- Wind and solar profiles and their capacity factor do not change either, which with the change of location and the improvement of technology they would.
- No analysis has been made of how the rest of technologies supply the net demand. This may be relevant since it is a key aspect to confirm if a scenario is or not sufficiently realistic. Indeed scenarios with too much renewable generation may not be supported with the available dispatchable capacity. However most scenarios

are almost directly borrowed from reports where this analysis is supposed to be done.

- Some extreme scenarios have been included to assess the different impact of wind and solar generation capacity in the net demand ramps, even if the scenarios may be unrealistic due to their imbalanced mix.

3.2 Data Gathering and Computation

Another step was to collect from REN's website hourly values about consumption and generation for the years 2008-2017 (excluding 2010 because data was unavailable).

An excel sheet was created in order to have all the elements that influence the net load characterization of a specific scenario then the net load was computed to all years and scenarios according to the following formula:

$$NL_h = L_h.\vartheta l - \sum_{w}^{s} VRE_h^w.\ \vartheta r^{\ w} \qquad\qquad \forall h \in T, \forall w \in s$$

NL_h*: Net load for an hourly period h [MWh]*

L_h *: Load for an hourly period h [MWh]*

ϑl *: Scaling factor for load data*

VRE_h^w*: Variable renewable generation by technology w for an hourly period h [MWh]*

$\vartheta r^{\ w}$: *Scaling factor for electricity generation by technology w*

$\forall h \in T$: *Hourly periods, running from 1 to T hours (T = 8,760 hours or T = 8,784 hours for leap years)*

$\forall w \in s$: *Renewable electricity generation technology, running from w, wind technology to s, solar technology.*

Ramps of the net load were also calculated, defined as the difference between net load in hour t and net load in hour t-1 (with t = 1,…,8760). These variations can be either positive, ramp upwards or negative, ramp downwards.

$$R_h = NL_{(h)} - NL_{(h-1)}$$

The results were computed for the scenarios made for 2030 and 2050 and for 2008-2017 (excluding 2010 because of unavailable data), making an historical evolution of the ramp requirements of the net demand vs the evolution of the renewable generation.

The display of the results is made in chapter 4 where they are analysed and compared to conclude the impact of the VRE, the risks with the types of scenarios and make possible suggestions or recommendations.

3.3 Metrics

The topic and the term flexibility requirements were shortly discussed in articles dealing with the search for metrics of flexibility [13] [28]. In it is formulated an attempt to propose a qualitative framework for measuring a system's flexibility needs in terms of three metrics: ramp magnitude, ramp frequency and response time. NERC's defines them as the following[29]:

- Ramp magnitude, refers to both the size of ramp events and the direction of that event. Traditional reserve calculations sometimes measure the requirements as the size of the first and second contingencies. Incremental flexibility is required at times of facility failures and net load increases
- Ramp frequency, refers to the number of times events of various magnitudes and responsiveness occur. Variable resources generally increase the frequency with which flexible resources must be used in response to small or medium events. This is usually a cost problem, as each time resources are used to balance supply and demand, operating costs are incurred.
- Ramp Response, refers to both the rate of change of net load and its predictability; the rate of increase of resources must be large enough to be available to respond to the system's ramping requirements.

In this thesis we focus only in the magnitude and frequency of net load ramps on an hourly basis that have to be balanced by the complementary system representing them by histograms.

Graphs of the annual duration curves of the load and net load were also created to explore the impacts of high VRE increments.

Tables with statistical measures, maximum, minimum, average and standard deviations where also created for the analysis of the annual data and to show the dispersion of it. It was thought relevant to also get the 0,05th percentile of max ramps since the maximum value measured could be considered an outlier or an extreme load event.

Some macros in excel were also created in order to automate the increase or decrease of the load and VRE installation so that when changing their respective factors in the different scenarios the calculation of the net load and its ramps would automatically be re-done and the charts and tables associated with it take new forms and values.

3.4 2030

For the scenario design were considered two recent studies already done for the energy market, in line with European framework, for the year 2030:

- "Report on the Monitoring of Supply Security in the National Electricity System for the 2017-2030 Period" (*RMSA 2017*)[30], made by the government, namely through the General Directorate of Energy and Geology (*DGEG*), which is the Portuguese public administration body responsible for the design, promotion and evaluation of policies and the definition of regulations concerning energy resources.
- "Energy Outlook 2017"(EO 2017) [31] made by *EDP,* the main company of the Portuguese energy sector at the level of production, distribution and commercialization of electricity. This report presents the EDP expected tendencies of the energy sector on the long run, focusing on the impact that decisions on the energy policy may have on the Portuguese energy market sustainability until 2030.

For the preparation of the RMSA were considered the policy guidelines on security of supply and prospects for promoting renewable energy sources and energy efficiency measures (embodied in the PNAER and PNAEE revision), in particular through projections for the level of demand and the additional supply capacity, planned or under construction, owing to analyze the balance between supply and demand in the national market, the quality and the level of maintenance of the networks and to carry out an analysis on the existence of risks of rupture in the face of extreme levels of demand and the failures of one or more producing or marketing centers.

EDP in their report for their study of the energy market in 2030, made two scenarios differentiated by means of elements of energy policy on the demand and supply side, calling them Thermal Scenario and Green Scenario.

The first one, Thermal Scenario, being in line with the RMSA expectations, characterized by having a business as usual approach with limited investments in renewable and other capital-intensive technologies. On the contrary, the Green Scenario assumes a more expansionary vision of renewables, energy efficiency and electrification, and is characterized by having policies to promote long-term contracts for renewables and a regulatory framework favoring the promotion of energy efficiency. All of this lead, for this scenario, to a faster growth of distributed generation and electrification of consumption.

Thus, it was thought to be interesting to calculate the net load for these two types of scenarios corresponding to different energy policies, with one scenario resulting from a more conservative growth whereas the other responds to a more environmental and optimistic evolution especially in the fields of distributed generation and electrification of consumption.

For practical purposes it will be given the same names to the scenarios as in the EDP's outlook report, Thermal Scenario and Green Scenario. Table 3.1 summarizes the main data of the described 2030 Scenarios.

Table 3.1 - Major data adapted from RMSA 2017 and EO2017 reports.

2030 Goals	***Thermal Scenario (2030T)***	***Green Scenario (2030G)***
Emissions Reduction (vs 2005)	≅- 35% of GHG	≅ -58% of GHG
Share of Res in the Power System	≅61%	≅84%
Wind capacity	5,6 GW	7,6 GW
Solar capacity	1,1 GW	5,7 GW
Energy Efficiency (accumulated savings of relatively to 2016) + *Distributed Generation*	6 TWh + 0,6 TWh	6,7 TWh + 2,5 TWh
Demand (taking account EE+DG)	≅53 TWh	≅ 54 TWh

3.5 2050

To design 2050 scenarios it was used a recent study made by Portuguese Association of Renewable Energies (APREN), “The Role of Electricity In The Decarbonization of The Portuguese Economy” [32]. This study questions to what extent electricity should contribute to the decarbonization of the Portuguese energy sector and what are the economic, budgetary and distributional impacts of policies to support the decarbonization of the Portuguese economy.

This report presents different decarbonization scenarios with different caps on GHG energy and industrial processes-related emissions corresponding to a 60%, 75% and 85% reduction in emissions by 2050 relative to 1990 values (named respectively CO2-60%, CO2-75% and CO2-85%).

In all modelled scenarios, the electricity consumption increases both in absolute terms relatively to 2017 (62 to 82 TWh).

Successive aggressive decarbonization targets conduct the power system to increasing renewable participation up to 98% in 2050. Hydropower, onshore wind and solar PV are the most cost-effective technological options, with the first two reaching the maximum technical potential considered.

