Impact of carbon neutrality roadmap in Power systems (Portuguese scenario)

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Resumo

Portugal apresentou recentemente o seu roteiro para a neutralidade carbónica em 2050. Este plano ambicioso, obriga a que sejam tomadas medidas urgentes e impactantes em todos os sectores da economia Portuguesa. Nesta tese são estudados os impactos que estas medidas têm na rede eléctrica Portuguesa nas décadas de 2030, 2040 e 2050. É também feito um estudo e analise critica sobre as decisões e medidas apresentadas e a sua respectiva viabilidade.

Para analisar a rede eléctrica nacional recorremos à ferramenta DPlan que permite a criação de modelos experimentais da rede eléctrica. De forma a obter dados fidedignos, foram utilizados os dados fornecidos publicamente pela REN, de todos elementos que constituem a rede. Após a validação do modelo, procedeu-se à integração no modelo da produção renovável proposta pelo roteiro para as próximas três décadas. De seguida foram criados vários cenários de consumo e produção de acordo com os valores estipulados pelo roteiro. Estes cenários permitem simular a rede de acordo com a disponibilidade dos recursos renováveis, assim como impacto causado pela sua distribuição geográfica.

Sobre o modelo foi realizada a analise de tensões e correntes, assim como uma análise das contingências da linha em n-1. Com os resultados desta dissertação, espera-se poder ajudar à tomada de decisão e ao planeamento da rede eléctrica para as próximas décadas, de forma a se conseguir integrar os objectivos e metas do roteiro para a neutralidade carbónica o melhor possível, de uma forma económica e que sirva para o desenvolvimento nacional.

Tendo em consideração os valores obtidos para os cenários propostos pelo roteiro, foi possível identificar os pontos fracos da linha, onde ocorreram as falhas, e os valores de carga de rotura.

Palavras-Chave: Neutralidade Carbónica, Transição Energética, Portugal 2050, Sistemas Elétricos, Energias Renováveis, Sustentabilidade

Abstract

The work presented in this dissertation, was realized with the objective of analyze and test the impacts that the roadmap for carbon neutrality (Portuguese case) will have on the Portuguese electrical grid. In order to achieve this objective a computational model of the Portuguese grid was created, this model started by being validated with a comparison between historical data, obtained from the grid operator, with the data obtained from the simulated grid. After obtaining similar results a series of scenarios of consumption load and production, were created. These scenarios with the output of the various sources of electricity varying with the availability of the inherent resource, were created for the decades of 2030, 2040, 2050. The results obtained can be crucial for planning the next interventions on the grid, concluding that the grid is prepared for the 2030 decade, but work is needed in 2040 and 2050 to deal with the expected ramp up of consumption due to the decarbonization goal, where fossil fuels will be replaced, resulting in an increased need for a higher electrified world.

Keywords: Carbon-neutrality, Energy Transition, Portugal 2050, Power Systems, Renewable energy, Sustainability

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List of Abbreviations

CH_4 – Methane

CO_2 – Carbon Dioxide

EC – European Commission

EN-H2 – Estratégia nacional para o Hidrogénio

ERSE – Entidade reguladora de serviços energéticos

ETS – European Emissions Trading Scheme

EU – European Union

G2G – gas to gas

GHG – greenhouse gas

GHI – Global Horizontal Irradiation

HFCs – Hydrofluorocarbons

IPCC – Intergovernmental Panel on Climate Change

L2G – liquid to gaseous

L2L – liquid-to-liquid

LNEG – Laboratório Nacional de Energia e Geologia

N_2O – Nitrous Oxide

OWF – offshore wind farms

P2FUEL – Power to Synfuel

P2G – Power to gas

P2I – Power to Industry

P2M – Power to Mobility

P2P – Power to Power(P2P):

ppm – parts per million

pu – Per Unit

PV – Photovoltaic

RNC2050 – Roadmap for Carbon-Neutrality 2050

RNT – Rede Nacional de Transmissão

RNTGN – Rede Nacional de Transmissão de Gás Natural

RQS – Regulamento da Qualidade de Serviço dos setores elétrico e do gás

SEN – Sistema Eléctrico Nacional

SMR – Small Modular Reactors

UN – United Nations

UNFCCC – United Nations Framework Convention on Climate Change

WI – Wobbe Index

Chapter 1

Introduction

The evolution and development of the human being is intimately related to the climate around it. If, in certain periods of history, the climate conditions favored the development of societies, in other periods less favorable led to the escalation of conflicts and even the downfall of civilizations [1][2]. It is in this sense that a growing concern with recent climate change, albeit minor, but with the probability of an aggravation with dramatic implications for the Planet and human societies during the 21st century. The last decades of the 20th century and the first years of the 21st century have revealed abnormally hot. From the beginning of the temperature records, approximately 150 years ago, when temperatures were never observed at such high global averages.

Human emissions are responsible of the atmospheric CO_2 concentration increases, which causes a change in Earth's energy balance [3].Since the industrial era, CO_2 concentration has increased by 40%, CH_4 by 150% and N_2O by 20%, while global average temperature has increased by 0.9°C (estimates range from 0.7 to 1.1) [3]. The result of such change in atmospheric composition increased the radiative forcing to 2.29 W/m2 relative to 1750 of which CO_2 emissions contribute 1.68 W/m^2[3]. This amount explains why international efforts focuses on tackling down CO_2 emissions.

The Paris Agreement, which is one of the most recent and ambitious international policy efforts aims to "*hold the increase of the global average temperature to below 2°C*" [4]. This threshold avoids dangerous climate impacts, governments accepted it and are working to mitigate human emissions. The agreement includes a mechanism to promote Determined National Contributions, which are a better tool than the Kyoto mechanisms. In the meantime, clean renewable technologies are developing. But are all those efforts enough to stay within the well-below 2°C goal?

The EU has embraced the target to make Europe a climate-neutral continent by 2050, and the European Commission proposed an EU Climate Law that would make this a legally binding objective [5]. From this directive the Portuguese roadmap for carbon neutrality 2050 was born[6].

Achieving a carbon neutral society is not an easy task, and it will be one of the biggest challenges the country and the entire world will face on our lifetime. In little over 30years the world will have to transform the way it produces, transforms and consumes its energy.

1.1 Motivation

Ever since I started high school, I've had a passion about science and physics, that only grew when I joined Instituto Superior Técnico. I noticed I started to enjoy even more electrical circuits and power production, and now finishing this journey, I had the opportunity to work on this theme which I find very important and interesting to address some of the biggest challenges the world is facing with the climate change and the transition to a carbon neutral economy.

Following the Paris accord on 22thApril 2016, the EU leaders reached an agreement that the final energy consumption in the EU should be produced from carbon-neutral sources with a 15% offset limit and excluding aviation and shipping. Renewables will play a key role in helping the EU meet its energy needs beyond 2020. EU countries have already agreed on a new renewable energy target of at least 27% of final energy consumption in the EU as a whole by 2030 as part of the EU's energy and climate goals for 2030 [6].

The purpose of these accords is to promote renewable energy and reduce dependency on fossil fuels. With these objectives defined on at a European level, Portugal, taking 2005 as a reference has decided to reduce its emissions on 96% by 2050.

Although intermittency is not currently a major problem as renewable energy sources account for a small share of total energy production, in the future an increase in the penetration of large renewable power plants into a local grid is likely to introduce new technical problems, such as voltage fluctuations, degradation of electrical power quality, stability problems and a faster management of the reserves to assure an equilibrium between production and consumption. Thus, for successful integration of renewable energy into the grid, it is essential to develop effective measures to overcome these technical challenges and control variability with different levels of renewable penetration.

But the biggest issue aimed to investigate on this dissertation will be the study and evaluation of the impacts that the planed measures to achieve a carbon-neutrality of the electrical system will have on the existing grid. As it will be seen, and analyzed in more detail through this document, the roadmap plans to decarbonize by removing fossil fuels from the economy and society, replacing them for a fully electrical and renewable society, this will obviously put a great strain on the already existing grid that was not originally planned for this objective. With this premise set, this thesis aims to evaluate the impact of this transition on the Portuguese electrical grid. It mainly aims to discover if the current grid is enough to satisfy the needs of a more electrified society, what changes need to be made? Where are the faults are going to occur?

1.2 Contributions

On this thesis the main goal of this thesis is to contribute for the analysis and comparison of the various climate change roadmaps being carried out by the member states of the European Union, these roadmaps have the common goal of making Europe the first carbon-neutral continent.

The two main contributions are the critical analysis of the Portuguese roadmap, it’s viability and feasibility, and the results obtained through simulating the Portuguese electrical grid with the proposed modifications on the roadmap.

1.3 Organization of the Document

This document aims to address the issue of climate change, the measures taken by the European Union and its member states, namely Portugal and what impacts they will have on the Portuguese electrical system.

On chapter 1 the document starts with a brief introduction about climate change, it's causes and effects on the planet and life on earth, following with what the global leaders have agreed to do during the Paris Accords, in order to reduce its impacts, on the lives of every living being.

In chapter 2 expands on the previous topics and includes the enrollment of the European union, Portugal and the proposed actions to battle climate change.

Chapter 3, after knowing the measures and objectives to be taken, proceeds with an analysis of the current Portuguese electrical grid, and the path its planned evolution will take. The main focus will be the various renewable energy power sources, and to make a critical analysis of the plan for each.

To finalize in chapter 4 and 5 explains how the simulation took place, from the creation of the model of the grid to its various scenarios. Afterwards presents the obtained results and analyzes and explain what they mean, and what impacts they will cause to the electrical grid.

Chapter 2

Energy Transition Context

2.1 Global warming

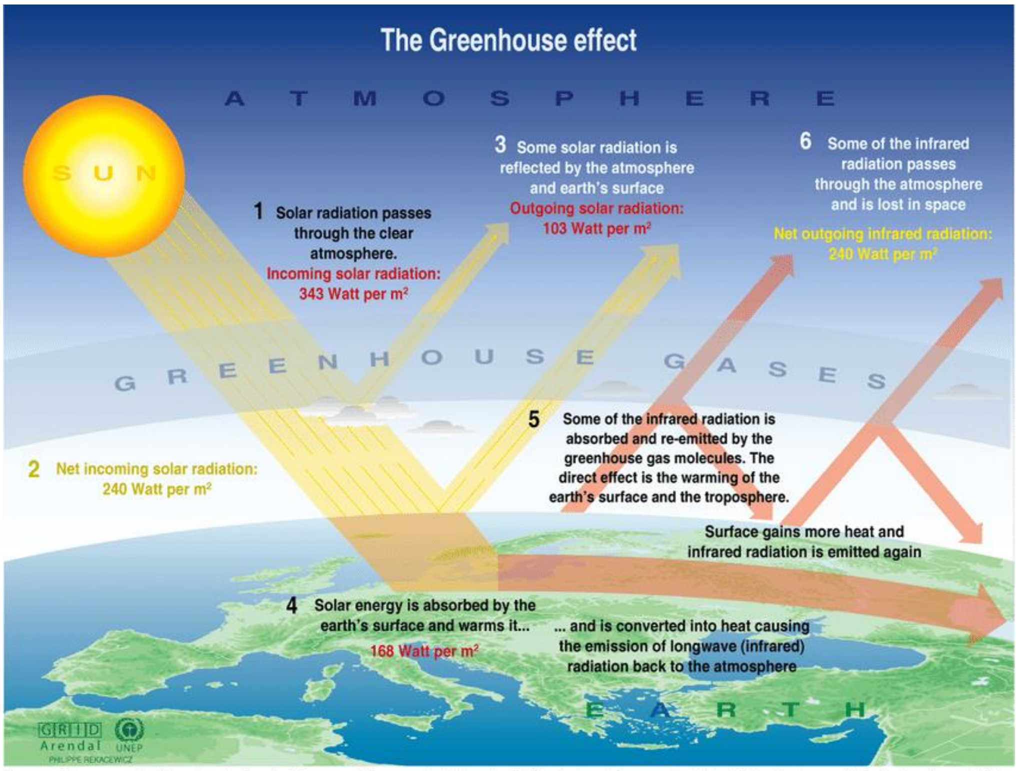
To the Intergovernmental Panel on Climate Change (or Intergovernmental Panel for Climate Change – IPCC), a scientific body created to investigate and assess climate change in order to provide clear knowledge on the matter and scientific support for the creation of policy measures, it is "unequivocal" that the global climate system is warming due to the observation of the increase in the global average temperature of the atmosphere and the oceans, the melting of the glaciers, the polar ice sheets and the subsequent global average increase in the level of the oceans of 24 cm since 1880 of which 9.13 cm were from 1993 to 2020 [7].

For the IPCC, climate change refers to “a change in the state of the climate that can be identified (eg using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer [8].

The temperature on the Planet results in a balance between the energy that enters the atmosphere system – Earth and that that leaves. The variation of the climate system occurs when there is an imbalance due to external forces, natural, anthropogenic or the result of a change in the internal dynamics of the climate. The two main natural external factors are volcanic eruptions and variations in solar radiation, the latter being essential to provide the energy that the climate system needs. “There are three fundamental ways to change the radiation balance of the Earth: 1) by changing the incoming solar radiation (e.g., by changes in Earth's orbit or in the Sun itself); 2) by changing the fraction of solar radiation that is reflected (called ‘albedo’; e.g., by changes in cloud cover, atmospheric particles or vegetation); and 3) by altering the longwave radiation from Earth back towards space (e.g., by changing greenhouse gas concentrations)” [9].

On the other hand, this variation may be caused by anthropogenic factors, namely greenhouse gas emissions, which, according to scientists, has been at the base of the recent global warming. Gases released from activities such as industry, transport and agriculture, among others, as well as changes in land use due to deforestation, irrigation or production of crops that alter the surface albedo and induce changes in the climate system [3].

Carbon dioxide, methane and water vapor exist naturally in the atmosphere, absorbing radiation from the Sun and especially that reflected by the Earth's surface as observed in Fig1. Being good absorbers of radiation, they heat the atmosphere like a greenhouse - hence the name "greenhouse effect" - approximately 33°C warmer than if these gases and clouds did not exist, keeping the Planet at a stable temperature and creating the possibility of existence of life on Earth. The growing increase in greenhouse gas (GHG) emissions such as carbon dioxide, methane, but also nitrous oxide, among others, has increased the atmosphere's capacity to absorb radiation, amplifying the existing natural greenhouse effect (enhanced greenhouse effect) and, consequently, increasing global temperatures. In fact, according to the IPCC *“Most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic GHG concentrations.”* [3].



Sources: Okanagan university college in Canada, Department of geography, University of Oxford, school of geography; United States Environmental Protection Agency (EPA), Washington; Climate change 1995, The science of climate change, contribution of working group 1 to the second assessment report of the intergovernmental panel on climate change, UNEP and WMO, Cambridge university press, 1996.

Fig. 1 – Greenhouse effect diagram [10].

Carbon dioxide is by far the most important gas emitted due to human activities, having contributed about 77% to the anthropogenic greenhouse effect [8]. Since the Industrial Revolution, human beings have been destabilizing this natural mechanism, increasing CO_2 emissions mainly due to the burning of fossil fuels

For thousands of years until the mid-eighteenth century, at the beginning of the Industrial Revolution, the natural variations of carbon dioxide in the atmosphere were within a range of 20 ppm (parts per million) from an average value of 280 ppm [11]. Since this period, values have been increasing gradually, with this increase being more accentuated from the second half of the 20th century onwards. At present the values are situated at 417 ppm (2021) as per Fig 2.

Fig. 2 – Global atmospheric CO_2 concentrations from 1700 to 2021 [12].

2.2 Paris Agreement

The Paris Agreement often referred to as the Paris Accords or the Paris Climate Accords, is an international treaty on climate change, adopted in 2015. It covers climate change mitigation, adaptation, and finance. The Agreement was negotiated by 196 parties at the 2015 United Nations Climate Change Conference near Paris, France.

The Paris Agreement was open for signature by states and regional economic integration organizations that are parties to the UNFCCC (the Convention) from 22 April 2016 to 21 April 2017 at the UN Headquarters in New York [13]. Signing of the Agreement is the first step towards ratification, but it is possible to accede to the Agreement without signing [14]. It binds parties to not act in contravention of the goal of the treaty [15]. On 1 April 2016, the United States and China, which represent almost 40% of global emissions confirmed they would sign the Paris Climate Agreement [6]. The Agreement was signed by 175 parties (174 states and the European Union) on the first day it was opened for signature [16]. As of March 2021, 194 states and the European Union have signed the Agreement [3].