The generated final demand and share of renewables in the electricity production of the energy system in *APREN*’s report models can be seen below:

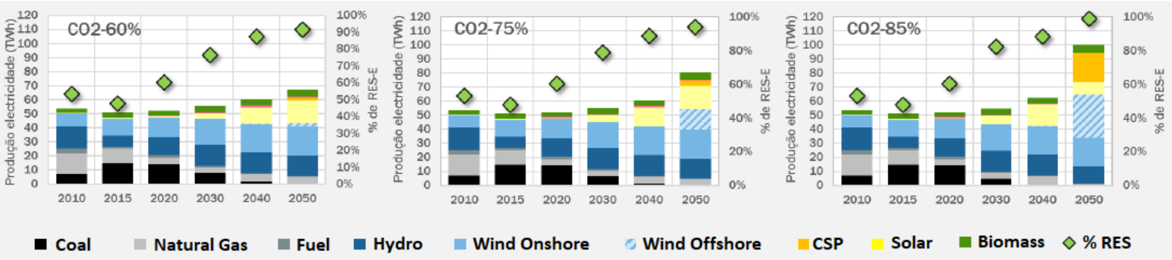

Figure 3.1 - Generated electricity per technology in the decarbonization modelled scenarios**[32]**

Since the report does not provide the exact generation from the technologies these were estimated directly from the figure 3.1. From the figure it was taken the percentage of wind (onshore + offshore) and solar generation of the total demand by measuring the graphs, which using the same capacity factor of 2017 was then taken the capacity installed.

All major data of APREN’s document can be seen in the table below.

Table 3.2 - Major data adapted from **“**The Role of Electricity In The Decarbonization of The Portuguese Economy”

2050 Goals		***CO2-60%***	***CO2-75%***	***CO2-85%***
Emissions Reduction (vs 2005)		≅- 60% of GHG	≅ -75% of GHG	≅ -85% of GHG
Share of RES in the the Electrical Power System		≅92%	≅94%	≅98%
	Wind share	35%	44%	51%
	Wind capacity	9,4 GW	15,6 GW	18,6 GW
	Solar share	25%	20%	8%
	Solar capacity	8,9 GW	9,1 GW	3,7 GW
Electrification of final consumption		36%	44%	51%
Demand		≅61,7 TWh	≅ 79,9 TWh	≅82,1 TWh

For 2050, some extreme scenarios were also created to assess the impact of solar and wind technologies on the net load and its ramps.

According to REN, for operational reasons of the electro producer system considering the current configuration and characteristics of the electricity transmission network, it is assumed a mandatory minimum electricity production of 15% overall fossil and hydro based[33]. This assumption is defined in order to guarantee the stability of the grid, which would not be guaranteed in a scenario of 100% VRE (due to the intermittence of renewable sources).

Thus, three scenarios of 85% share of VRE in the total annual power generation were formulated, with a ratio of 80% to 20%, 50% to 50% and 20% to 80% between wind and solar total annual production.

The demand of "2050 CO2-85%" scenario was used in for all 3 models, since is the one that is more ambitious and that complies with the European targets.

3.6 Scenarios summary

In table 3.3 we have the main input values of all scenario cases.

It can be seen that today's wind power technology has already a relevant amount of capacity installed whereas solar doesn't, so it makes sense that the main growth of capacity installed in the future is going to be in PV solar technology as it is observed in some scenarios with solar reaching almost 20 times of today's installed capacity while wind only about 3,5.

Note that the extreme scenarios don't mean to be realistic, they are meant to evaluate the different impacts of wind and solar in the net load and its ramps.

Table 3.3 - Major assumptions and input values of all scenario cases

	2017	**2030t**	**2030v**	**2050 CO2 -60%**	**2050 CO2 -75%**	**2050 CO2 -85%**	**2050 80w20s**	**2050 50w50s**	**2050 20w80s**
wind									
capacity(MW)	5313	5600	7600	9446	15609	18569	24759	15475	6190
growth rate (vs 2017)	1,0	1,1	1,4	1,8	2,9	3,5	4,7	2,8	1,2
capacity factor	26%	26%	26%	26%	26%	26%	26%	26%	26%
total annual production(TWh)	11,97	12,62	17,13	21,29	35,17	41,85	55,80	34,87	13,95
share in annual production	24,1%	23,8%	31,7%	34,5%	44,0%	51,0%	68,0%	42,5%	17,0%
solar									
capacity(MW)	481	1100	5700	8894	9055	3717	7900	19749	31598
growth rate (vs 2017)	1,0	2,3	11,9	18,5	18,8	7,7	16,4	18,0	65,7
solar capacity factor	20%	20%	20%	20%	20%	20%	20%	20%	20%
total annual production(TWh)	0,85	1,94	10,06	15,71	15,99	6,56	13,95	34,87	55,80
Share in annual production	1,7%	3,7%	18,6%	25,5%	20,0%	8,0%	17,0%	42,5%	68,0%
Demand(TWh)	49,64	53,00	54,00	61,70	79,94	82,05	82,05	82,05	82,05
VRE share	25,8%	27,5%	50,4%	60,0%	64,0%	59,0%	85,0%	85,0%	85,0%

Chapter 4

Results

4.1 Future Net Load Analysis

Table 4.1 - Summary data on Load, Net Load, VRE shortages and VRE surpluses in all scenario cases, 2017-2050

	units	2017	2030t	2030v	2050 CO2 -60%	2050 CO2 -75%	2050 CO2 -85%	2050 80w20s	2050 50w50s	2050 20w80s
Load										
Total	TWh	49,64	53,00	54,00	61,70	79,94	82,05	82,05	82,05	82,05
Max	MWh	8733,7	9325,7	9501,6	10856,5	14066,5	14437,6	14437,6	14437,6	14437,6
Min	MWh	3412,7	3644,0	3712,8	4242,2	5496,5	5641,5	5641,5	5641,5	5641,5
Aver	MWh	5666,1	6050,2	6164,4	7043,4	9125,9	9366,7	9366,7	9366,7	9366,7
σ	MWh	968,1	1033,7	1053,2	1203,4	1559,3	1600,4	1600,4	1600,4	1600,4
VRE										
Wind	TWh	11,97	12,62	17,13	21,29	35,17	41,85	55,80	34,87	13,95
Solar	TWh	0,85	1,94	10,06	15,71	2,50	2,97	13,95	34,87	55,80
Total	TWh	12,82	14,56	27,19	36,99	37,67	44,82	69,74	69,74	69,74
Share of VRE	%	25,8	27,5	50,4	60,0	47,1	54,6	85,0	85,0	85,0
Net Load										
Total	TWh	36,81	38,44	26,81	24,71	42,27	37,24	12,31	12,31	12,31
Max	MWh	8314,2	8879,5	9002,2	10267,9	13224,0	13512,6	13366,1	13585,8	13805,5
Aver	MWh	4202,4	4387,9	3277,3	2820,6	4825,7	4250,8	1405,0	1405,0	1405,0
σ	MWh	1350,9	1391,8	1842,3	2521,1	3205,3	3701,9	4662,0	5080,9	7778,9
Total hourly positive NL (VRE shortage) p.a.	TWh	36,81	38,44	27,21	26,34	43,58	40,09	23,88	25,77	37,32
Total number of positive NL hours	Hrs	8756	8752	8304	7559	8010	7517	5788	5556	5807
Total hourly negative NL (VRE surplus) p.a	GWh	0,63	0,98	406,44	1630,87	1302,66	2855,51	11568,08	13465,34	25007,90
Total number of negative NL hours	Hrs	4	8	456	1200	750	1244	2971	3204	2954

The impact of VRE on the requirements of the residual power plant system can be seen with the help of Table 4.1 and with the illustrations of the annual duration curves (sorting hourly values for a full year from the highest to the lowest value), as shown in the below figures. These duration curves allows to illustrate the relationship between generating capacity requirements and capacity utilization.

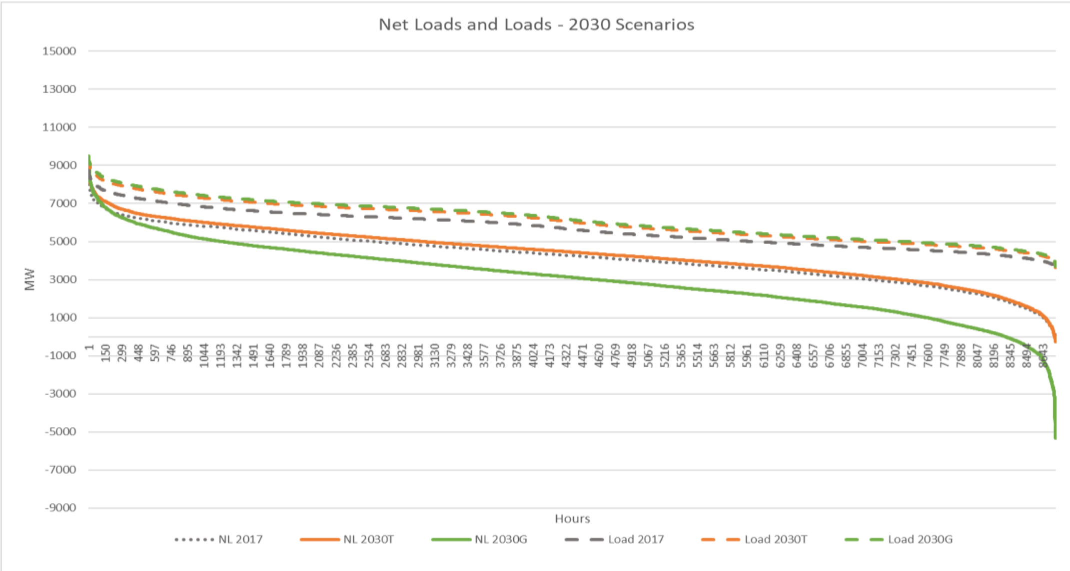

Figure 4.1 - Annual duration curves of the Net Load for 2030 scenarios

In figure 4.1 it can be seen that 2030t (in orange) is very similar to 2017(in dotted line) since they share approximately the same VRE in power generation, unlike 2030g (in green) where VRE capacity almost doubles, evidenced by the gap between the load and net load that corresponds to solar and wind generation.

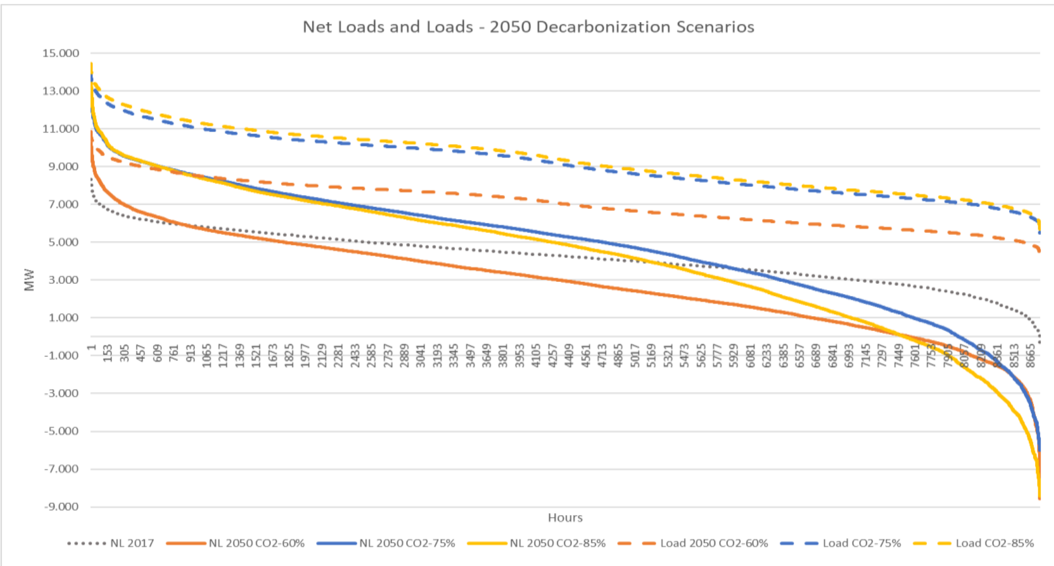

Figure 4.2 - Annual duration curves of the Net Load for 2050 decarbonization scenarios.

Now in figure 4.2, due to the increase in power supply from VRE sources, in 2050 scenarios, it's more perceivable that in peak hours situations the gap between the load and net load duration curve is small implying that dispatchable power plants and imports must cover almost the entire load, regardless of the capacity share of VRE. Meaning that firm capacity should be the same regardless of generation situations although some types of flexibility options could change that such as power imports, demand response or using storage during surplus hours.

Whereas the need for peak load capacity increases, the need for base load decreases and consequently power plants must show a high level of flexibility and reduce their output more frequently.

An increasing share of power production from sun and wind leads, hence, to a growing variability and an increase in extreme values of net load, implying a higher need for flexibility to deal with these VRE-induced characteristics of the net demand.

Hourly net load becomes then much more variable behaving distinctly with different shares of wind and solar capacity. In 2050 CO2-85%, it even varies between approximately -9 GW, a large VRE surplus (negative net load), and +1,4 GW, a large VRE shortage (positive net load), compared to -0,2 GW and +0,85 GW in 2017, respectively.

As the share of VRE generation in total load increases significantly over the period 2017-2050, both the number of hours with a VRE surplus, the maximum hourly VRE surplus and the total hourly VRE surplus per annum tend to increase as well. For example, while the VRE share in total load increases from about 26% in 2017 to about 60% to 64% in 2050 decarbonation scenarios, the number of VRE surplus hours increases from approximately zero to 750-1250, while the total hourly VRE surplus rises from about zero to approximately 1,3 to 2,8 GWh depending in which scenario.

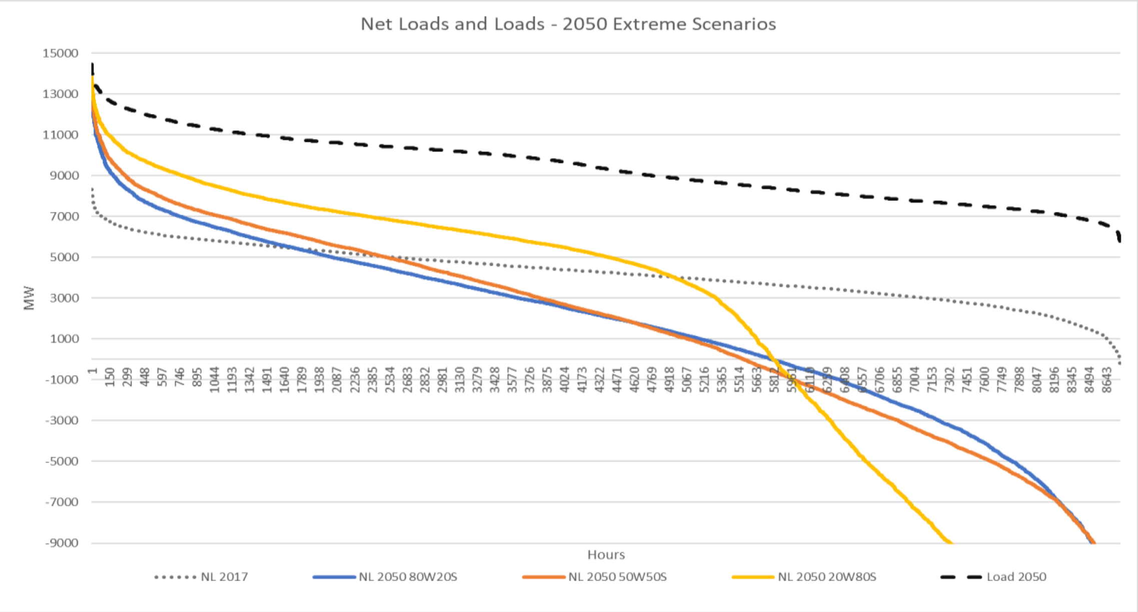

Figure 4.3 - Annual duration curves of the Net Load for 2050 extreme scenarios.