The Paris Agreement's long-term temperature goal is to keep the rise in mean global temperature to well below 2 °C above pre-industrial levels, and preferably limit the increase to 1.5 °C, recognizing that this would substantially reduce the impacts of climate change. Emissions should be reduced as soon as possible and reach net-zero by the middle of the 21st century [17].

It aims to increase the ability of parties to adapt to climate change impacts, and mobilize sufficient finance. Under the Agreement, each country must determine, plan, and regularly report on its contributions. No mechanism forces a country to set specific emissions targets, but each target should go beyond previous targets.

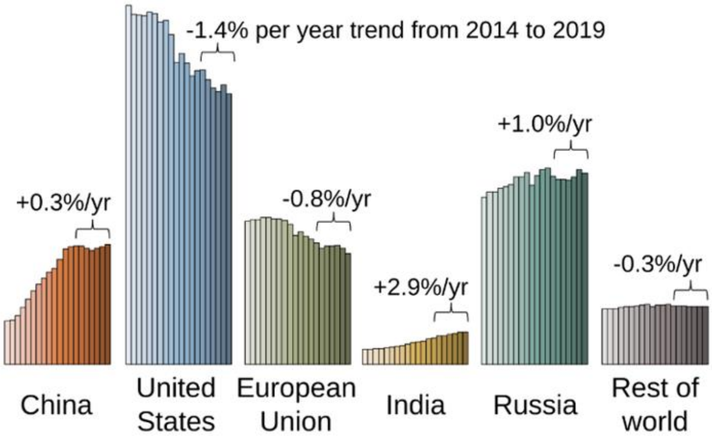


Fig. 3 – Per capita fossil CO_2 emissions from 2000 – 2019 [18].

The Agreement would become fully effective if 55 countries that produce at least 55% of the world's greenhouse gas emissions (according to a list produced in 2015) ratify or otherwise join the treaty [4]. After ratification by the European Union, the Agreement obtained enough parties to enter into effect on 4 November 2016 [5].

The aim of the agreement, as described in Article 2, is to have a stronger response to the danger of climate change; it seeks to enhance the implementation of the United Nations Framework Convention on Climate Change through: [5]

a) Holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change;
b) Increasing the ability to adapt to the adverse impacts of climate change and foster climate resilience and low greenhouse gas emissions development, in a manner that does not threaten food production;
c) Making finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development.

Following the Paris accord, on December 2019, the European green deal was presented. The European Green Deal is a set of policy initiatives by the European Commission with the objective of making Europe climate neutral in 2050 [5]. An impact plan will also be presented to increase the EU's GHG emission reductions target for 2030 in between 50% to 55% compared with 1990 levels.

The plan is to review each existing laws on its climate merits, and also introduce new legislation on the circular economy, building renovation, biodiversity, farming and innovation [3].

The European Commission's climate change strategy, launched in 2020, is focused on a promise to make Europe a net-zero emitter of greenhouse gases by 2050 and to demonstrate that economies will develop without increasing resource usage. However, the Green Deal has measures to ensure that nations that are already reliant on fossil fuels are not left behind in the transition to renewable energy.

2.3 European Enrollment in Environment and Climate Actions

To respond to the climate crisis and to help protect Europe's unique ecosystems and biodiversity, the EU has launched several ambitious policies. One of these is the European Green Deal which aims to move to a clean, circular economy while restoring biodiversity and cutting pollution. The European Commission defined three basic objectives to encourage action by Member States, to fulfill these objectives and provide funding to the member states, the LIFE program [19] was created, those objectives are:

- Contribute to the shift towards a clean, circular, energy-efficient, low-carbon and climate-resilient economy, including through the transition to clean energy.
- Protect and improve the quality of the environment.
- Halt and reverse biodiversity loss, thereby contributing to sustainable development.

LIFE will also expand into four new sub-programmes: nature and biodiversity, circular economy and quality of life, climate change mitigation and adaptation, and clean energy transition. It will ease the transition towards an energy-efficient, renewable energy-based, climate-neutral and resilient economy. And it aims to remove the market barriers that can hamper the socio-economic transition to sustainable energy.

It is intended to indicate the direction in which EU climate and energy policy should go and to serve as a framework for what the EU sees as its long-term contribution to achieving the temperature targets of the Paris Agreement, in line with the United Nations Sustainable Development Goals, which will affect a broader set of Union policies. This Strategy raises the need to plan in an integrated way, in the long term, the reduction of emissions and adaptation. It should also be noted that the European Commission, through its Sustainable Finance Action Plan and its regulatory development, works to convert the finances of the European Union into a key tool for the fulfillment of the 2030 Agenda and its Sustainable Development Goals, as well as the Paris Agreement, so that they are not a marginal issue unrelated to the rules of operation of the markets, but rather be a key element of decisions. Among the measures already in place in this area, the development of a common language for the identification of sustainable economic activities stands out, that is, a unified classification system (or taxonomy) included in a Community Regulation, which will help investors and companies to make investment decisions that contribute to the achievement of six environmental objectives, including adaptation to climate change. In the context of adaptation, the taxonomy has identified 68 adaptation activities to climate change to guide investors on what falls within the definition of “sustainable”, distinguishing between two types of adaptation activities: those that increase the Climate resilience by integrating measures to perform well in a changing climate and activities that allow adaptation of other economic activities.

2.4 Portuguese Enrollment in Environment and Climate Actions

In 2016, the Portuguese government pledged to ensure the neutrality of its emissions by the end of 2050, outlining by 2050 means achieving a neutral balance between GHG emissions and carbon sequestration, for which substantial reductions in emissions and/or substantial increases in national carbon sinks will be required.

All sectors must contribute to reducing emissions, increasing efficiency and innovation, promoting improvements, notably in buildings, agriculture, waste management and industry, with the energy system making the greatest contribution, particularly as regards electricity generation and transport.

Portugal is a country with a proven record of climate policy, having met the goals defined in the Kyoto Protocol. The first step towards achieving the 2030 European Climate and Energy Package at a national level was taken in 2015 with approval of the Strategic Framework for Climate Policy (QEPiC), established that Portugal taking 2005 values as reference, should reduce its GHG emissions from -18% to -23% by 2020 and from -30% to -40% by 2030 [6]. Both of these goals were achieved in 2020 when a reduction from 64.6 Mt CO_2 (2005) to 41.3 Mt CO_2 (2020) [20] was obtained, which translates to a total decrease of -23.3 Mt CO_2 or -36.06%, these figures are already in the range of the 2030 objective.

In the roadmap for carbon-neutrality (RNC2050), it was stated that it is possible to achieve a national emissions reduction of between -50% and -60%, compared to 1990, which corresponds to a reduction of -60% to -70% in the energy sector compared to 1990.

The realisation of this strategic vision rests on eight key premises, described in more detail in the following sections:

- iPromote the transition to a competitive, circular, resilient and carbon-neutral economy, generating more wealth, employment and well-being;
- Identify decarbonization vectors and lines of action that underlie the route to carbon neutrality by 2050;
- Contribute to resilience and the national capacity to adapt to climate change vulnerabilities and impacts;
- Stimulate research, innovation and knowledge production in key areas to achieve the goal of carbon neutrality;
- Guarantee financing conditions and increase investment levels;

- Ensure a fair and cohesive transition that contributes to valorization of the country;
- Ensure effective conditions for monitoring progress towards the goal of carbon neutrality (governance) and ensure the adoption of carbon neutral objectives in the sectoral areas;
- Involve society in the challenges of climate change, focusing on education, information and awareness raising, contributing to increasing individual and collective action.

The goal of decarbonization must also be addressed in the context of adaptation to climate change. The more marked these changes, the greater the costs that the country will have to bear with the disruption of agriculture, with fires, with degradation of the coastline, with the health and safety of people, particularly during heatwaves and other extreme climate events.

Chapter 3

Trajectories For Carbon Neutrality By 2050

3.1 Carbon Neutrality trajectories in Europe

To fulfill the EU strategy for the carbon neutrality, each state had the liberty to study what would be the best solution for them to meet the targets set by the EU. They would then present their respective climate plans, with measures or objectives to implement to achieve the common goal of a carbon neutral society.

European energy policy has developed strongly, in particular, several European documents have set targets for:

- limiting greenhouse gas emissions;
- increasing energy efficiency;
- increasing the energy generated from renewable sources.

The climate energy package, adopted under the French EU presidency in 2008, set the "3x20" targets for 2020: [21]

- -20% GHG emissions
- 20% improvement in energy efficiency;
- 20% renewable energy in final EU energy consumption.

With these targets fulfilled as renewable sources generated 38% of Europe’s electricity [22], and the EU greenhouse gas emissions reduced by 24% between 1990 and 2019 [23], new objectives were needed. The European Union adopted new targets for 2030 in December 2018. The new objectives were to target a reduction of the EU's greenhouse gas emissions by at least 40% in 2030 compared to 2005, with the Renewable Energy Directive setting targets and the framework for the coming decade [24].

The objective of reducing GHG emissions will be achieved through the revision of the European Emissions Trading Scheme (ETS) and the distribution of effort among Member States for non-quota sectors where the objective is to reach at least 32% renewable energy in energy consumption, binding objective at the European level. The directive also provides for a target of 14% renewable energy in transport, with a ceiling for first generation biofuels, as well as new provisions for renewables and recovered energy for heating and cooling. The text revises the existing directive on energy efficiency to adapt it to the post-2020 period. A new governance regulation now requires each Member States to publish a ten-year integrated national energy-climate plan, which will match the Multi-Annual Energy Plan and the Low-Carbon National

Strategy. In addition to the public consultation, Member States shall consult neighboring countries and the European Commission.

It’s in this context that each country in the EU made its own individual strategic climate plan, which translates into over 25 different roadmaps, this dissertation will only cover Spain [25], France [26] and the Netherlands [27] due to the proximity and strategical interests, despite all of them being quite similar as they follow the same guidelines. The first conclusion that can be made from all of the different roadmaps, is that only Portugal has fully defined it’s path until 2050, all the other members so far only plan, and provide values up until 2030, some earlier like France, that finishes its route in 2028 [28], for 2050 they very vaguely state the goals.

Nowadays the rapid cost decline of renewable energy, technological developments and the urgency to drastically reduce greenhouse emissions, are opening up new possibilities. This creates an expectation on renewable electricity to decarbonize a large share of the EU energy consumption by 2050, but not all of it. Due to the intermittency nature of renewable sources and the necessity for renewable energy storage on a European level, a technology that can help bridge this gap is the was required. This leads to a common strategy regarding the creation of a renewable hydrogen ecosystem, the European Commission, through the European clean hydrogen alliance plans to develop an investment agenda to stimulate the roll out of production and use of hydrogen and build a concrete pipeline of projects. This strategy is contemplated in three phases of renewable hydrogen development. The first phase, (2020-2024), is planned to have at least 6 GW of electrolyzers installed in the EU, plus up to one million tons of renewable hydrogen produced, the second phase comprises the installation of at least 40 GW of electrolyzers and the production of up to 10 million tons of renewable hydrogen between 2025 and 2030; in the third phase, between 2030 and 2050, it is intended that renewable hydrogen will reach maturity and the various technologies will be implemented on a large scale to reach all sectors where decarbonization via hydrogen is a viable alternative where other technologies are not viable or have higher costs [29].

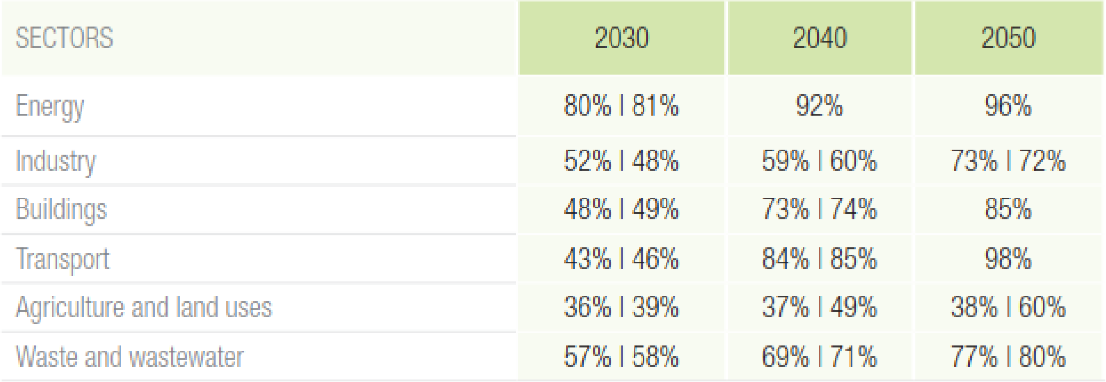
On this field, can be observed that all the selected countries follow a very similar strategy, with Spain, France and the Netherlands installing 4 GW, 5.3 GW and 4 GW respectively.

In regard to other energy sources, each country tries to maximize its renewable production in proportion to the availability of the resource. At the same time that these countries ramp up the renewable electricity production, they also keep a common goal of slowly phasing out from nuclear energy. By 2035 France aims to produce 50% [30] of its total electricity needs from nuclear power, a decrease of ~20% when compared to 2020, while this seems a phase out from nuclear, it is needed to take into consideration that the electricity needs will increase drastically over the next 30 years. Spain projects to a nuclear phaseout without providing any goals at the moment, The Netherlands at this stage wants to maintain it’s only Nuclear powerplant, with plans for a potential investment in Small Modular Reactors (SMR) after 2040.

3.2 Carbon Neutrality trajectories in Portugal

To obtain a carbon-neutral society we need to equalize the level of GHG emissions with the carbon sink level by the year 2050 (net emissions equal to zero). Taking 2005 as a reference, Portugal's emissions that year were 64.6 Mt CO2 [20]. When broken down by sector, national emissions are distributed by: 25% in energy production, 25% in transport, 23% in industry, 10% in agriculture, 8% in other energy uses; and 8% in waste.

Table 1 – Potential emissions reduction in relation to 2005 [6]



SECTORS	2030	2040	2050
Energy	80% I 81%	92%	96%
Industry	52% I 48%	59% I 60%	73% I 72%
Buildings	48% I 49%	73% I 74%	85%
Transport	43% I 46%	84% I 85%	98%
Agriculture and land uses	36% I 39%	37% I 49%	38% I 60%
Waste and wastewater	57% I 58%	69% I 71%	77% I 80%

By 2050, based on a trajectory of emissions reductions of -45% to -55% by 2030, -65% to -75% by 2040 and -85% to -90% by 2050, compared to 2005, assuming a carbon sink can be obtained, with a value between -9 and -13 Mt CO2, currently Portuguese forests, give us an average carbon sink value of -8.5 Mt CO2 (from -13 to +7 Mt CO2) [6], making it possible to be a carbon-neutral society.

Energy production and consumption will therefore become based on endogenous and renewable sources of energy, which will contribute to the biggest transformation of the energy paradigm in Portugal since the industrial revolution.

On the electricity sector a profound transformation will occur (96% reduction in GHG emissions compared to 2005) and will require significant investments in a lot of new renewable capacity, in particular wind and photovoltaic energy, and also while a big reduction or abandonment of electricity produced from fossil fuels such as coal and natural gas.

For the transport sector, the transformation needs to be revolutionary, the reduction in GHG will be almost total (98% reduction in GHG emissions compared to 2005) and will be based fundamentally on strengthening the role of the public transport system and replacing current fossil fuel vehicles with a mainly electric fleet. This revolution starts by replacing the current fossil fuel with use of hydrogen and advanced biofuels and finishes with the conversion of mobility in private vehicles into other forms of mobility (public, active, shared, autonomous) by doing thar, it will significantly increase the volume of passengers or goods transported, without the need to increase fleets, particularly that of private cars.

Both residential and service buildings will also make a significant contribution to decarbonization (reductions of over 85% compared to 2005), due to an almost total electrification of energy consumption, further supported by large energy efficiency gains through reinforcing the insulation of buildings, the use of solar heating and heat pumps.

In industry the reductions of the emissions will be less significant but still quite large. Reductions of around 80%, The use of fluorinated gases will be reduced by 54% by 2050, compared to the emissions values observed in 2005. This is due to the reduction imposed by the implementation of the Kigali Agreement and the European Regulations, which restrict the production, consumption and market availability of Hydrofluorocarbons (HFCs).

Emissions from agriculture, particularly those from animal production, have a lower reduction potential, and this sector will reduce its emissions by 9% to 30% by 2050. Possible options include improvements in animal feed and manure management systems, and reduced fertilization and water needs boosted by biological and precision agriculture, respectively. Agricultural land and pastures have the potential to cease being a source of emissions and become sources of sequestration, through conservation agriculture, by replacing mineral fertilizers with organic fertilizers and sowing improved and biodiverse pastures.

Forests, can significantly increase current sequestration levels (8.5 Mt CO_2) to around 11-13 Mt CO_2, and for this to happen, it is essential to control areas set on fire annually and to achieve productivity increases across forestry species in general.

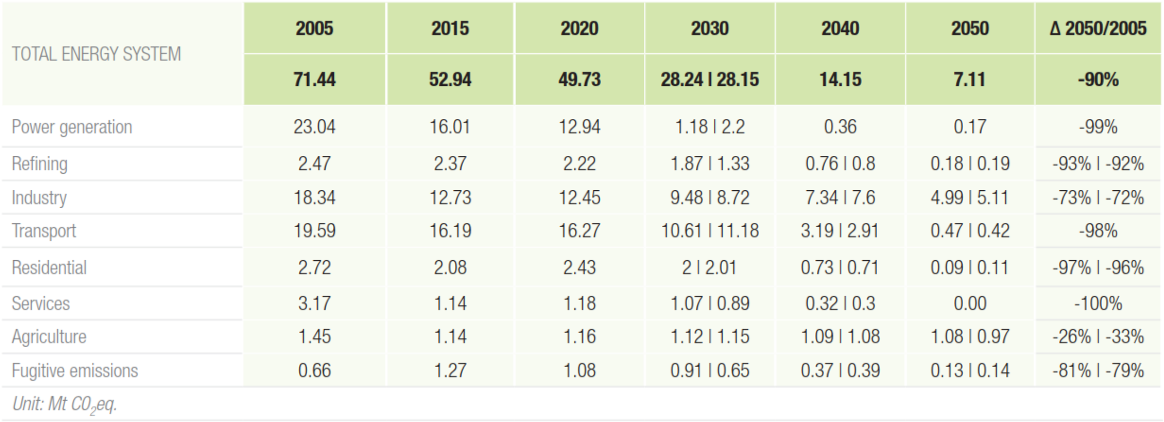
For waste and wastewater, reductions will be more significant (around 75% compared to 2005) due to a sharp increase in the circularity of the economy, the elimination of organic waste in landfills and the reduction of total and organic waste produced per capita.

3.3 Power systems evolution in Portugal

The energy system is made of all the manners of energy production, transport, distribution and final energy consumption in the various sectors (industry, transport, residential and services and agriculture).

By identifying which of the current technologies have the most potential to be developed and evolve into cost-effective options to achieve the neutrality objectives of reductions in the emission of GHG a series of plans can set up to maximize their evolution. By doing so it minimizes the cost to the national energy system, through progressive substitution.

Table 2 – Evolution of energy system emissions [6]



TOTAL ENERGY SYSTEM	2005	2015	2020	2030	2040	2050	Δ 2050/2005
	71.44	**52.94**	**49.73**	**28.24 I 28.15**	**14.15**	**7.11**	**-90%**
Power generation	23.04	16.01	12.94	1.18 I 2.2	0.36	0.17	-99%
Refining	2.47	2.37	2.22	1.87 I 1.33	0.76 I 0.8	0.18 I 0.19	-93% I -92%
Industry	18.34	12.73	12.45	9.48 I 8.72	7.34 I 7.6	4.99 I 5.11	-73% I -72%
Transport	19.59	16.19	16.27	10.61 I 11.18	3.19 I 2.91	0.47 I 0.42	-98%
Residential	2.72	2.08	2.43	2 I 2.01	0.73 I 0.71	0.09 I 0.11	-97% I -96%
Services	3.17	1.14	1.18	1.07 I 0.89	0.32 I 0.3	0.00	-100%
Agriculture	1.45	1.14	1.16	1.12 I 1.15	1.09 I 1.08	1.08 I 0.97	-26% I -33%
Fugitive emissions	0.66	1.27	1.08	0.91 I 0.65	0.37 I 0.39	0.13 I 0.14	-81% I -79%

Unit: Mt CO_2eq.

In fact, the path towards carbon neutrality will lead to a much wider use of endogenous renewable energy resources of which over two thirds will be sun and wind, accounting for over 80% of primary energy consumption by 2050. The national energy system thus moves from an essentially fossil base to an essentially renewable base by 2050 [6], with positive consequences for the energy bill, the trade balance and the reduction of energy dependency, which drops from the current 78% of dependence on foreign countries to less than 20% in 2050.

What can be concluded is that the transformation of the energy system is what will lead us to be a carbon neutral society, as it was seen, by almost fully electrifying our means of transportation, our houses, our industry, the services and agriculture. Portugal will either remove or steeply reduce the production of energy, in all these sectors, from fossil fuels and replace them with clean and renewable energy, to then eliminate the emissions of GHG and reduce their impact on the planet and our health.

Currently one of the leading national GHG emitters (around 29%) the power generation sector will be one of the major contributors to decarbonization. Furthermore, as seen preciously, given the expected role of electrification in the decarbonization process of the remaining sectors, emissions from power generation will also have a very significant indirect contribution to make to decarbonization of the economy,

From the Fig. 4 bellow, we can observe that the higher the penetration of the renewable electrical power production technologies is, the lower the GHG emissions from the power generation sector will be, this is a direct cause, due to the nature of these power production methods, that use renewable natural resources without the need to burn fuels that produce GHG.

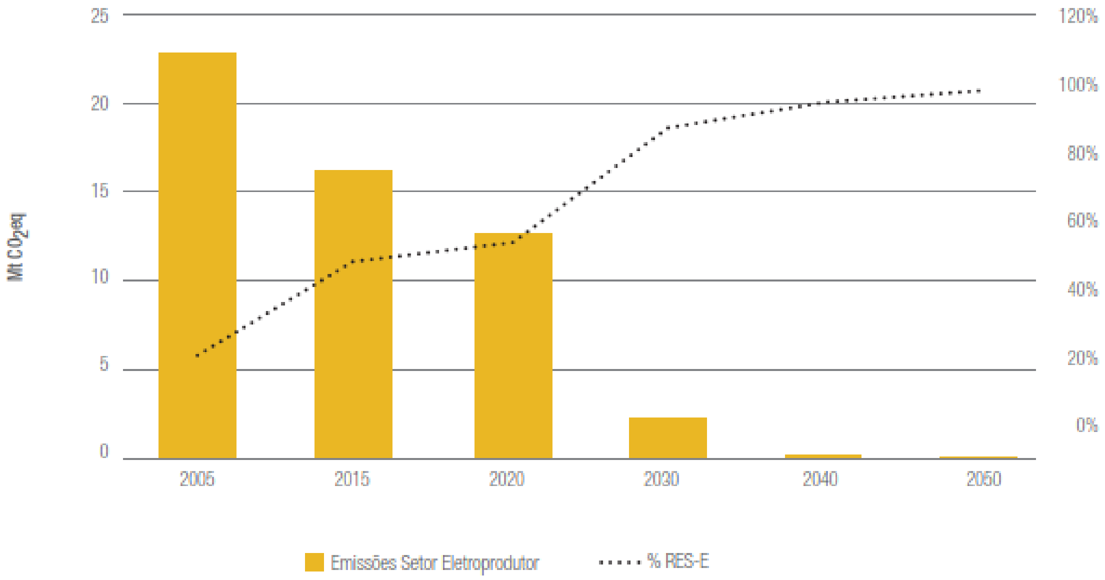


Fig. 4– Evolution of emissions from the power generation sector vs % incorporation of renewables [6].

The transition is facilitated by the cost reduction of renewable-based technologies for electricity generation that has been observed in recent years, this trend is expected to continue in the foreseeable future, especially in technologies associated with solar photovoltaics and wind (costs expected to halve when compared to 2019) [31] and [32]. In fact, it is this cost reduction, coupled also with an expected rapid fall in the cost of storage solutions such as batteries and hydrogen (costs of producing 'green' hydrogen from renewable electricity should fall by up to 85% from the present day to 2050) [33], that will allow renewable energy to have a participation close to 100% in electricity production in 2050.

Photovoltaic solar technology will be developed rapidly by increasing its importance and reaching an installed power capacity of 13 GW of both centralized and decentralized solar energy by 2050. Onshore wind energy is also increasing its share greatly more than doubling its installed capacity. These two technologies have a cost-effective potential to jointly supply 50% of the electricity generated in 2030 and 70% in 2050 [6].

Maintaining some natural gas capacity in the national power system until 2040, even if marginally used, ensures the necessary backup to bring about the transition to a renewable-based power system, allowing time for the development and installation of technological storage solutions.

In this context, batteries will become a cost-effective technology that is necessary for the stability of the system as early as 2025 (187 MW) [6]. However, it is from the 2030s onwards that the weight of this technology gains expression, reaching values between 0.6 and 1.0 GW in 2030 and growing up to 4 GW by 2050, accounting for between 7% and 8% of the total installed capacity in a 100% renewable system.

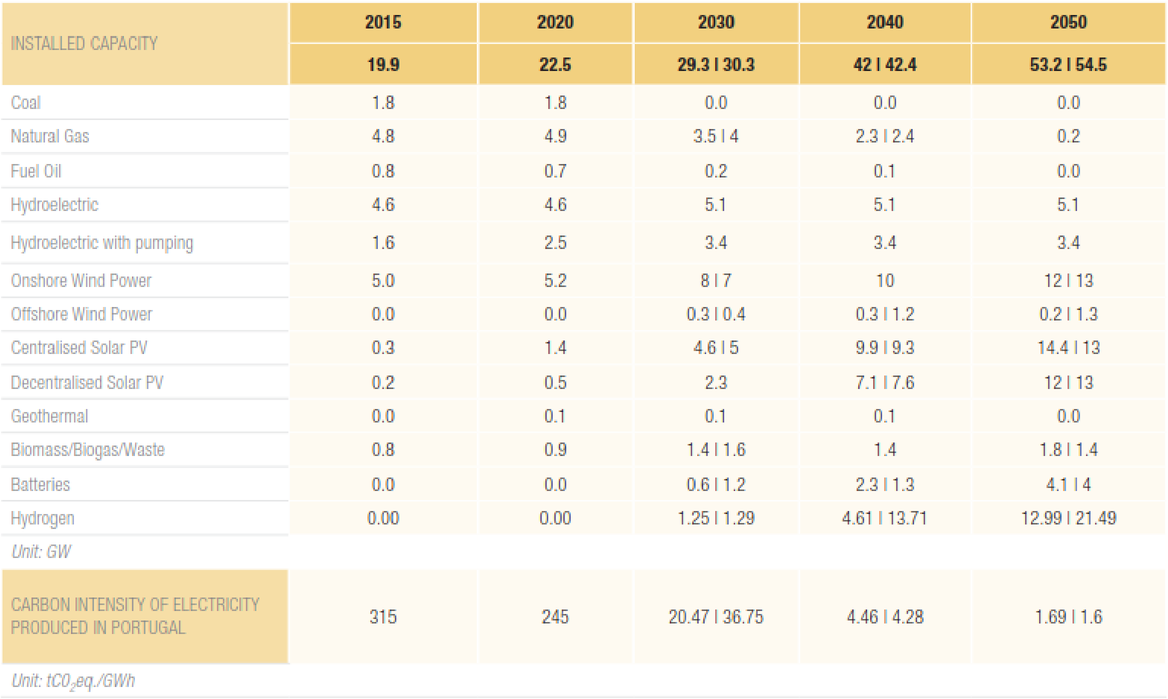
Along with batteries, mostly associated with decentralized solar energy, hydroelectric production using pumped water will also continue to play an important role in regulating the power system. The existing capacity together with the investments in progress means that in 2030 there will be 3.4 GW of pumped hydroelectric capacity an increase 600 MW from the 2.8 GW from 2020 [34]. When combined, batteries and pumped hydroelectric, in 2050, will account for 7.5 GW, about 14% of total installed capacity, offering storage and facilitating efficient management of the electric supply/demand equilibrium.

With the electrification of the economy, the requirements for the expansion of the transmission and distribution network which needs to be linked to an efficient consumption management (e.g. in industry) shall allow the creation of new business models and solutions that contribute to the flexibility of the system.

New regulatory models will allow new players to enter the electricity market, such as energy production cooperatives and energy communities [35]. For example, currently there's a pilot project called "Comunidade de Energia Renovável – Agra do Amial", in Porto. This pilot project, which covers a housing district, Agra do Amial, and a school, EB1/JI da Agra, is aimed at social housing and combating energy poverty and aims to test the technical and economic feasibility of practices and technologies innovative, providing for the self-consumption of renewable energy and the integration of storage, energy efficiency and charging solutions for electric vehicles [35].

The increase in installed capacity of decentralized solar to 2.3 GW by 2030 and 12 to 13 GW by 2050 demonstrates the cost-effectiveness of decentralization in solar electricity generation, allowing one to envisage the important role of producers/ consumers in the future. Families and other small producers may account for more than 20% of total electricity production. Of course, this vision requires the development of smart distribution networks.

Table 3 – Evolution of installed capacity of the power generation sector (including cogeneration) and the carbon intensity of electricity generation [6].



INSTALLED CAPACITY	2015	2020	2030	2040	2050
	19.9	**22.5**	**29.3 I 30.3**	**42 I 42.4**	**53.2 I 54.5**
Coal	1.8	1.8	0.0	0.0	0.0
Natural Gas	4.8	4.9	3.5 I 4	2.3 I 2.4	0.2
Fuel Oil	0.8	0.7	0.2	0.1	0.0
Hydroelectric	4.6	4.6	5.1	5.1	5.1
Hydroelectric with pumping	1.6	2.5	3.4	3.4	3.4
Onshore Wind Power	5.0	5.2	8 I 7	10	12 I 13
Offshore Wind Power	0.0	0.0	0.3 I 0.4	0.3 I 1.2	0.2 I 1.3
Centralised Solar PV	0.3	1.4	4.6 I 5	9.9 I 9.3	14.4 I 13
Decentralised Solar PV	0.2	0.5	2.3	7.1 I 7.6	12 I 13
Geothermal	0.0	0.1	0.1	0.1	0.0
Biomass/Biogas/Waste	0.8	0.9	1.4 I 1.6	1.4	1.8 I 1.4
Batteries	0.0	0.0	0.6 I 1.2	2.3 I 1.3	4.1 I 4
Hydrogen	0.00	0.00	1.25 I 1.29	4.61 I 13.71	12.99 I 21.49
Unit: GW					
CARBON INTENSITY OF ELECTRICITY PRODUCED IN PORTUGAL	315	245	20.47 I 36.75	4.46 I 4.28	1.69 I 1.6
Unit: $tCO_2eq./GWh$					

3.3.1 Hydro

The hydroelectric power, currently the heart and soul or our electrical system, as it's our only, and natural mean of power storage, that is available to compensate the intermittent nature of the renewable power generation. By starting to observe table 3 there is currently (2021) an installed capacity of 7 086 MW [34], and that it's planned to only marginally increase it, by 1500 MW until 2030 and to stagnate at this level until 2050. Currently, in 2021 Portugal has under execution various projects such as the dam in Alto Tâmega that alone will increase the installed capacity by 1766 MW [36], with this project alone, immediately can be seen that when added together it already slightly surpasses what the roadmap plans for 2050(by 200 MW), it's quite bizarre that no further installations are planned.

The situation become stranger, when analyzing the hydroelectrical potential on Fig. 5, a study [37] shows that Portugal only utilizes 46% of its total available capacity. Having Portugal such a high level of hydroelectric potential, shouldn't it be more utilized when trying to make a carbon-neutral society? Shouldn't it be used more to mitigate the intermittency of the solar and wind, since it's the most ecological, and natural means of power storage?

Fig. 5 – Hydroelectric potential harnessed at the end of the 1st decade of the XXI century [37].

Another thing that is needed to take into consideration when planning the use of water resources is its availability. With the global warming reaching the expected increase value of 1.5ºC [3] it is expected for the availability of the water to change drastically [38], with flood and droughts becoming more frequent in the entire world. To make an effective plan for the future, it is needed to consider the conditions that are expected to be faced, as knowing that flood and droughts are going to become more frequent, to mitigate these changes [39] more water reservoirs and dams are needed. Not only there will be a higher demand for electricity, but the creation of water reservoirs and dams becomes of prime importance, not only to serve as storage of power, but to assure the supply of water to the population, to the agricultural fields and the industry. It will also protect the riverside provinces from flooding, while at the same time, being a matured and well proven technology, capable to provide and store electricity by the addition of pumping capacity respectively.