Figure 4.3, illustrating the annual curves of the extreme scenarios helps to comprehend that according to different ratios of solar and wind capacity the net load behaves differently.

In the "2050 20w80S" scenario (20% wind and 80% solar ratio in the annual production), being significant more extreme and non-ideal with its high VRE surpluses and shortages while

"2050 50W50S" not being so suggestively different than "2050 20W80S" because of having similar solar installed capacities.

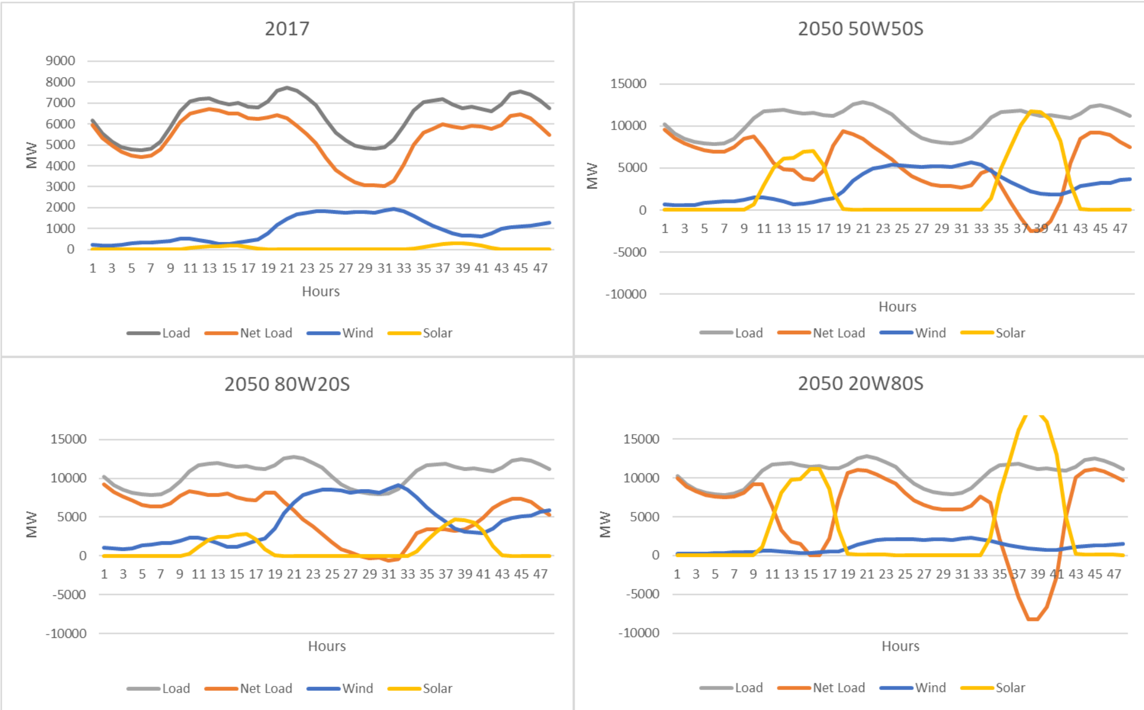

Figure 4.4 - Load, net load, wind and solar profiles of days 5 and 6 of January in reference year and 2050 extreme scenarios.

The simulations described in figure 4.4 stress the influence of high VRE penetration in the net load and the need for a good balanced mix in the generation, unlike these scenarios created.

With the high impact of solar in the scenario "2050 20W80S" in the first day it is perceivable the phenomenon "duck curve"[34], a term coined by NREL where the net load graph resembles the silhouette of a duck because of solar flooding the generation and then dropping off in the evening as electricity demand peaks, creating a situation where dispatchable generation must rapidly increase power output around the time of sunset to compensate for the loss of solar generation. Moreover, it can be see a major spillage during the day and the obvious no solar power during the night, explaining the annual curve of this non-ideal solar induced scenario with extreme VREs shortages and surpluses and the drawback of creating a scenario where solar has to cover 68% of the total generation. Additionally, about surpluses it should be noted that it could be dealt with other flexible mechanism such as storage, for example, although the continuing increment of solar capacity and some curtailment can be a more cost-significant option.

Wind profiles, unlike solar, are a lot more spread out and one cannot see a characteristic pattern from one day to another, although in this case and in others a synergy between the sun and wind can be observed, where wind is stronger at night when there's no sun, and less stronger at day time when there's sun, complementing each other in some way.

4.2 Net Load Ramps Analysis

While the duration curves and the residual power generation illustrate the requirements of the net load in the power plant, it has its limits as the time-dependence between hourly net load values is lost. This is why is also important to look at the time series of the net load in order to further understand the dynamics of the flexibility challenge.

The ramps are going to be presented in histograms with a bin width of 75 MWh and the same scale of the horizontal axis between groups for the comparison of their shapes except in the extreme scenarios where the bin width is 150 MWh and the x-axis is not fixed between scenarios.

4.2.1 2008-2017

Table 4.2 - Summary data on Load, Net Load and Net Load Ramps for years 2008-2017

	unit	2008	2009	2011	2012	2013	2014	2015	2016	2017
Load										
Total	TWh	50,57	49,86	50,50	49,06	48,82	48,82	48,97	49,27	49,64
Max	MWh	8954,6	9193,9	9166,8	8508,2	8292,7	8291,2	8577,9	8113,8	8733,7
Min	MWh	3541,1	3429,5	3407,0	3439,8	3526,3	3363,9	3393,1	3510,7	3412,7
Aver	MWh	5757,5	5691,8	5764,7	5585,2	5610,8	5573,6	5589,6	5609,1	5666,1
σ	MWh	1083,1	1097,1	1051,3	997,6	975,9	966,8	965,9	947,9	968,1
VRE										
Wind	TWh	5,69	7,49	9,00	10,01	11,75	11,81	11,33	12,19	11,97
Solar	TWh	0,03	0,15	0,26	0,36	0,44	0,60	0,76	0,78	0,85
VRE	TWh	5,73	7,64	9,26	10,37	12,19	12,41	12,09	12,97	12,82
Share of VRE	%	11,3%	15,3%	18,3%	21,1%	24,8%	25,4%	24,7%	26,3%	25,8%
Net Load										
Total	TWh	44,85	42,22	41,23	38,69	36,41	36,41	36,87	36,30	36,81
Max	MWh	8325,9	9126,3	8474,5	7969,1	7598,4	7856,1	8465,2	7535,1	8314,2
Aver	MWh	5105,4	4819,5	4707,1	4404,9	4218,9	4156,9	4209,2	4132,3	4202,4
σ	MWh	1162,8	1225,8	1319,7	1297,1	1302,5	1245,6	1318,6	1359,5	1350,9
1h Ramp Up										
Max	MWh	1314,2	1265,1	1387,1	1307,5	1295,7	1365,4	1252,8	1457,0	1225,8
0,05th percentile of Max	MWh	1289,8	1250,0	1291,6	1174,3	1167,6	1211,6	1150,9	1256,7	1170,6
Aver	MWh	311,8	308,8	305,2	296,1	285,2	280,6	268,9	276,4	274,2
σ	MWh	267,5	259,7	258,2	245,3	240,9	239,3	230,6	230,7	228,2
Number of ramp-up hours	Hrs	3812	3868	3905	3922	4002	4024	4072	4062	4097
1h Ramp Down										
Max	MWh	1098,5	1208,6	1122,6	1067,3	1108,5	1175,0	1151,0	1046,4	1180,9
0,05th percentile of Max	MWh	996,3	1072,5	1107,6	1035,8	1050,1	1038,0	1005,3	981,5	1054,3
Aver	MWh	239,3	244,4	245,6	239,0	240,0	238,0	234,0	237,3	241,2
σ	MWh	185,9	190,2	191,6	183,0	186,2	181,4	180,4	182,0	187,4
Number of ramp-down hours	Hrs	4971	4891	4854	4861	4757	4735	4687	4721	4663

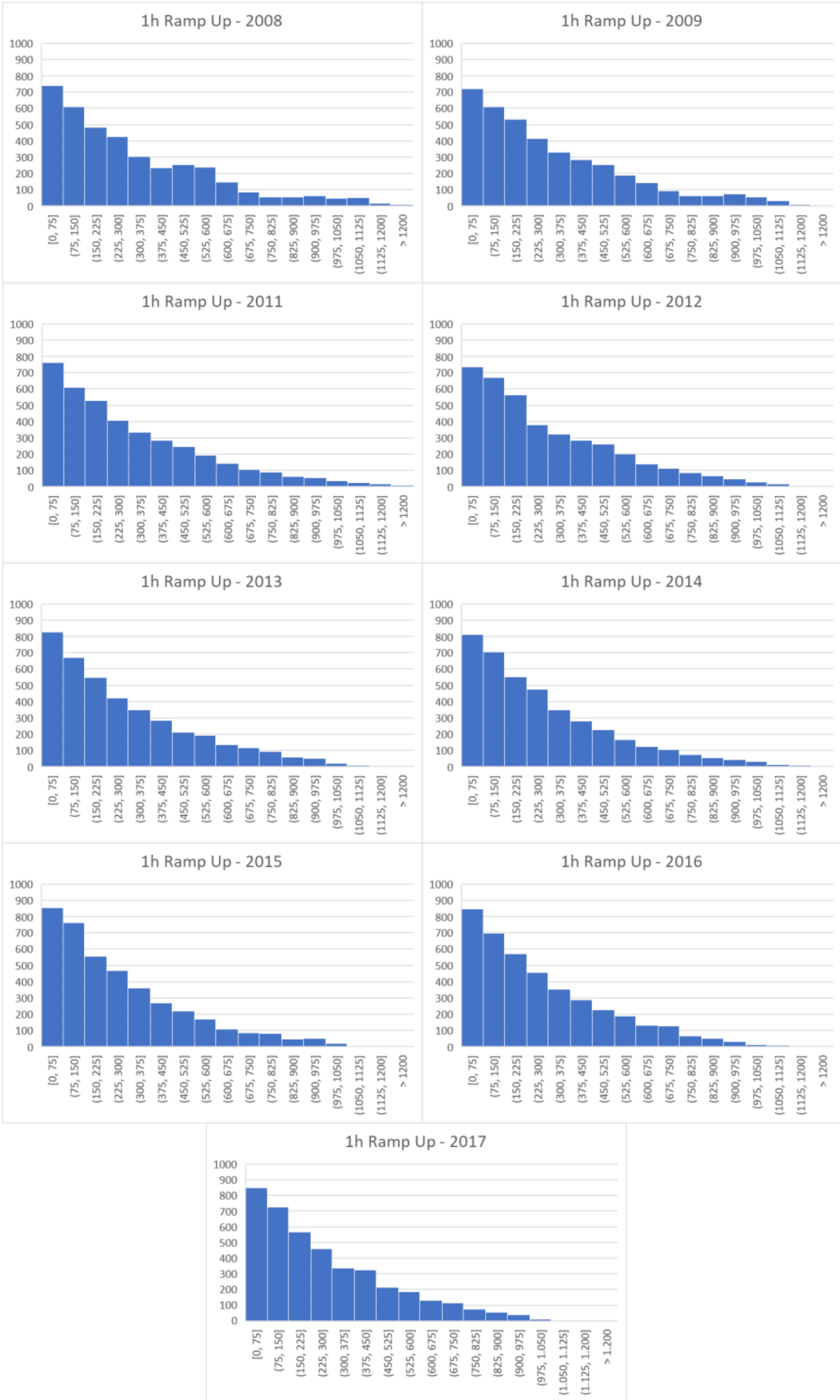

Figure 4.5 - Hourly ramp upwards of the Net Load for the period 2008-2017

From the hourly ramp up histograms for the period 2008-2017 it can be observed that they maintain more or less the same shape, where the left part representing small ramps are more frequent and as the magnitude drops, its frequency also drops, following the trend of exponential type of distribution.

One can also perceive that has the years pass the number of hourly ramp up rises.