3.3.2 Wind

When analyzing the roadmap plans for the wind technology, it can immediately be observed that a booming technology such as the offshore wind farms (OWF) is not having much focus or interest by the roadmap. While it’s known that Portugal is not ideal for fixed turbines, as the Atlantic Ocean is very deep [40] it’s possible to utilize floating devices that can be an important future source of electricity for Portugal. A policy in complete contrast with the majority of the European coastal countries.

As for comparison in 2020 countries like Netherlands, Denmark and Belgium, have an installed capacity of 2.6GW, 2.26GW and 1.7GW respectively [41]. This number is expected to grow in the coming years as per their respective roadmaps for carbon neutrality, while currently no values are provided for 2050, the Dutch government is planning an installed capacity of 11 GW for 2030 [42].

With the emergence of the floating wind power, and despite Portugal having a large coastline with a small potential for fixed offshore wind power(1.4 to 3.5GW) and over 40GW for the floating systems [43][44], the planed capacity is only 0.2|1.3GW for 2050, a small fraction of all it's potential, and it seems rather low and very unoptimistic for the development of the technology. Currently the Windfloat Atlantic project, a cooperation between EDP Renováveis and Engie proving to be a reliable and resilient technology with 4000h of power availability, capable of surviving storms of 140km/h and 14m waves [45] a complete contrast with the plans for green hydrogen, as so far no large scale production, power production and vehicle usage is proven to work for long periods of time. This technology also provides environmental opportunities with offshore wind implementation as it generates sanctuaries for marine life, since fishery is prohibited around OWF [40].

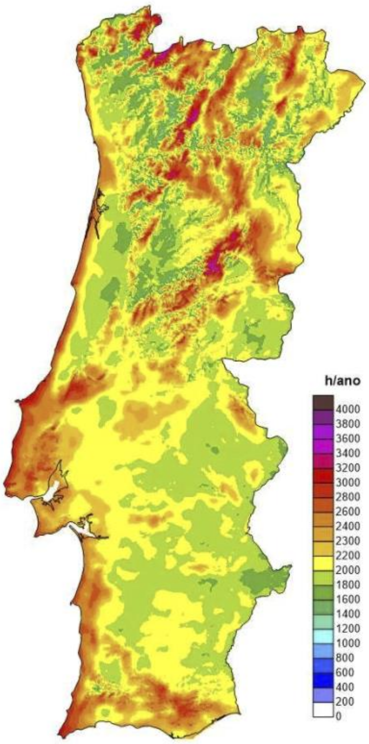


Fig. 6 – Onshore Number of equivalent hours of operation at rated power (h/year) [44].

When making the same analysis for the onshore wind power, something quite different can be noticed, Portugal already one of the largest producers as a percentage of its consumption, being the 3rd worldwide [46], plans to more than double its installed capacity from 5 GW to 13 GW. This all sounds good on paper, but a study carried by LNEG [44], states that if Portugal were to install only wind turbines with a nominal power of 3 MW, in all the available viable spots, it estimates that the sustainable wind potential in Mainland Portugal is 13,7 GW.

This places Portugal dangerously close to the theoretical limit of how many wind turbines can have, while technological advances can allow the use of turbines with a nominal power higher than 3 MW, this still requires us utilize almost all the land with high wind potential, and not only that in 2017, the average installed capacity was 2,3 MW [47]. To add to it, there is also the additional problem that a great number of those turbines are nearing their end of life, by reaching their 20 to 25 year old life expectancy as per the respective fabricant instructions [48]. While these old turbines can see their life expectancy slightly extended, depending on the conditions they were exposed, eventually will need to be either replaced or decommissioned.

3.3.3 Photovoltaic Power

The roadmap puts a lot of focus on solar PV capacity building due to competitive prices and abundance of the resource. The plan envisages a cumulative capacity of 6,9 GW to 7,3 GW [6] (when adding centralized with decentralized power) of solar PV capacity by 2030 a steep increase from the 1,9 GW of 2020. Photovoltaic solar technology will be developed rapidly by increasing its importance and reaching an installed power capacity of 13 GW of both centralized and decentralized solar energy by 2050.

Solar resource assessment is essential for the different phases of solar energy projects, and as such this document will start by analyzing the availability of the solar power in Portugal.

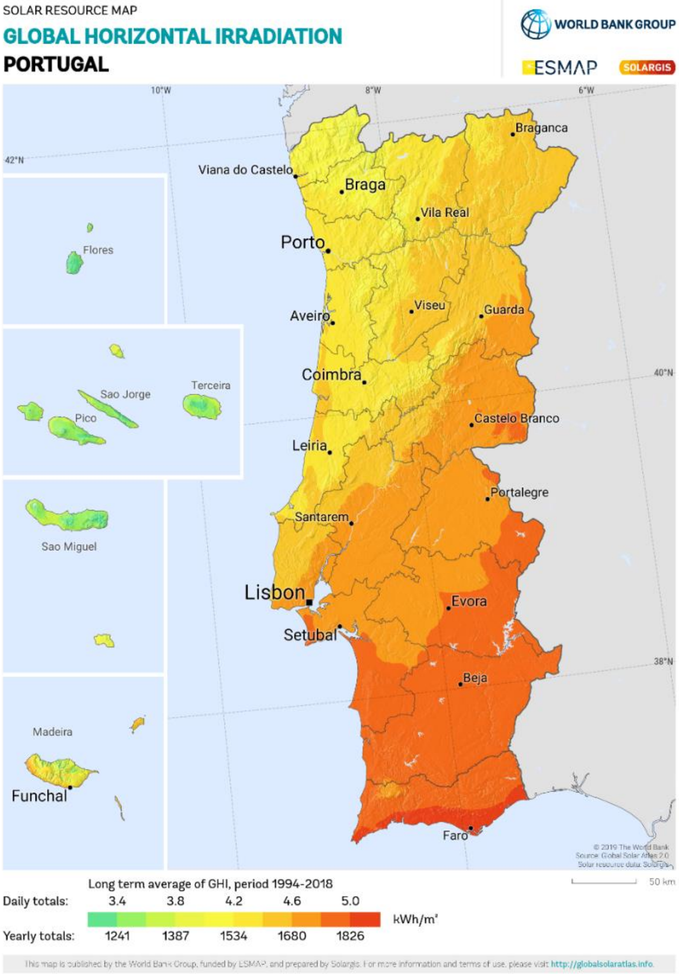


Fig. 7 – Global Horizontal Irradiation (GHI) in Portugal [49]

On the Fig. 7 it is possible to observe that the global horizontal irradiation (GHI) availability is higher on the South due to the latitude effect and the higher average cloudiness in the North region of Portugal. On the other hand, GHI availability also increases from West to East, especially in the North and Center regions most probably due to the frequent formation of fogs in seaside (because of earth-sea interactions) [50]. Portugal also possesses an average of over 200 days per year without rain [51], this data makes PV power of prime importance to Portugal. Portugal awarded 1150 MW at the 2019 solar auction to install in the coming years with prices ranging from 14,57 €/MWh to 31,16 €/MWh, the 2020 auction reached the lowest tariff in the world, in the amount of 11,14 €/MWh [52]. With a proven tendency for decreasing prices, already cheaper than the current values paid for gas and coal, solar power has everything to be the cornerstone of the Portuguese electrical production.

3.3.4 Hydrogen

Regarding Hydrogen, the analysis will start by an overview of the established goals by the EN-H2 (Estratégia nacional para o Hidrogénio), to be met by 2030 are the following [53]:

- 10% to 15% green hydrogen injection into natural gas networks;
- 2% to 5% of green hydrogen in the energy consumption of the industry sector;
- 1% to 5% of green hydrogen in road transport energy consumption;
- 3% to 5% of green hydrogen in the energy consumption of domestic maritime transport;
- 1.5% to 2% of green hydrogen in final energy consumption
- 2 GW to 2,5 GW of installed capacity in electrolyzers;
- Creation of 50 to 100 hydrogen filling stations.

For the purposes of the EN-H2, Portugal will only produce green hydrogen which is produced exclusively from processes that use energy from renewable sources. Hydrogen is an invisible, colourless gas, these colourful term are essentially colour codes, called the hydrogen rainbow, are used to identify how the hydrogen was produced and as such different colours are assigned to the hydrogen. Aside from green hydrogen there is also have, blue hydrogen, brown hydrogen, yellow hydrogen, turquoise hydrogen and pink hydrogen [54].

The main objective is to introduce an element of incentive and stability for the energy sector, the priority goes into the development of renewable hydrogen produced mainly through wind and solar energy. For the purpose of developing a new hydrogen ecosystem in Europe, a gradual trajectory has been designed that goes as [55]:

- The first phase comprises the installation of at least 6 GW of electrolyzers and the production of up to 1 million tons of renewable hydrogen between 2020 and 2024;

- The second phase comprises the installation of at least 40 GW of electrolyzers and the production of up to 10 million tons of renewable hydrogen between 2025 and 2030;
- In the third phase, between 2030 and 2050, it is intended that renewable hydrogen will reach maturity and the various technologies will be implemented on a large scale to reach all sectors where decarbonization via hydrogen is a viable alternative where other technologies are not viable or have higher costs.

The production of hydrogen by electrolysis consumes water as a raw material in the order of 9 L/kg of hydrogen produced. However, electrolyzer suppliers refer to different values, depending on the technology, and which on average are around 13.4 L/kg of hydrogen, which corresponds to around 400 m3/GWh of hydrogen produced. Knowing that the hydrogen economy to be created required large amounts of water, and as mentioned previously, the coming climate change is going to reduce its availability, it’s even more odd that the roadmap, does not include a great deal of hydro power, dams and water reservoirs to fulfill this need.

The hydrogen projects will create a new economy for Portugal, that will work in three phases, which comprise the production of hydrogen, its storage, distribution and supply and end use.

Production - The first stage of the hydrogen value chain comprises the production of hydrogen, with different pathways, processes and associated technologies being identified. In function of the required scale, a distinction is made between large-scale (centralized) production and small- and medium-scale (decentralized) production, ideally close to the place of consumption. In the case of Portugal, the strategy will involve a combination of large-scale centralized production (eg, Sines project) with variable-scale decentralized production associated with various sectors and forms of use.

Storage, distribution and supply - The second stage in the value chain for hydrogen is its storage, distribution and supply. Starts with storage and completes upon delivery for your final use. This stage includes processes that break down into sub-processes. A sub-process may refer to underground gas storage, liquefaction, compression, storage and distribution in gas networks, road and maritime transport or refueling. Probable combinations of hydrogen supply processes could be:

i. road or rail distribution, or both in an intermodal solution, in the form of liquefied/compressed gas, ending with a liquid-to-liquid (L2L) replenishment process for liquid to gaseous (L2G) cryogenic hydrogen storage systems and gas to gas (G2G) at various scales;

ii. distribution of hydrogen by ships in the form of liquefied hydrogen, including delivery for end use with oil pipelines and road transport;

iii. distribution of gaseous hydrogen through a pipeline system; (iv) mixing of hydrogen with natural gas in the current natural gas infrastructure.

End-use - In the third stage, the hydrogen supply chain is addressed to the main end-use applications in the transport and industrial sectors. In residential and industrial stationary applications, mixtures of hydrogen and natural gas can be applied to generate heat and electricity. In the particular case of industry, it can also be used in the form of raw material (ammonia, methanol and others), combined with the capture and use of CO2, promoting a faster replacement of raw materials produced from fossil fuels.

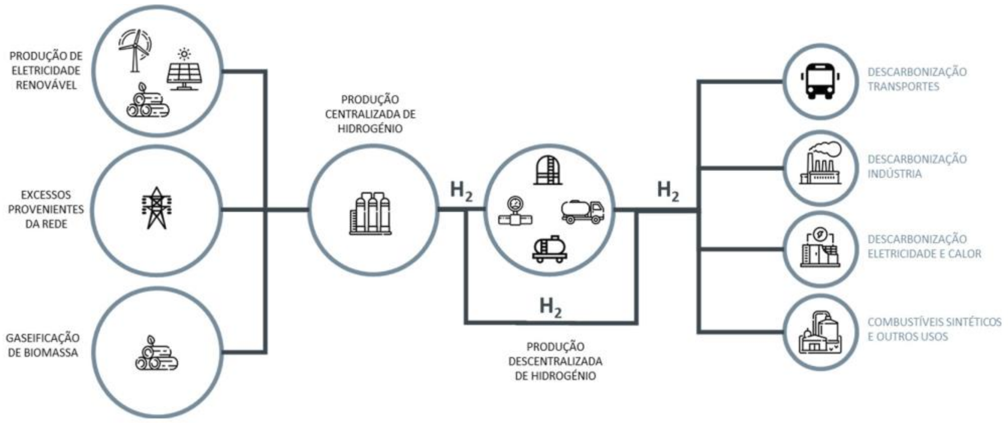


Fig. 8 – Generic scheme of the hydrogen value chain, from production to end use [55].

The current characteristics of the national energy system determined the selection of a set of strategic configurations for the hydrogen value chain, which includes:

- POWER-TO-GAS (P2G): Green hydrogen can be injected directly into natural gas networks or by converting hydrogen into synthetic methane via a methanation process;
- POWER-TO-MOBILITY (P2M): Hydrogen is transported, or produced locally, to supply vehicle fueling stations;
- POWER-TO-INDUSTRY (P2I): Replacing natural gas with hydrogen in the industrial sector contributes more quickly to the reduction of its GHG emissions;
- POWER-TO-SYNFUEL (P2FUEL): The use of green hydrogen has a great potential to decarbonize the production of fuels, replacing them with synthetic fuels of renewable origin;
- POWER-TO-POWER (P2P): Excess renewable electricity can be converted into hydrogen, stored and later converted back into electricity through fuel cells or in suitably adapted and converted gas plant turbines.

The production of electric energy using properly adapted gas turbines or stationary fuel cells fueled by hydrogen, which is itself produced with electricity, is, at first sight, an energy inefficient option, if its purpose is to participate in the market of electricity supply. However, it is interesting from the point of view of system services, especially with regard to storage, in addition to batteries and dams with a pumping system, and is an option that enhances security of supply in a context of accelerated decarbonization of the electrical system. For example, and to deal with dry hydrological years, in which there is less availability of water resources, large amounts of stored hydrogen could be used to power stationary fuel cells with high power (or possibly hydrogen turbines), and in this way, strengthen the security of supply.

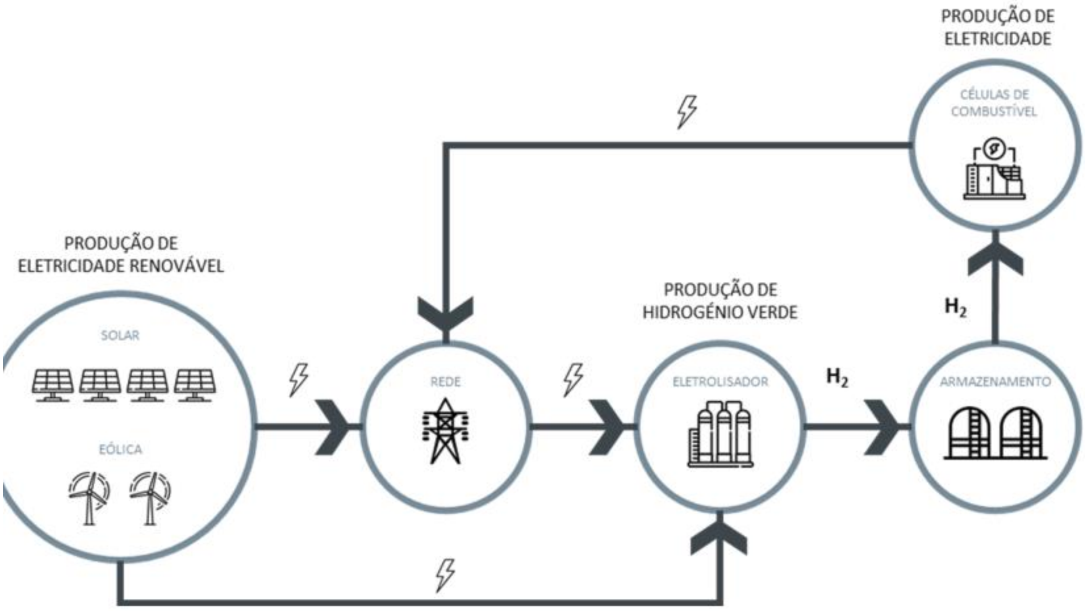


Fig. 9 – Value chain of P2P [55].