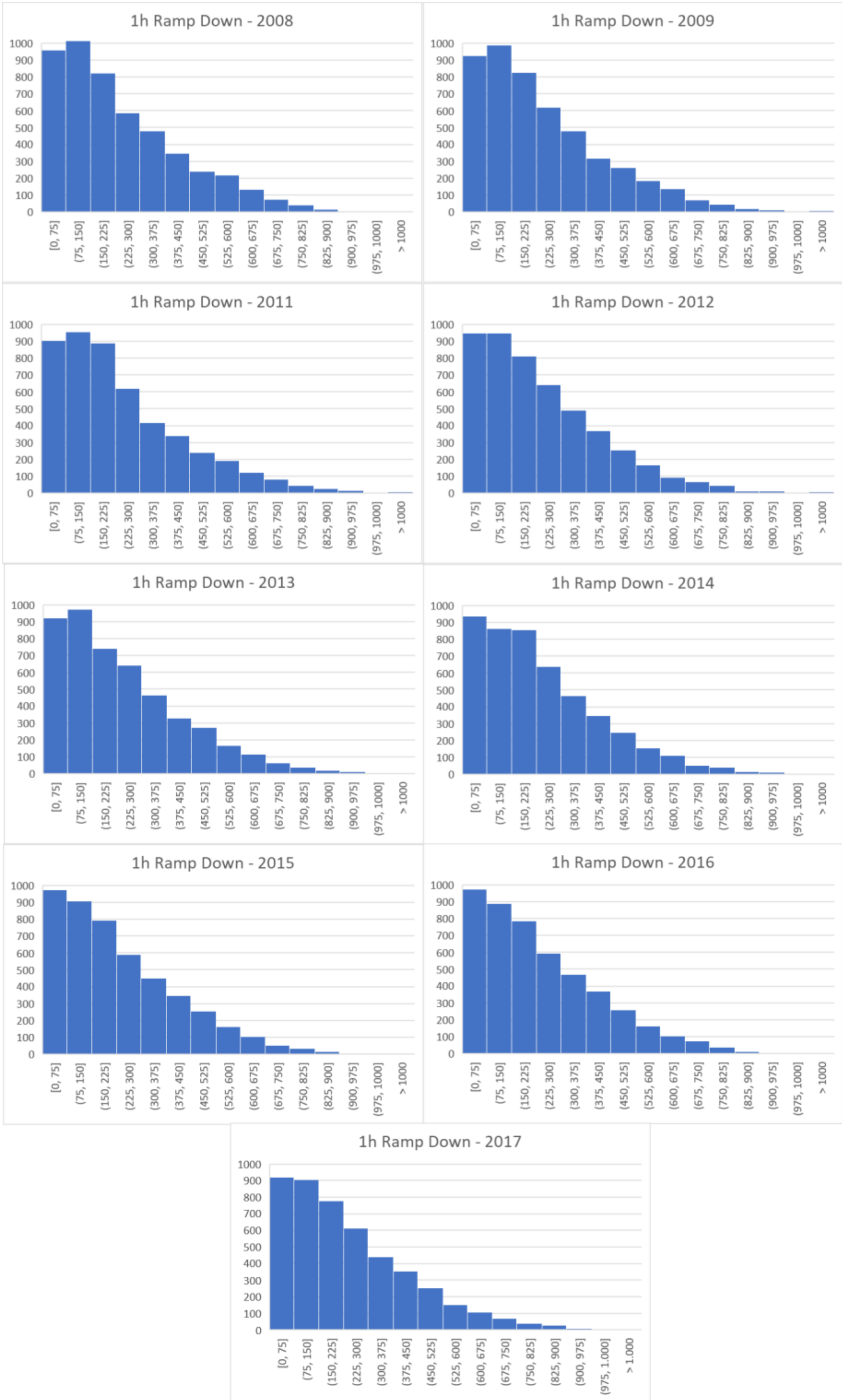

Figure 4.6 - Hourly Ramp Downward of the Net Load for the period 2008-2017

As for the hourly ramp down histograms for the same period they sort of maintain the same form between each other, although in the first years there were ramps of higher magnitude, as the years pass one can witness that the number of hours that ramp down decreases while ramping up increases.

For a better perception of how the max and its percentile of the net load ramps increase over the years the graph in Figure 4.7 was created relatively to the investments in VRE capacity.

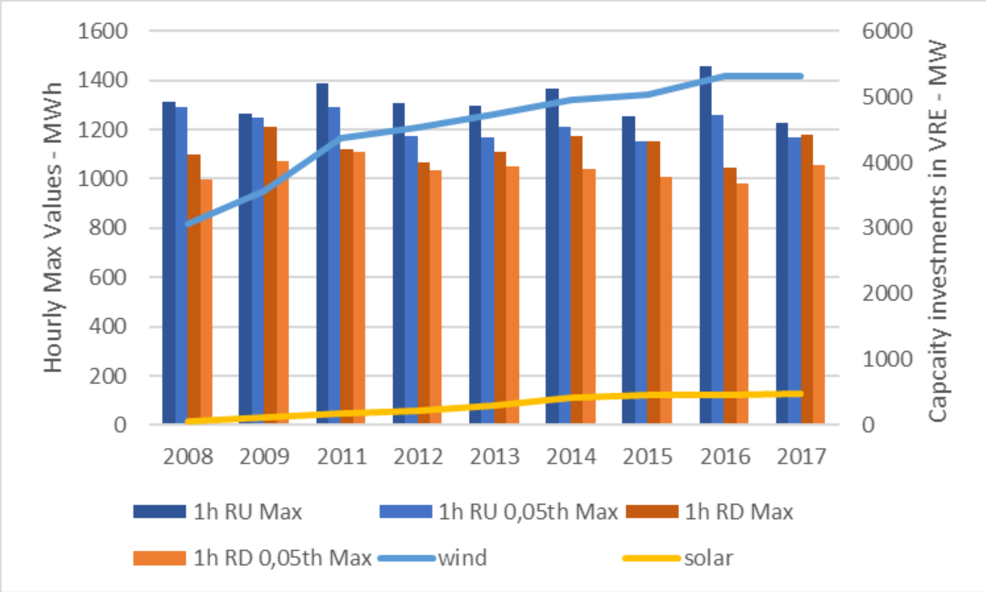

Figure 4.7 - Evolution of Hourly Ramp's Max Values and capacity investments

As the capacity investments in VRE grew, mostly in wind technology, the net load max ramps did not change considerably, possibly because of the effect of spreading geographically the wind turbines, and compensating each other's profile, decreasing the variability in the net load.

4.2.2 2030-2050

Table 4.3 - Summary data on Load, Net Load and Net Load Ramps for all scenarios

	unit	2017	2030t	2030v	2050 CO2-60%	2050 CO2-75%	2050 CO2-85%	2050 80w20s	2050 50w50s	2050 20w80s
Load										
Total	TWh	49,64	53,00	54,00	61,70	79,94	82,05	82,05	82,05	82,05
Max	MWh	8733,7	9325,7	9501,6	10856,5	14066,5	14437,6	14437,6	14437,6	14437,6
Min	MWh	3412,7	3644,0	3712,8	4242,2	5496,5	5641,5	5641,5	5641,5	5641,5
Aver	MWh	5666,1	6050,2	6164,4	7043,4	9125,9	9366,7	9366,7	9366,7	9366,7
σ	MWh	968,1	1033,7	1053,2	1203,4	1559,3	1600,4	1600,4	1600,4	1600,4
VRE										
Wind	TWh	11,97	12,62	17,13	21,29	35,17	41,85	55,80	34,87	13,95
Solar	TWh	0,85	1,94	10,06	15,71	2,50	2,97	13,95	34,87	55,80
VRE	TWh	12,82	14,56	27,19	36,99	37,67	44,82	69,74	69,74	69,74
Share of VRE	%	25,8%	27,5%	50,4%	60,0%	47,1%	54,6%	85,0%	85,0%	85,0%
Net Load										
Total	TWh	36,81	38,44	26,81	24,71	42,27	37,24	12,31	12,31	12,31
Max	MWh	8314,2	8879,5	9002,2	10267,9	13224,0	13512,6	13366,1	13585,8	13805,5
Aver	MWh	4202,4	4387,9	3277,3	2820,6	4825,7	4250,8	1405,0	1405,0	1405,0
σ	MWh	1350,9	1391,8	1842,3	2521,1	3205,3	3701,9	4662,0	5080,9	7778,9
1h Ramp Up										
Max	MWh	1225,8	1264,8	2165,9	3139,0	2794,0	3222,3	4459,7	6490,6	9872,2
0,5th percentile of Max	MWh	1170,6	1211,7	1967,6	2997,0	2774,9	3179,7	4054,6	6409,8	9837,6
Aver	MWh	274,2	273,3	449,8	657,5	525,1	575,4	738,5	1375,6	2238,4
σ	MWh	228,2	225,2	386,6	595,1	433,9	478,3	627,1	1333,0	2218,7
Number of ramp-up hours	Hrs	4097	4244	3782	3695	4187	4209	4124	3624	3426
1h Ramp Down										
Max	MWh	1180,9	1254,6	1970,6	2742,0	2834,3	3287,1	4205,1	5368,4	8631,7
0,5th percentile of Max	MWh	1054,3	1121,5	1453,1	2317,1	2507,1	2860,2	4195,0	5315,4	8471,3
Aver	MWh	241,2	257,3	342,2	480,3	481,8	533,3	658,5	971,6	1438,3
σ	MWh	187,4	201,9	247,7	365,7	386,0	433,9	535,7	905,0	1720,4
Number of ramp-down hours	Hrs	4663	4515	4977	5064	4572	4550	4635	5135	5333