Currently, there are already several companies and promoters with P2P projects in progress or in the project phase, which demonstrate the interest and dynamics already generated in the hydrogen domain and in particular in the domain of this value chain. The following projects are already underway in Portugal, namely:

- Hydrogen at the Ribatejo Thermoelectric Power Plant: Local production of hydrogen of green origin, based on renewable electricity, storage and co-combustion with natural gas used in the combustion of the gas turbines at the Ribatejo combined cycle power plant.
- Green hydrogen at the Tapada do Outeiro Thermoelectric Power Plant: Local production of green hydrogen, based on renewable electricity, and co-generation with natural gas used in the combustion of the gas turbines at the Tapada do Outeiro combined cycle power plant.
- Hydrogen production from Offshore Energy: Development and commercialization of a modular and standardized system that aims to produce hydrogen by electrolysis using electricity generated from offshore energy.

3.3.5 Natural Gas

In the last three years, the cost of importing natural gas in Portugal represented, on average, about 15% of total annual energy imports, standing at 1.2 billion euros [55], and recently is facing a steep increase in price reaching historical high prices [56]. Despite having lower emissions than coal, the continuous rise in price of natural gas and the addition of the carbon tax [57] begins to make it less financially viable, especially when seeing that renewable energy costs are reducing to levels below that of the gas [58].

With regard to the installed capacity for electricity production, Portugal, in 2018, had a total of 5 GW [55]. The roadmap [6] plans to keep using natural gas as a backup system to mitigate the intermittency of the renewables up until 2040. While Portugal will keep using natural gas until 2040, at the same time it will be slowly phase-out as it gets replaced with other methods of storage such as hydrogen and batteries.

In order to mitigate the emissions from natural gas while used until 2040, the EN-H2 [55], plans to start mixing it with hydrogen(blending) on its *Power-to-gas* strategy. Currently, national legislation and regulations do not allow the injection of hydrogen into natural gas networks. Regulamento da Qualidade de Serviço dos setores elétrico e do gás (RQS), under the responsibility of the Entidade reguladora de serviços energéticos (ERSE), determines that natural gas, at the entry points of the Rede Nacional de Transmição de Gás Natural (RNTGN), must respect the maximum and minimum values of the Wobbe Index(WI) [59] for natural gas transported on the national grid, respectively 57.66 MJ/m3 (maximum WI) and 48.17 MJ/m3 (minimum WI) [55]. Based on these parameters, it is possible to calculate a maximum calorific value of 13.51 kWh/m3 (PCSmax) and a minimum of 10.05 kWh/m3 (PCSmin) [55].

Considering an average PCI for natural gas of 11.9 kWh/m3, taking into account the natural gas that circulates in the transport network, and 3 kWh/m3 for hydrogen, according to the literature, it means that the injection of Hydrogen in the natural gas transport network will translate into a reduction in the calorific value of the gas that will circulate in the networks. Based on this information, it is possible to determine, from a theoretical point of view, how much hydrogen can be injected into the natural gas transport network without compromising the characteristics of the gas carried in the RNTGN [55].

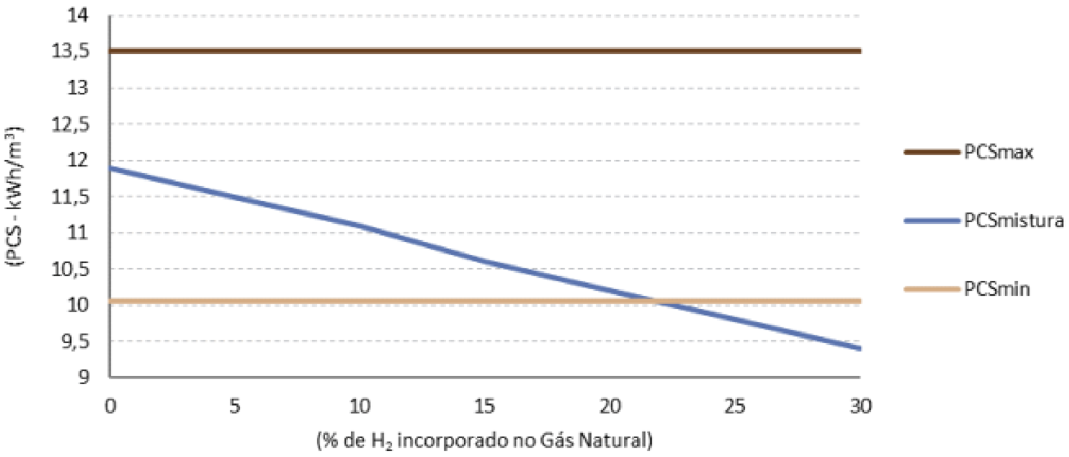


Fig. 10 – Representation of the evolution of the PCS of the gas with the incorporation of hydrogen [55].

3.3.6 Critical Analysis

Analyzing all the documents above mentioned, it is possible to conclude that the roadmap has some slight contradictions and big constrictions. Starting by stating that the hydrogen production is mostly destined to the transport infrastructure and to aid in the grid stability, by serving as storage capacity. The document [6] proposes in 2050 an installed electrical power production capacity ranging from 12.99 GW to 21.49 GW, in addition to this capacity, from the EN-H2 Portugal will also have at least an additional 2.5 GW of electrolyzers. As we'll see from our experiment, in 2040 the Portuguese grid consumption already peaks at 10 GW, this value will overload a great number of the substations, not allowing for any contingency to remain on the grid. To minimize this problem the document proposes that this production to be mainly done by dedicated solar panels and wind turbines (self-consumption). This also presents us with a big technical challenge since, if Portugal tries to match this load requirement with only solar panels, with a yearly daily average solar irradiance of $600W/m^2$ and a panel efficiency of 15% it would require us a surface area of $23.14km^2$ of Solar panels just to match the entire peak production of H_2 (2.5 GW) just in 2030, a value that is expected to increase in 2040 and 2050 without any official number given as of 2021. As a comparison, the total surface area of Lisbon metropolitan area is $100km^2$. This value can be reduced with the inclusion of wind turbines, but as the document states, onshore wind as a source of electricity will be used at almost at its full available potential peaking at 13 GW.

This problem could be partially bypassed by the inclusion of offshore wind power, especially in the coastal areas as Sines and Tapada do Outeiro projects, we've seen that WindFloat Atlantic is providing very promising results with over 4000hours of production per year which translates to a load factor of approximately 48%, this while surviving storms of 140km/h and waves of 14m [45]. But the issue here is that offshore wind technology is being very neglected or ignored by the roadmap, only foreseeing an installed capacity of 1.3GW [6], when it seems that is the most important factor in making the hydrogen project viable on its current goals of installed capacity.

Another issue with the EN-H2 is stated that basing the entire value chain of hydrogen production [53], around the exportation, namely to the Netherlands and the fellow European union members, but as of 2021, the Netherlands is yet to define its hydrogen strategy [60]. Not only that, the North Sea, provides the Dutch with easy access to offshore wind, with already an installed capacity of 2.6GW, and with plans to further develop this means of power production by 11 GW until 2030 [42], by comparison, the Netherlands are planning more wind power by 2030 than Portugal on 2050, the viability of the exportation comes into question.

About wind and hydro as it was shown previously, they show heavy constrains. Portugal only has the potential to install 13.7 GW of onshore wind, when considering an average power of the generator of 3 MW [44], with the current average being 2,3 MW [47], it comes into question it's feasibility. Not only it's required to either install bigger new generators, the ancient ones need to be replaced, and even if the average of 3MW is attained, it requires to use all the land with theoretical potential for wind power. As we know, some of these lands is not suitable for construction for being located in tops of mountains, inaccessible sites, etc, a further technical study is necessary to plan the value of 13 GW of onshore wind.

In hydro power plants, as mentioned in the section 3.2.1 the roadmap plans for 2050 is to increase the total installed capacity by only 1500 MW, it's quite strange that it is not planned further explore this resource, since, when analyzing the hydroelectrical potential on Fig. 5, a study [37] shows that Portugal only utilizes 46% of its total available capacity.

As for PV installations the 13 GW of centralized power production, if we are generous and consider an average daily irradiance of 600 W/m^2 with a 15% efficiency Portugal would need a surface area of 120 km^2 of solar panels, it would occupy a land greater than Lisbon metropolitan area (100 km^2). The decentralized seems more attainable since it would be installed mostly on top of the house's roofs, or the sides of buildings and wouldn't have much impact in land usage.

As far as we've seen all of the plans only present possible trajectories, technologies in which to invest and why, but none of them tackled the main issue that is the need to develop even further the cross-border interconnections. All the roadmaps present a very individualist view of a problem that is proposed by the European Commission to be solved as a community. On July 2021, a problem in an interconnection between France and Spain, cause a nation-wide blackout in both Portugal and Spain [61]. Another study, trying to simulate the feasibility of a 100% renewable European power system by 2050, concluded that "*We find that a 100% renewable European power system could operate with the same level of system adequacy as today when relying on European resources alone, even in the most challenging weather year observed in the period from 1979 to 2015. However, based on our scenario results, realizing such a system by 2050 would require: (i) a 90% increase in generation capacity to at least 1.9 TW (compared with 1 TW installed today), (ii) reliable cross-border transmission capacity at least 140 GW higher than current levels (60 GW),"* [62]. While all the roadmaps make plans regarding generation, and go in the direction of the above quoted study, all of them never plan for the interconnectivity, in fact the only directive that could found from the European Commission dates from 2018 and presented a interconnectivity target of 10% of each country total production, a target that was already met by 17/27 member states at the date of conception [63].

3.4 Power Systems Evolution - Portuguese grid

On December 31, 2019, RNT had 68 substations, 11 switching stations, 2 sectioning stations, 1 transition and a set of transmission lines in service. The values of the total lengths of the line circuits at the different voltage levels and the total installed transformer and auto-transformation powers are summarized in the table below.

Table 4 – Main RNT equipment [Source: Ren]

Length of service lines (km)	31/12/2019	31/12/2018
400 kV	2711	2714
220 kV	3746	3611
150 kV	2544	2582
Total	**9002**	**8907**
Power of transformers into service		
Autotransformer(MAT/MAT)	14470	14470
Transformer(MAT/AT)	23673	22848
Transformer(MAT/MT)	320	320
Total	**38463**	**37638**

In 2019, the consumption of electricity supplied from the public grid totaled 50.3 TWh. This value reflects the aggregate of net production injected into the public network by the power generation centers, of renewable and non-renewable origin, and the balance of international trade, minus consumption for hydroelectric pumping

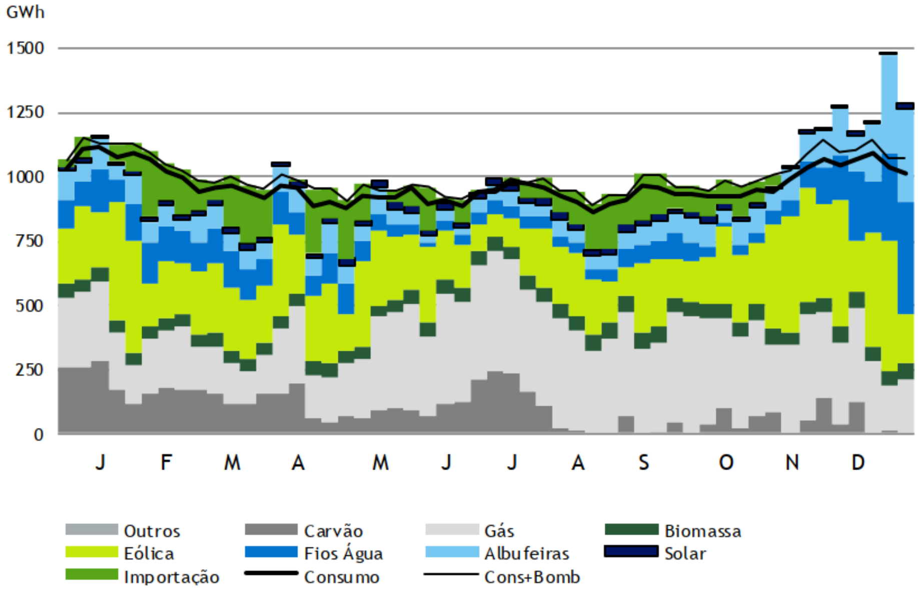


Fig. 11 – Evolution of consumption weeks in 2019 [64].

Electricity consumption in 2019 showed, compared to the previous year, a variation of -1.1%, or -0.2% considering the correction of the temperature effect and the number of working days. This consumption value is 3.6% below the historical maximum recorded in 2010, which was 52.2 TWh.

In 2019, the maximum synchronous consumption load peak verified in the National Electric System (SEN[1]) was 8 650 MW, which occurred on January 15 at 20:00 h. This value was about 140 MW below that recorded in the previous year, and about 750 MW below the 2010 historical maximum.

Fig. 12 shows the maximum values for peak loads in the RNT and consumption in the Public Service Electric Networks, which occurred in each month throughout the year.

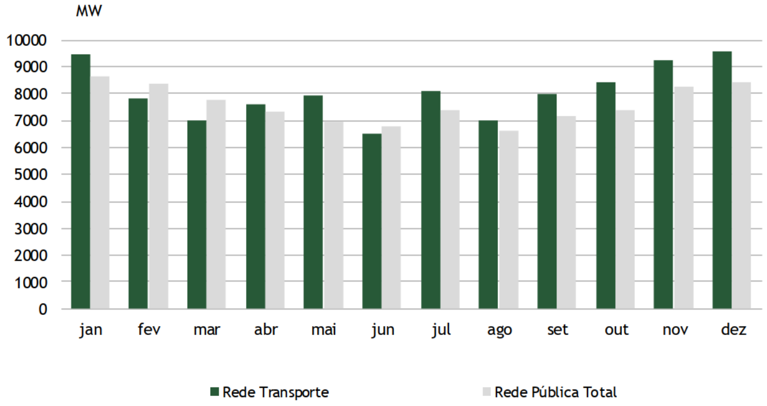


Fig. 12 – Load peaks in 2019 [64].

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[1] In Portuguese - Sistema Eléctrico Nacional (SEN)

Fig. 13 contains four load diagrams representing total consumption in mainland Portugal, referring to the annual peak day (in 2019, which occurred in winter) and three other illustrations of the seasonal periods of spring, summer and autumn. This data will be used as a basis to create the various possible scenarios for simulating the RNT.

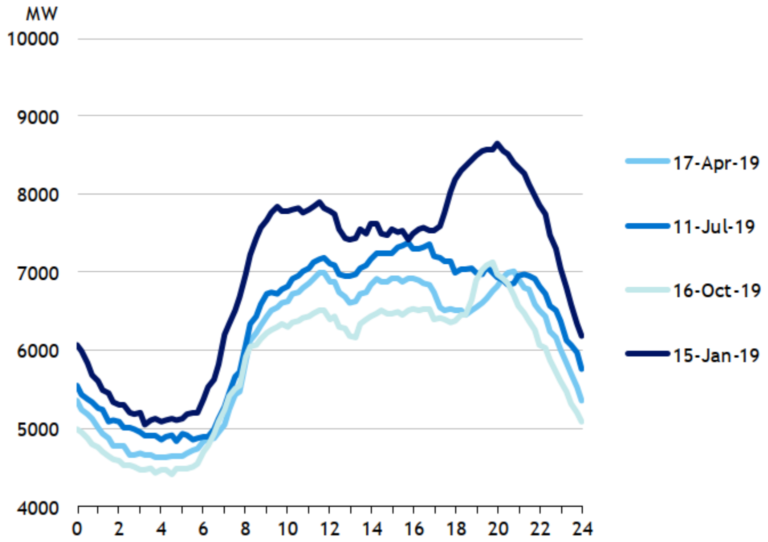

Fig. 13 – Characteristic load diagrams by season [64].

At the end of 2019, the total value of installed production power was 20,208 MW, of which 13,847 MW were from renewable sources and 6,361 MW were non-renewable.

The value of installed capacity in 2019 increased by 240 MW, compared to 2018, reaching 20,208 MW at the end of the year, of which 14,889 were connected to the RNT. In wind power plants, there was an increase of 63 MW, with emphasis on the Penacova plant with 47 MW, while in photovoltaic plants the growth was 160 MW, highlighting the new plant in Ourique, with 44 MW, which became be the largest photovoltaic installation in Portugal.

Table 5 – installed power Portugal 2019 [64].