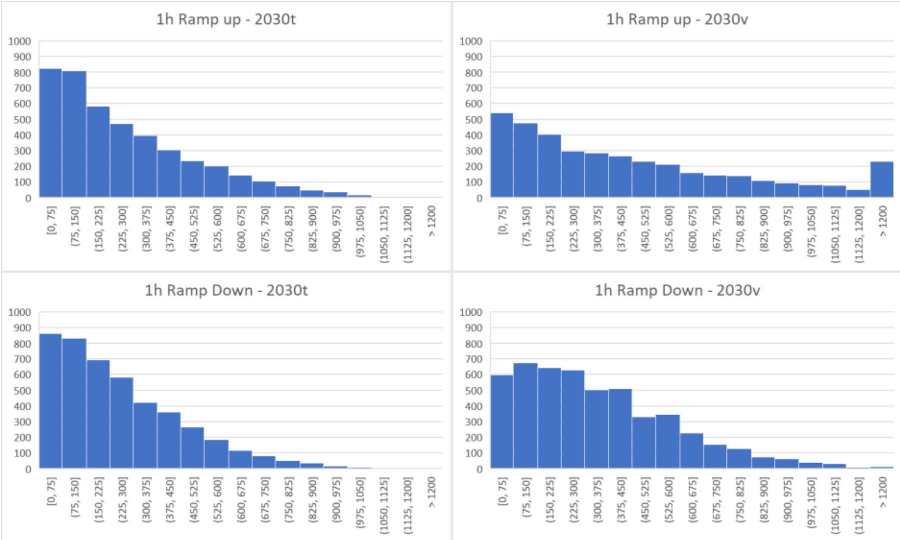

Figure 4.8 – Hourly net load ramps histograms for the 2030 scenarios

Regarding 2030 ramps, in figure 4.8, in the Thermal Scenarios are very similar to the year 2017 since they share approximately the same VRE share and capacity. Yet in the Green Scenario the wind capacity installation rises very slightly compared to Thermal one but PV capacity installation is more than ten times bigger. The frequency of ramps up close to zero is reduced nearly by half, the occurrence of high ramps rises dramatically, and the max ramps, either up or down almost double.

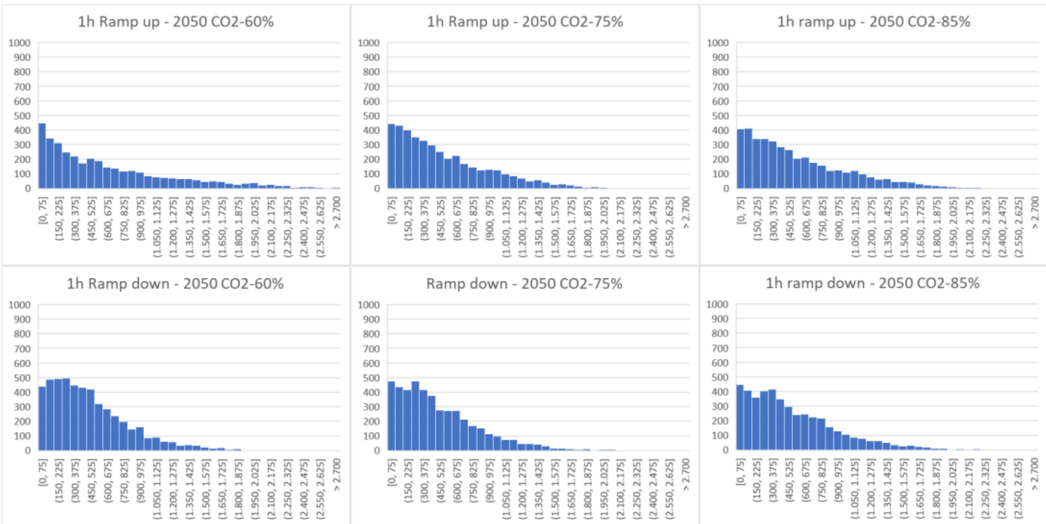

Figure 4.9- Hourly net load ramps histograms for 2050 decarbonization scenarios

As for the 2050 decarbonization scenarios the same phenom in different levels can be observed with the ramps up close to zero reducing immensely and with the appearance of high ramps compared to today's ramps

So to have a notion of how different ratios of wind and solar capacity affect the ramps of the net load, the extreme scenarios can prove helpful.

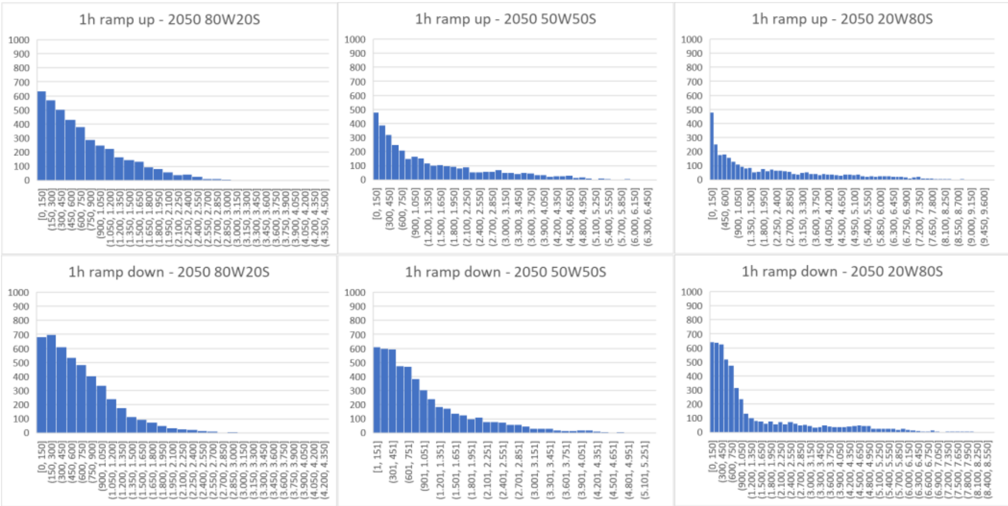

Figure 4.10 – Hourly net load ramps histograms for 2050 extreme scenarios

It is perceivable straight away how the scenario of 20w80s, dominated by solar production, in the right, although it has a similar amount of ramps in the 150 MWh magnitude its tail is much longer having ramps that reach the double of magnitude of the maximum ramp of the 80W20S scenario.

It is also observed how volatile and fluctuant the magnitude of the higher ramps is, compared to the 80W20S, where the wind production dominates, that follows an exponential dispersion as the ramps seen through the 2008-2017 period, although with much higher magnitude, correlated with the capacity installation.

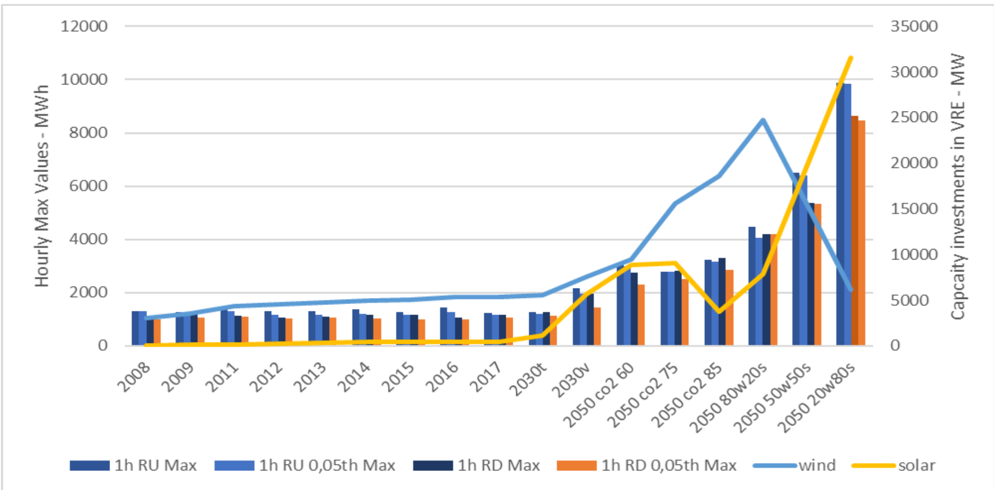

Figure 4.11 - Evolution of Hourly Ramp's Max Values and capacity investments

Looking now at the future max ramps of future scenarios it is interesting to see how in the extreme ones, having the same demand and share of renewables in the final consumption, the max ramp change considerably being solar capacity the clear dominant factor. It should be noted that using 2017 wind profiles can be a constraint since that with the deployment of new wind turbines spreading across the country their profiles could balance each other spreading out and thus decreasing net load variability.