Installed Power [MW]	**2019**	**2018**
Total	**20208**	**19970**
Renewable	**13847**	**13587**
Hydro	7216	7215
Wind	5208	5145
Biomass	693	658
Combined heat	341	356
Solar	730	569
Non Renewble	**6361**	**6383**
Coal	1756	1756
Natural Gas	4597	4606
Combined heat	768	777
Others	8	21
Combined heat	8	8
Pumping	**2698**	**2698**
Dispatchable plants	12366	12396
Non-Dispatchable plants	7842	7574

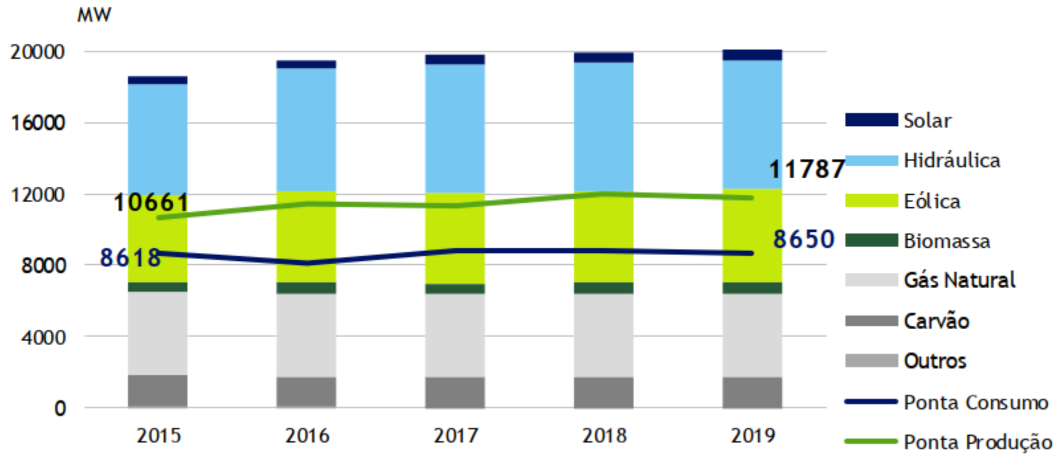

Fig. 14 – Installed power vs annual peak power [64].

In 2019, renewable production supplied 51% of consumption, slightly below the 52% of the previous year. Wind generation, with a productivity index of 1.07, supplied 26% of consumption, the highest share of this technology ever. Hydro production, with a productivity index of 0.81, supplied 17% of consumption; in the remaining renewables, biomass supplied 5.5% of consumption and photovoltaics 2.1%.

In non-renewable production, coal supplied 10% of consumption and natural gas (combined cycle and cogeneration) 32%. In international exchanges, the annual balance was imported, interrupting exporters 3 years in a row, equivalent to around 7% of national consumption.

The global pattern of transits in the RNT is quite varied, depending not only on the load diagram, but also on the time of year, and also, given the greater concentration of hydro and wind power stations north of the Tejo and thermal plants south of this river (the thermal plants now with a lower weight than in the past), from the situation of hydraulicity and wind power.

It should also be noted that internal transit values in some areas of the RNT are subject to significant changes, depending on the value and direction of the balance of trade with Spain. Transits are also influenced by the natural circulation of energy that is established between the RNT and its counterpart in Spain, with mutual benefits.

In 2019, the RNT transported 43.0 TWh, the production centers connected to the RNT injected 32.6 TWh into the Transmission Network, corresponding to 68% of the total national production. The production directly connected to the Distribution Network, 15.6 TWh, corresponded to 32% of the national production, although part of this energy, 2.4 TWh, ended up being injected into the Transmission Network, due to the lack of local consumption. This injection of the distribution network into the Transmission Network was the highest recorded to date, with a peak close to 1500 MW.

In Fig. 15, it can be seen that the power associated with the energy transmitted by the RNT grew continuously between 2015 and 2019, from 8 412 MW to 9 606 MW

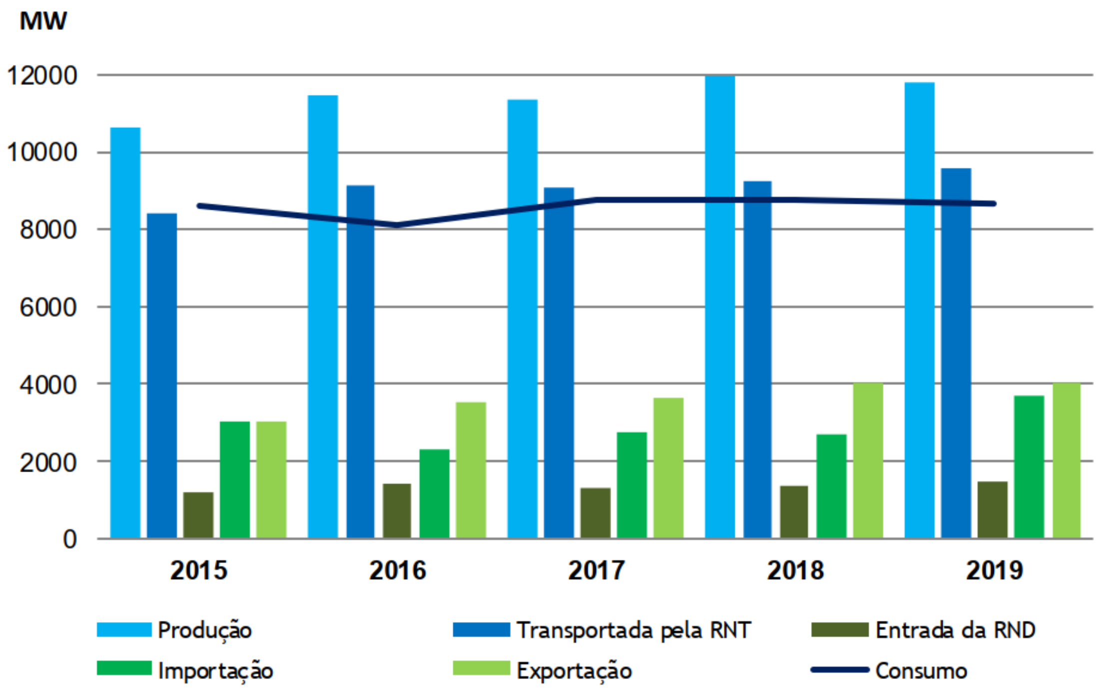

Fig. 15 – Power peaks of RNT [64].

Chapter 4

Experiment methodology

On this experiment the objective is to model the entire Portuguese national electrical grid, on the software tool DPLAN[2], created and provided by AMBERTREE. To do this it’s required to create a catalog with the existing equipment on the substations and the respective cables, according to the information that REN provides on their annual grid report.

The software requires us to work on a power base power of 100MVA, for the transformers, since REN gives the information on the base of power of the transformer a simple calculus to convert to the base and then to a power base of 100MVA is needed.

$$R_{100} = R_{SbaseT} \times \frac{100}{S_{BaseT}} \tag{1}$$

$$X_{100} = X_{SbaseT} \times \frac{100}{S_{BaseT}} \tag{2}$$

$$B_{100} = B_{SbaseT} \times \frac{S_{BaseT}}{100} \tag{3}$$

$$G_{100} = G_{SbaseT} \times \frac{S_{BaseT}}{100} \tag{4}$$

Using the equations 1, 2 & 3 to calculate de values for R, X, G and B, all in pu, R_{100}, X_{100}, B_{100}, G_{100} are the values of the resistance, reactance and magnetic field, in pu (per unit), in the base of 100 MVA, respectively. R_{SbaseT}, X_{SbaseT}, B_{SbaseT}, G_{SbaseT} are the same values in pu, but in the base of power of the transformer. S_{BaseT} is the power of the transformer.

The data has been analyzed, a very strong relation between the parameter values and the type of refrigeration, type of transformer, voltage level and its power was observed. To reduce the complexity of the catalog, they were grouped them together using a pivot table and calculated the average, this process reduced the number of the catalog entries from 200 to 29.

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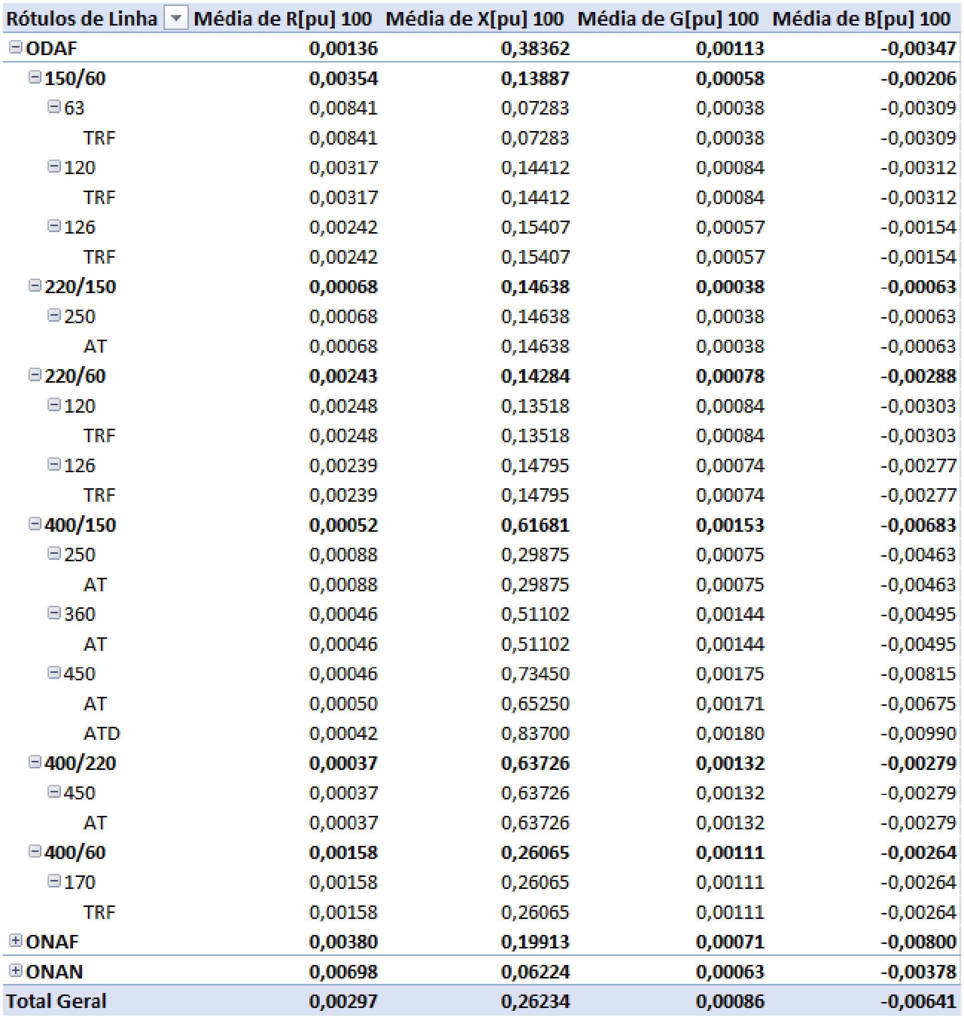
[2] https://dplan.net/

Table 6 – Transformer data



Rótulos de Linha	Média de R[pu] 100	Média de X[pu] 100	Média de G[pu] 100	Média de B[pu] 100
⊟ODAF	**0,00136**	**0,38362**	**0,00113**	**-0,00347**
⊟150/60	**0,00354**	**0,13887**	**0,00058**	**-0,00206**
⊟63	0,00841	0,07283	0,00038	-0,00309
TRF	0,00841	0,07283	0,00038	-0,00309
⊟120	0,00317	0,14412	0,00084	-0,00312
TRF	0,00317	0,14412	0,00084	-0,00312
⊟126	0,00242	0,15407	0,00057	-0,00154
TRF	0,00242	0,15407	0,00057	-0,00154
⊟220/150	**0,00068**	**0,14638**	**0,00038**	**-0,00063**
⊟250	0,00068	0,14638	0,00038	-0,00063
AT	0,00068	0,14638	0,00038	-0,00063
⊟220/60	**0,00243**	**0,14284**	**0,00078**	**-0,00288**
⊟120	0,00248	0,13518	0,00084	-0,00303
TRF	0,00248	0,13518	0,00084	-0,00303
⊟126	0,00239	0,14795	0,00074	-0,00277
TRF	0,00239	0,14795	0,00074	-0,00277
⊟400/150	**0,00052**	**0,61681**	**0,00153**	**-0,00683**
⊟250	0,00088	0,29875	0,00075	-0,00463
AT	0,00088	0,29875	0,00075	-0,00463
⊟360	0,00046	0,51102	0,00144	-0,00495
AT	0,00046	0,51102	0,00144	-0,00495
⊟450	0,00046	0,73450	0,00175	-0,00815
AT	0,00050	0,65250	0,00171	-0,00675
ATD	0,00042	0,83700	0,00180	-0,00990
⊟400/220	**0,00037**	**0,63726**	**0,00132**	**-0,00279**
⊟450	0,00037	0,63726	0,00132	-0,00279
AT	0,00037	0,63726	0,00132	-0,00279
⊟400/60	**0,00158**	**0,26065**	**0,00111**	**-0,00264**
⊟170	0,00158	0,26065	0,00111	-0,00264
TRF	0,00158	0,26065	0,00111	-0,00264
⊞ONAF	**0,00380**	**0,19913**	**0,00071**	**-0,00800**
⊞ONAN	**0,00698**	**0,06224**	**0,00063**	**-0,00378**
Total Geral	**0,00297**	**0,26234**	**0,00086**	**-0,00641**

Regarding the cables, in the data that REN provides, the parameters are in [pu/km] but the software needs it to be in [Ω/km] so a similar calculus needs to be made.

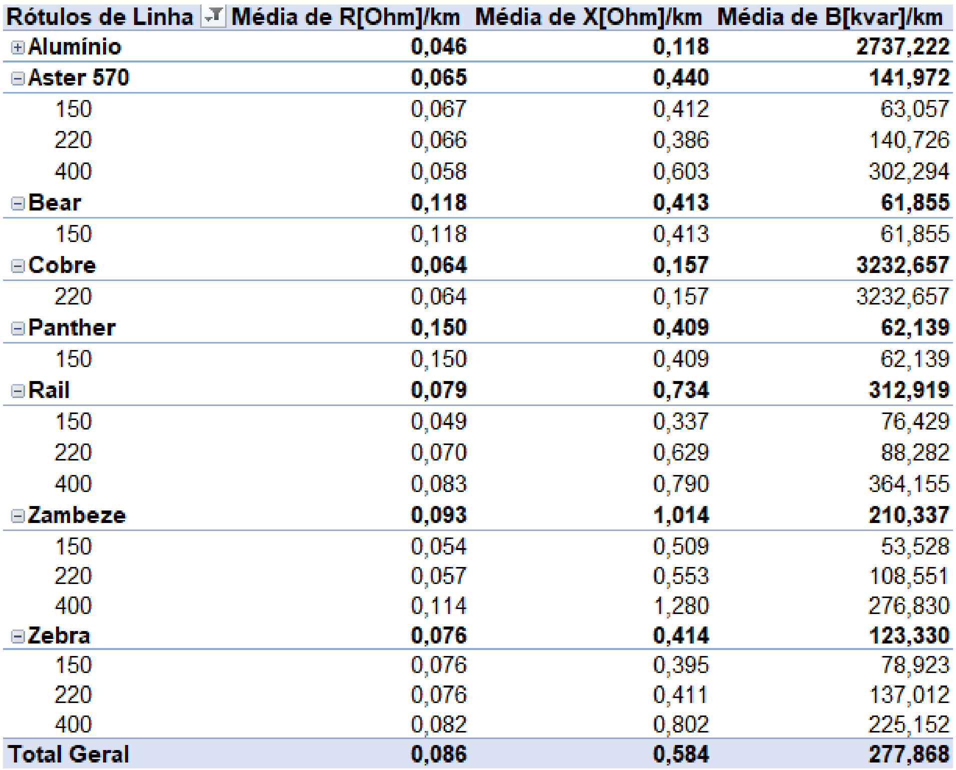
$$R = \left(\frac{\left(R_{base}\times\frac{S_{base}}{V^2}\right)}{d}\right)\times n^{\underline{o}}linhas \qquad (5)$$

Aside from the resistance and reactance of the cable it is also need to know it's maximum current, fortunately REN [64] provides us with the S [MVA] of the cable, from here and knowing its voltage is a very straightforward calculation.

$$I_{max} = \frac{S}{V\times\sqrt[2]{3}} \qquad (6)$$

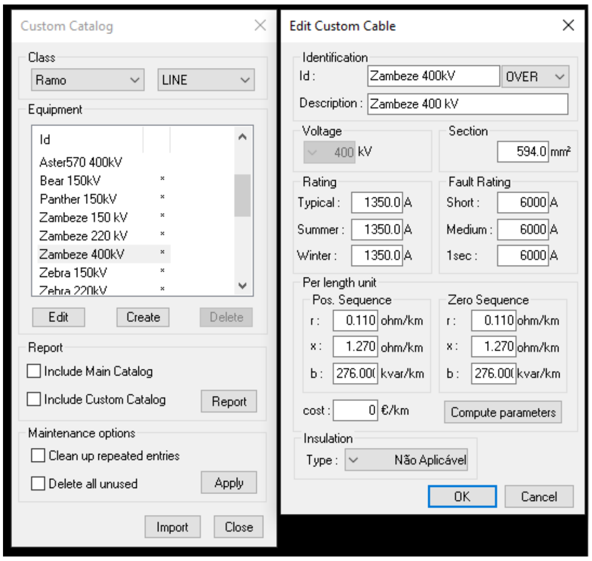
As with the transformer, it was observed a very strong correlation on the cable parameters between the type of cable and voltage level, so again they were grouped them together with a pivot table and calculated the average to reduce the catalog entries from over 300 to 16.

Table 7 – Cable data



Rótulos de Linha	Média de R[Ohm]/km	Média de X[Ohm]/km	Média de B[kvar]/km
⊞ **Alumínio**	**0,046**	**0,118**	**2737,222**
⊟ **Aster 570**	**0,065**	**0,440**	**141,972**
150	0,067	0,412	63,057
220	0,066	0,386	140,726
400	0,058	0,603	302,294
⊟ **Bear**	**0,118**	**0,413**	**61,855**
150	0,118	0,413	61,855
⊟ **Cobre**	**0,064**	**0,157**	**3232,657**
220	0,064	0,157	3232,657
⊟ **Panther**	**0,150**	**0,409**	**62,139**
150	0,150	0,409	62,139
⊟ **Rail**	**0,079**	**0,734**	**312,919**
150	0,049	0,337	76,429
220	0,070	0,629	88,282
400	0,083	0,790	364,155
⊟ **Zambeze**	**0,093**	**1,014**	**210,337**
150	0,054	0,509	53,528
220	0,057	0,553	108,551
400	0,114	1,280	276,830
⊟ **Zebra**	**0,076**	**0,414**	**123,330**
150	0,076	0,395	78,923
220	0,076	0,411	137,012
400	0,082	0,802	225,152
Total Geral	**0,086**	**0,584**	**277,868**

With all the data processed in our hands, the process of introducing all the necessary equipment in the program began, in order to afterwards create the model of the Portuguese electrical grid, below is an example of a catalog entry.



Custom Catalog

Class: Ramo, LINE

Equipment

Id
Aster570 400kV
Bear 150kV ×
Panther 150kV ×
Zambeze 150 kV ×
Zambeze 220 kV ×
Zambeze 400kV ×
Zebra 150kV ×
Zebra 220kV ×

Report
☐ Include Main Catalog
☐ Include Custom Catalog

Maintenance options
☐ Clean up repeated entries
☐ Delete all unused

Edit Custom Cable

Identification
Id: Zambeze 400kV OVER
Description: Zambeze 400 kV

Voltage: 400 kV
Section: 594.0 mm²

Rating
Typical: 1350.0 A
Summer: 1350.0 A
Winter: 1350.0 A

Fault Rating
Short: 6000 A
Medium: 6000 A
1sec: 6000 A

Per length unit
Pos. Sequence
r: 0.110 ohm/km
x: 1.270 ohm/km
b: 276.00(kvar/km
Zero Sequence
r: 0.110 ohm/km
x: 1.270 ohm/km
b: 276.00(kvar/km

cost: 0 €/km

Insulation
Type: Não Aplicável

Fig. 16 – Example of a catalog line

Following the creation of the equipment list, the next step was to create the substations, and add all the equipment that REN lists (Transformers, Breakers, Inductances, Capacitators, etc.) and connect with the respective cables and busbars.

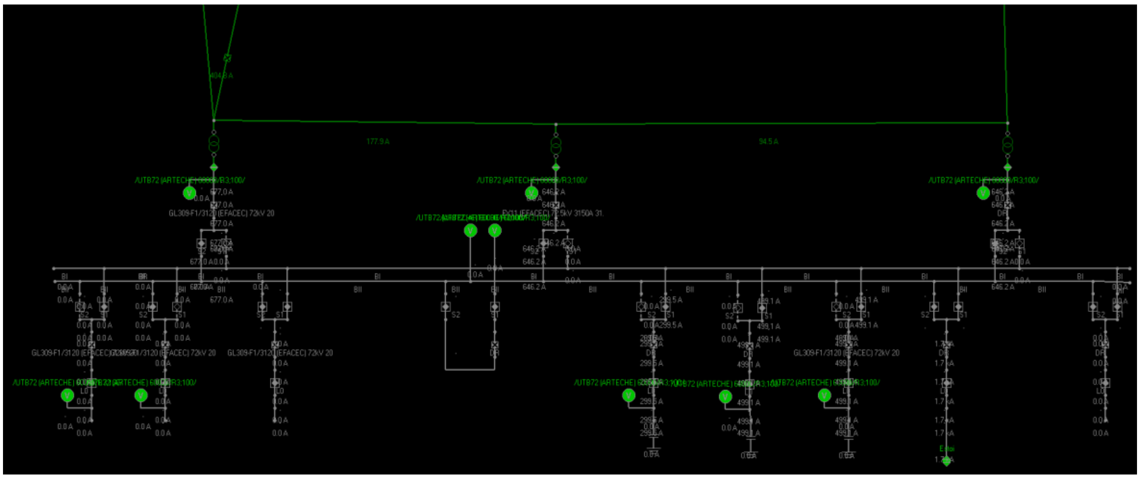


Fig. 17 – Example of substation (ESTOI)

With all the equipment added inside the substations, and powerplants it was time to connect them all according to the list of interconnections that REN provides. In the next coming years a few modifications to the grid are being made and planed, since as of 2030 they should already be completed it was decided to include them in our model. However, since the information of the cables and transformers to install is not available, we simply added them and assumed the most common type of line/transformer existing on the current grid. The changes were as follows:

- New line of 400kV and 150kV from Tavira to Campo de Ourique and from there to Ferreira do alentejo.
- New Substation of 400kV in Divor, with 2 new lines one to Alqueva and the other to Pegões.
- New line of 400kV from Fanhões to Rio maior.
- New substation in Fundão with 2 new lines of 400kV and 200kV to Castelo Branco connecting to Fundão, and a 220kV to Ferro.
- New substation of 400kV in Ponte de Lima with a line coming from Vila nova de Famalicão and another going to the north of Spain.
- New substation of 400kV in Ribeira de pena with 3 new lines of 400kV connecting to Carrapatelo, Frades and the Alto Tamega dam complex.
- New 400kV lines in the interconnections with Spain in Brovales and Puebla de Guzman.

Then, to carry out the experiment, it was required to estimate the increase in electricity consumption for 2030, 2040 and 2050. From the Portuguese roadmap [6], the expected yearly total consumption for each decade can be obtained, from these values it can very easily be obtained the increase in relation to 2020.

Table 8 – Calculus of the increase in energy consumption

Year	2020	2030	2040	2050
Electricity (PJ)	173.59	199.41	269.7	316.72
Increase (%)	0	14.87	55.36	82.45

While these values are not the best or the most accurate for every situation and that they do not represent the seasonal or transitory peaks of consumption, it is fair to assume that on the average day on these decades will have an increase of 15%, 55% and 82% in electrical energy consumption in relation to 2020.

Regarding to the production, knowing that at every instant the production will match the consumption plus the losses, with the data of the installed power, and with historical data from REN [64] taking into account that the RNT has around 10% of its load as reactive power, a series of scenarios can created according to the weather, geography and the availability of natural resources, on when and where there will be more solar, hydro or wind production.

From historical weather patterns it’s expected to produce very large amounts of solar electrical power in the summer, especially on the south part of the country, while during winter Portugal will have more hydro and wind coming from the north and center of the country.

With all the parameters for the experiment defined, the consumption data from REN electrical substations, present on their annual report [64] was utilized. The selected days for January and August correspond to the peak of consumption for winter and summer respectively.

In each substation the load increased in the amounts calculated in table 9 per each decade. In Table 10 can be seen a proposed scenario with the total yearly consumption of electricity on the high voltage network on a winter day.

Table 9 – Total yearly energy consumption per decade during Winter

2020		2030		2040		2050	
P[MW]	**Q[MVAr]**	**P[MW]**	**Q[MVAr]**	**P[MW]**	**Q[MVAr]**	**P[MW]**	**Q[MVAr]**
6958.48	693.48	7946.58	791.95	10735.54	1069.90	12723.58	1272.35

For the hydroelectric power was simply adding the new hydro power under construction, such as Gouvães, Daivão, Alto Tâmega, as there aren’t any further plans. Regarding PV, the production will focus more on the south of the country on Alentejo and Algarve region, as they have the most favorable conditions. Wind turbines will be more in the mountainous areas of the north and center of the country. To reduce complexity issues, it was decided to group all the new powerplants per region and connect them to three nearby major substation of the region, this allows us to have just five powerplants per technology instead of hundreds of small PV or wind powerplants. To reduce the impact on the functioning of the grid these power plants were defined as a P-V node, in order to control the voltage and prevent the grid to “use” the additional line as an extension of the current network.

To decide how to distribute the new production it was decided to follow the ratio of what already was installed and simply increase on the same proportion to match the capacity to install. From the REN report [64] it is known how much wind, solar, small-hydro power capacity there is per substation, by categorizing them per region its total can be obtained. With simple math, a conversion to the percentage of the total installed power per region is made and then proceed to distribute the new power capacity to add to the already existing as per the table below.

Table 10 – Wind Power distribution per region (Based on [64]).

Pinst [MW]	Algarve [%]	Alentejo [%]	Lisboa [%]	Centro [%]	Norte [%]
5306.9	6.15	1.53	12.47	36.80	43.02

Table 11 – Wind Power to add per region in each decade.

Year	Padd [MW]	Algarve [MW]	Alentejo [MW]	Lisboa [MW]	Centro [MW]	Norte [MW]
2030	2693.1	165.62	42.44	335.91	991.24	1158.70
2040	4693.1	288.62	73.96	585.37	1727.37	2019.21
2050	7693.1	473.12	121.24	959.56	2831.58	3309.96

By using the same logic, the following results can obtain for the solar power to install on the next decades.

Table 12 – Solar Power distribution per region (Based on [64]).

Pinst [MW]	Algarve [%]	Alentejo [%]	Lisboa [%]	Centro [%]	Norte [%]
790	53.09	18.23	9.95	11.86	6.87

Table 13 – Solar Power to add per region in each decade.

Year	Padd [MW]	Algarve [MW]	Alentejo [MW]	Lisboa [MW]	Centro [MW]	Norte [MW]
2030	4210.00	2235.03	767.39	418.87	499.34	289.37
2040	9210.00	4889.46	1678.78	916.34	1092.38	633.04
2050	12210.00	6482.12	2225.62	1214.82	1448.20	839.24

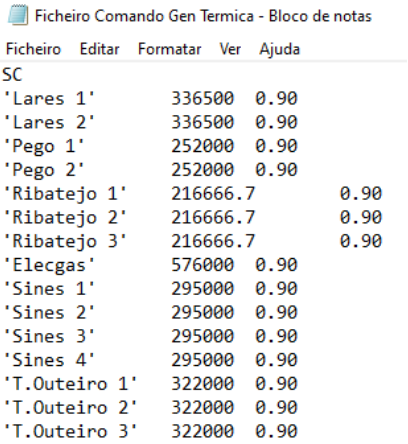
With our additional production defined, it is time to go back to our model and add the new power generation and consumption into the grid. With this final step everything to test the scenario is ready. In order to facilitate the testing process, a series of files were created. These files contain the consumption and production data for a given substation or production plant. The consumption files were created for each decade and production files for each of the 4 considerate decades and for each resource availability, in this way a mix of different availabilities of different resources, can be created to observe the impacts on the network.

Chapter 5

Simulation Results

5.1 Energy Transition 2020 – Baseline Scenario

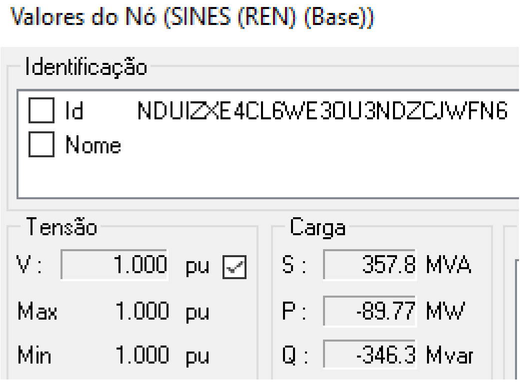
The experimental method involves the manipulation of variables to establish cause and effect relationships. Following this principle, what was required for this experiment, was to simulate the grid behavior by providing a load and production to the system. The process to validate the model, began by applying the load and production of the peak days of four seasons and observe if any fault, or if the reference of the grid would be over or under stress. This was done by creating a datafile listing all the production and consumption sites, and them adding the respective values of active power and reactive power or power factor.



```
SC
'Lares 1'       336500  0.90
'Lares 2'       336500  0.90
'Pego 1'        252000  0.90
'Pego 2'        252000  0.90
'Ribatejo 1'    216666.7        0.90
'Ribatejo 2'    216666.7        0.90
'Ribatejo 3'    216666.7        0.90
'Elecgas'       576000  0.90
'Sines 1'       295000  0.90
'Sines 2'       295000  0.90
'Sines 3'       295000  0.90
'Sines 4'       295000  0.90
'T.Outeiro 1'   322000  0.90
'T.Outeiro 2'   322000  0.90
'T.Outeiro 3'   322000  0.90
```

Fig. 18 – Example of a datafile for thermal powerplants.

With all the values inserted the experiment continued by verifying first, if the power flow converged, secondly if there were any faults in the line or transformers, and what might have caused them in order to discover mistakes (being this real data, it was mandatory for the power flow to work 100% correctly). After verifying that the model didn’t possess any fault to the lines and transformers. To fully validate the model, it requires that the difference between the simulation values, and the data from REN [64] should be equal or very similar. This can be done by seeing the value on reference node, as it will be 0 if they fully match, or have a difference in the case that it is compensating an eventual lack or excess of production.


Valores do Nó (SINES (REN) (Base))

Identificação

☐ Id NDUIZXE4CL6WE3OU3NDZCJWFN6

☐ Nome

Tensão

V : 1.000 pu ☑

Max 1.000 pu

Min 1.000 pu

Carga

S : 357.8 MVA

P : -89.77 MW

Q : -346.3 Mvar

Fig. 19 – Data obtained from the reference node

In Fig. 19 the validation of our model was obtained, as these values needed to be equal or close to 0, there is an excess of about 89 MW in production which translates in an error 2% which is acceptable. Although an slight discrepancy in the reactive power can be observed, this is due to the REN report [64] not having the actual value from the reactive power production, the document only provides the produced active power so there's some assumptions to be made, the choice was to use "typical values" of the power factor from the synchronous machine, and chose strategically and on a balanced way some generators in P-V mode, by fixing a value for the voltage and the given active power, to balance the excess of reactive power on the electrical grid, within a certain limit. Still, this gives a close approximation.

With all the premises verified, it can be concluded that the created model is a close approximation to the real grid and can be used as baseline to simulate the grid for 2030, 2040 and 2050 with the expected increases in production and consumption of the national system.

Additionally, to further test the viability and strength of the model an analysis of the contingencies of the system was made. According to Diário da República [65], the contingency regime n-1 is defined as when "*the failure of any element of the RNT (single line, double line circuit, generator set, autotransformer, transformer, capacitor bank), without exception, must not have cause violations of the voltage and overload on the others, without any topological reconfiguration at the RNT level*" [65]. This means that whenever any element of the grid is taken down, the grid must maintain its full functionality without any violation of voltage criteria or overload, or without reconfiguring the system.

DPlan software is equipped with a function, that helps us with this analysis, and shows us which lines don't follow the n-1 contingency rule, and that cause an overload or voltage violation in case a fault happens. The program uses a color code for lines in which, green means there are no active contingencies, yellow means that the contingencies will cause an overvoltage or overcurrent somewhere in the electrical grid, the red color results in a catastrophic failure of the system, where the power flow will fail to converge. The gray color means that it is a radial line, where there is no contingency, these situations only appear in the connection of some electrical producers to the substations.

On the Fig. 20, can observed that all lines follow the n-1 contingency regulation [65].