Chapter 5

Conclusion and Future Work

5.1 Conclusion

In this dissertation, it has been evaluated some of the impacts of large-scale wind and solar PV power integration on the features of the net load in the system and its hourly ramps. The analyses were performed using both historical data from past years and also future simulated data scenarios for years 2030 and 2050. The future scenarios were based on reports about the expectancy of the Portuguese power system accounting economic and environmental restraints.

The simulated net load time series are analyzed from a variety of perspectives, such as daily shapes, load and net load duration curves and histograms of hourly ramps. The main contribution of this dissertation is to provide a discussion on how the net load characteristics would deviate from what power systems are accustomed to today when a significant amount of wind and solar power generation is integrated into the grid.

Another observation was made on load and net load duration curves where negative net loads in scenarios with significant wind and solar PV power integration are expected in future years, meaning that VRE surpluses are going to happen and have to be dealt with.

Hourly analysis of the resulting net load and its ramps can also help to quantify the flexibility requirements in future Portuguese electricity system. It has been shown that the rising share of wind and solar energy in annual electricity consumption will dramatically increase the need for flexibility. In particular, large PV contributions will encourage this trend since the variability in solar has bigger impact than wind in the net load and its ramps.

It also has to be noted that using 2017 wind profile can be misleading since wind production is different every year and with new wind turbines on new spots geographically could help to smoothen its profile and decrease variability in the net load improving flexibility in the power system. The same for the load profile where with the expected increasing electrification and demand response technologies in the future it would alter the load profile in a flexible way.

5.2 Future Work

Regarding future work it is suggested an improvement in the way of transposing the load curve to the future considering the expected future electrification and demand side technology which would alter the profile in a flexible way and thus get better estimations to the ramp requirements in the future.

In addition to the operational time horizon of 1 hour, which was the focus of our analysis, flexibility requirements in the time horizon of minutes for the design of automatic generation controls are important. The ramping behavior of the net load calls for new strategies for market and system operation to ensure the security of the grid.

References

[1] COM (2015), “The Paris Protocol – A blueprint for tackling global climate change beyond 2020.” .

[2] European Commission, “2020 climate & energy package,” *Climate Action - European Commission*, 23-Nov-2016. [Online]. Available: https://ec.europa.eu/clima/policies/strategies/2020_en. [Accessed: 30-May-2018].

[3] European Council, “2030 CLIMATE AND ENERGY POLICY FRAMEWORK.” .

[4] “Renewable energy directive - Energy - European Commission,” *Energy*. [Online]. Available: /energy/en/topics/renewable-energy/renewable-energy-directive. [Accessed: 25-Jun-2018].

[5] European Commission, Ed., *Energy roadmap 2050*. Luxembourg: Publications Office of the European Union, 2012.

[6] “UNFCCC | Climate Change Connection.” [Online]. Available: https://climatechangeconnection.org/solutions/international-solutions/unfccc/. [Accessed: 20-Jun-2018].

[7] “Resolução do Conselho de Ministros n.º 20/2013 - Diário da República n.º 70/2013, Série I de 2013-04-10,” *Diário da República Eletrónico*. [Online]. Available: https://dre.pt. [Accessed: 03-Jun-2018].

[8] Agência Portuguesa do Ambiente, “Programa Nacional para as Alterações Climáticas (PNAC2020/2030).” .

[9] Ministerio do Ambiente and Governo de Portugal, “Compromisso para o Crescimento Verde.” .

[10] “Portugal precisa de mais energia renovável.” [Online]. Available: https://www.jornaldenegocios.pt/empresas/energia/detalhe/portugal-precisa-de-mais-energia-renovavel. [Accessed: 27-Mar-2018].

[11] APREN, “2017 Electricidade Renovável em Revista.” .

[12] REN, “Dados Técnicos ’17.” .

[13] J. Ma, V. Silva, R. Belhomme, D. S. Kirschen, and L. F. Ochoa, “Evaluating and Planning Flexibility in Sustainable Power Systems,” *IEEE Trans. Sustain. Energy*, vol. 4, no. 1, pp. 200–209, Jan. 2013.

[14] J. Widén *et al.*, “Variability assessment and forecasting of renewables: A review for solar, wind, wave and tidal resources,” *Renew. Sustain. Energy Rev.*, vol. 44, pp. 356–375, Apr. 2015.

[15] D. Lew and M. Milligan, “The Value of Wind Power Forecasting,” p. 13.

[16] Matthias Huber, “Flexibility in Power Systems - Requirements, Modeling, and Evaluation.” .

[17] G. Crabtree *et al.*, “Integrating Renewable Electricity on the Grid,” 2011, pp. 387–405.

[18] J. Cochran, D. Lew, and N. Kumar, “Evolution from Baseload to Peaking Plant,” p. 10.

[19] International Energy Agency, Ed., *The power of transformation: wind, sun and the economics of flexible power systems*. Paris, France: International Energy Agency, 2014.

[20] Nick Parker and SPP Market Design, “Ramp Product Design.” .

[21] N. Navid and G. Rosenwald, “Ramp Capability Product Design for MISO Markets,” p. 68.

[22] K. H. Abdul-Rahman, H. Alarian, M. Rothleder, P. Ristanovic, B. Vesovic, and B. Lu, “Enhanced system reliability using flexible ramp constraint in CAISO market,” in *2012 IEEE Power and Energy Society General Meeting*, 2012, pp. 1–6.

[23] M. Hummon and S. Kiliccote, “DR Resources for Energy and Ancillary Services in the West,” p. 43.

[24] P. Cappers, A. Mills, C. Goldman, R. Wiser, and J. H. Eto, “An assessment of the role mass market demand response could play in contributing to the management of variable generation integration issues,” *Energy Policy*, vol. 48, pp. 420–429, Sep. 2012.

[25] B.-M. Hodge, C. Brancucci Martinez-Anido, Q. Wang, E. Chartan, A. Florita, and J. Kiviluoma, “The combined value of wind and solar power forecasting improvements and electricity storage,” *Appl. Energy*, vol. 214, pp. 1–15, Mar. 2018.
[26] L. Bird, J. Cochran, and X. Wang, “Wind and Solar Energy Curtailment: Experience and Practices in the United States,” NREL/TP--6A20-60983, 1126842, Mar. 2014.
[27] J. Cochran *et al.*, “Flexibility in 21st Century Power Systems,” NREL/TP-6A20-61721, 1130630, May 2014.
[28] E. Lannoye, D. Flynn, and M. O’Malley, “Power system flexibility assessment #x2014; State of the art,” in *2012 IEEE Power and Energy Society General Meeting*, 2012, pp. 1–6.
[29] North American Elctric Reliability Corportaion, “Flexibility Requirements and Potencial Metrics for Vaariable Generation: Implications for System Planning Studies.” .
[30] DGEG, “Relatório de Monitorização da Segurançade Abastecimento do Sistema Elétrico 2017.”
[31] EDP, “Energy Outlook 2017.”
[32] CENSE and FCTUNL, “The Role of Electricity in The Decarbonization of The Portuguese Economy.”
[33] Center for Environmental and Sustainability Research and Estudos e Projectos em Ambiente e Economia S.A., “RNBC 2050: Roteiro Nacional de Baixo Carbono Modelação de gases com efeito de estufa: ENERGIA E RESÍDUOS.” .
[34] P. Denholm, R. Margolis, and J. Milford, “Production Cost Modeling for High Levels of Photovoltaics Penetration,” NREL/TP-581-42305, 924642, Feb. 2008.