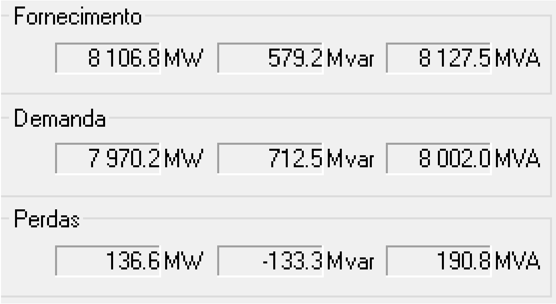
Fig. 20 – Contingency analysis of the system

A simple visual analysis, can conclude that the modeled electrical grid fulfills all the performance requirements assuring to be a good approximation to the real model. Not only does it meet the requirements for consumption, production and losses on the line, but also the contingency rules. With this it can be thus concluded that this model can be used to analyze the impacts that the carbon neutrality plan will have on the national electricity grid.

After completing the validation of the national electricity grid model, the experiment proceeded to study the impacts of the plan for carbon neutrality in 2050, where it will analyze each decade from the present to the end date.

5.2 Energy Transition 2030

The experiment started by testing the 2030 hypothesis, for 2030 the same values from the thermal production were maintained, since on the example there isn't any production from the coal powerplants, and the natural gas and co-generation is still in full operation. As with the previous simulation, it starts by observing that all the data on Fig. 21 is inserted and loaded correctly to eliminate obvious errors caused by inserting it wrongly.



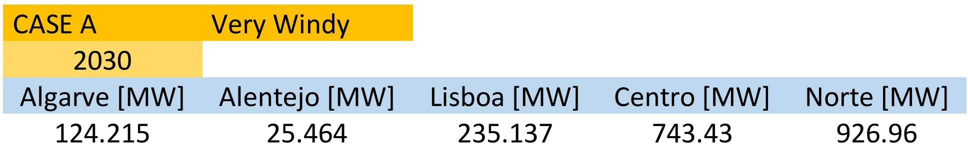
Fornecimento	8 106.8 MW	579.2 Mvar	8 127.5 MVA
Demanda	7 970.2 MW	712.5 Mvar	8 002.0 MVA
Perdas	136.6 MW	-133.3 Mvar	190.8 MVA

Fig. 21 – Supply, demand and losses values on the grid 2030.

Afterwards the next step it to verify if the supply from the scenarios created is enough. The scenarios were created based on the season of the year, as it defines which resource is more readily available.

During the winter season, historically there is more wind and hydro power available than solar, while on summer it is expected to have a high amount sun hours and thus a lot of PV power production, while at the same time having a lack of rain and hydro power.

Table 14 – example 2030 wind energy case



CASE A	Very Windy			
2030				
Algarve [MW]	Alentejo [MW]	Lisboa [MW]	Centro [MW]	Norte [MW]
124.215	25.464	235.137	743.43	926.96

Following the Tables 12 and 14 depending if the availability of the resource is either very abundant, average or scarce a case, can created to each respectively to apply to our model. On Table 15 it’s an example where the wind is widely available which translates on very high levels of production. This table was obtained by multiplying the value from table 12, with an arbitrary percentage of production related to the availability of the resource (in this case wind). The percentage is different per region, as historically, it is more likely to have high amounts of wind on the mountains on the north and center of the country than one the plains of Alentejo.

By adding all of these scenarios together, it is possible to define the global available power supply. To adjust the grid, as the supply needs to meet the demand plus the losses, it is possible to use either import/export electricity through the interconnections available on the grid with Spain, or pump water to store for later use in production. The interconnections are represented on the model by a generator and a load per point, that will either produce electricity when Portugal is importing or consume when it is exporting.

At the start the simulation the value of the import and export energy is set to 0, after running the scenarios and verifying everything was inserted correctly, we move into our reference node that in this case is Sines. Despite the Sines powerplant being already decommissioned at the beginning of 2021 [66], the electrical grid was designed by considering Sines as it's reference. Additionally, with the plans to produce, consume and export hydrogen as explored through this dissertation, considering Sines its main hub, it will likely still be used as a powerplant in the future. On the reference node the compensations being made by the system can be seen, with one look it can be seen if the balance between supply and demand, just like at a control center. With this information it is possible to later redispatch the network, by either exporting or importing, to clear excess power or fill the lack of it, or pump water for storage.

For 2030 no constrains for the operation could be found, as seen in Fig. 22, not a single line, transformer, protection systems had parameters violations, while it's true that there is some slight overcurrent in very few transformers, it's under 10% and within operational parameters and only during the peak of consumption, so we can conclude that the grid is resilient enough for the proposed 2030 changes.

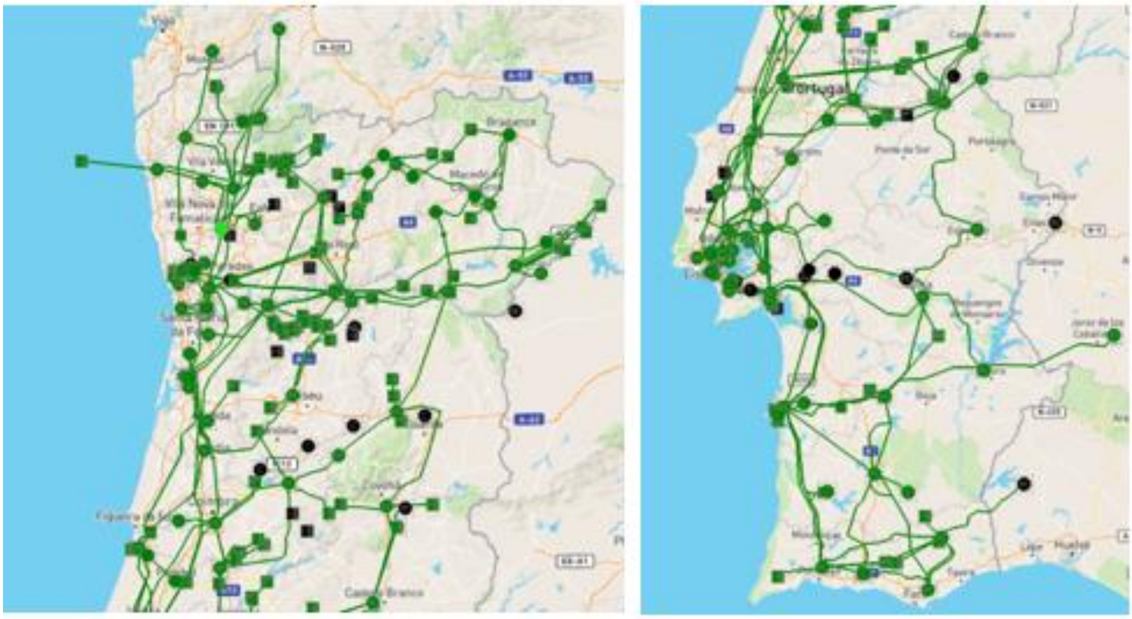


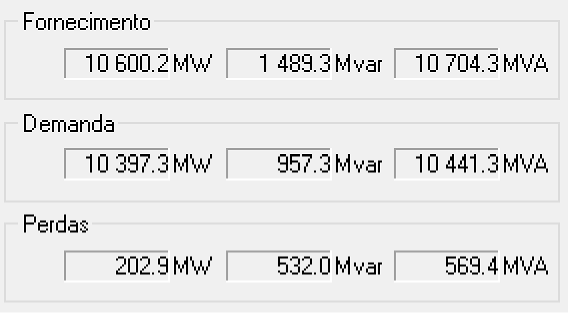
Fig. 22 – Voltage and current analysis 2030 a) North of Portugal b) Center and South of Portugal.

With all the checks made, and with the various simulations made, the next step, will be verifying that the grid maintains all the contingencies in n-1, for 2030, from observing Fig. 23, it is possible to conclude that the grid is fully capable of withstanding the predicted additional load, while at the same time maintaining its full functionality and safety measures. The strength of the Portuguese grid is seen as there is still the capacity to export some of the production during peak hours.

Fig. 23 – Contingency analysis 2030.

5.3 Energy Transition 2040

On the decade of 2040 the situation becomes more complicated. The experiment starts by repeating the same process of data checks between Table 10 and Fig. 21, and the reference node. As the comparisons clearly shows that all that was inserted correctly.



Fornecimento	10 600.2 MW	1 489.3 Mvar	10 704.3 MVA
Demanda	10 397.3 MW	957.3 Mvar	10 441.3 MVA
Perdas	202.9 MW	532.0 Mvar	569.4 MVA

Fig. 24 – Supply, demand and losses values on the grid 2040.

The next step will be to add the production values like previously, to exemplify it was chosen a case where the wind was very abundant, the same was done to hydro but working at half power, since this peak happened during night hours, solar power was 0. With all the production inserted we went to the reference node, and adjusted the slack bus. This was done by increasing the value of exportation and adding some pumping to the hydroelectric.

Table 15 – Example 2040 wind energy case.

2040				
Algarve [MW]	Alentejo [MW]	Lisboa [MW]	Centro [MW]	Norte [MW]
216,465	44,376	409,759	1295,528	1615,368

Afterwards by observing Fig. 25 that shows the current and voltage analysis, a great amount of overcurrent is occurring in the equipment of the substations. The substations, represented by the circles in red have critical failures, while the orange and yellow are less critical, as the overcurrent is still within operating parameters of the equipment, regarding to the lines, no restrictions of voltage or current is observed.

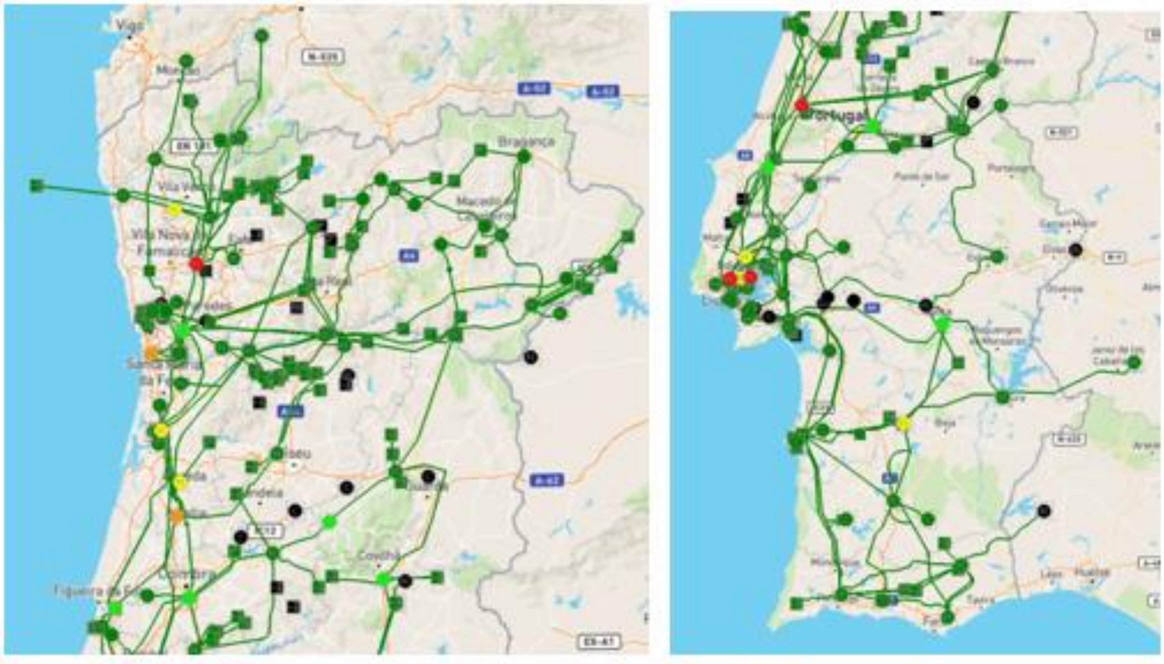


Fig. 24 – Current and voltage analysis 2040 a) North of Portugal b) Center and South of Portugal.

Aside from this analysis, it is also possible to analyze the contingencies in n-1. As it can be observed in Fig. 26, the entire system is under contingencies, as the yellow color of the lines means that in case of failure it will cause an overcurrent or overvoltage somewhere in the electrical grid, and cannot assure the normal functionality and integrity of the grid. The system also possesses a critical point, represented here in the red line, that connects Penela – Coimbra – Paraimo, here a fault results in a non-convergency issue for the entire system.

Fig. 25 – Contingency analysis 2040.

5.4 Energy Transition 2050

The last simulation will be for the year of 2050. On this year we took a special approach, as it's expected from the roadmap, Portugal will be on a carbon neutral society, with fully renewable energy sources and a higher level of decentralized power production. The problem on this particular case is that the simulation is for a Winter day at 21:00 without any sun. In order to mitigate the high amount of increase in electricity consumption, a result of the higher level of electrification to reduce the need of using fossil fuels [67], there is a need to have a decentralized electrical system in order to not overload the electrical grid greatly. Following this logic, since there was no sun, the only technologies currently available were batteries and maybe domestic fuel cells. As per the roadmap batteries will make around 7-9% [6] of the total installed capacity, but those are grid connected battery banks, the information needed is about domestic batteries and fuel cells, to which unfortunately there is no information. Nonetheless it was decided to use an arbitrary value of a 20% reduction in consumption (from Table 11) due to decentralized domestic power production. Afterward the additional production values of hydro and wind were added according to the Table 18.

Table 16 – Example 2050 wind energy case

2050				
Algarve [MW]	Alentejo [MW]	Lisboa [MW]	Centro [MW]	Norte [MW]
354.84	72.74	671.69	2123.68	2647.96

On the Fig. 27 below the first thing that can observe is that all the lines held the required load, but when analyzing the substation, the case is quite different. Immediately can note that a great number of substations have a critical overcurrent, on their transformers and subsequent protection systems. At first glance it’s seen, that all the constrains appear mostly on the coastal region, where the population is higher, and thus the consumption as well, and on a few interior cities on the center of the country. For 2050 it was not possible despite numerous attempts to obtain any sort convergence of the grid. With or without the considered load mitigation from the decentralized power, the load is just too massive for the current transformers to hold.

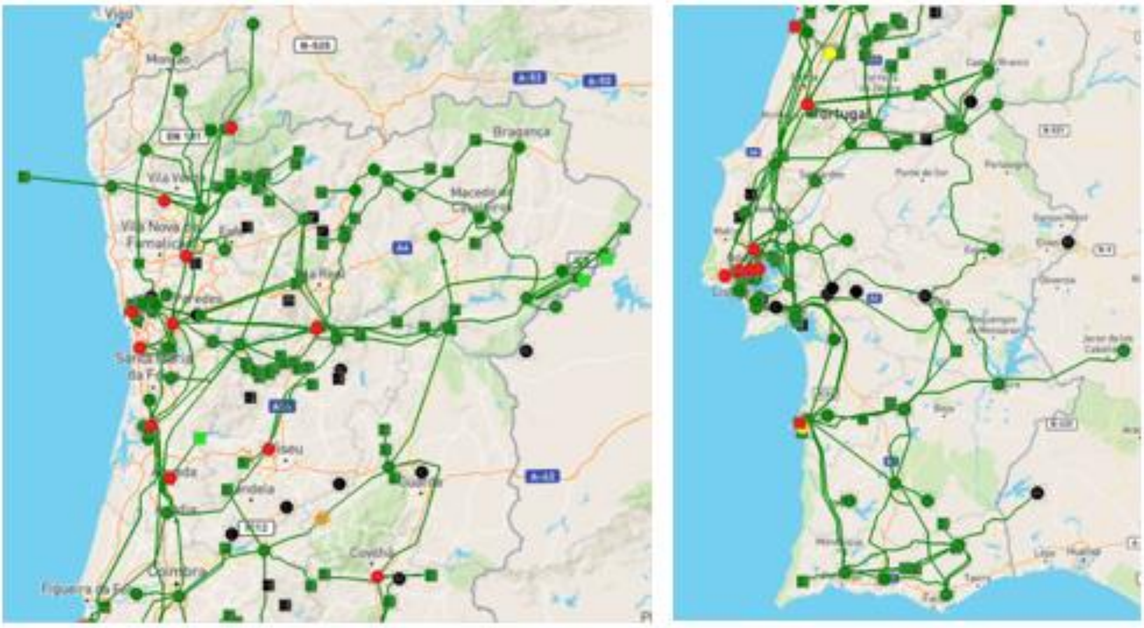


Fig. 26 – Current and voltage analysis 2050 a) North of Portugal b) Center and South of Portugal.

Chapter 6

Conclusion

The research presented was intended to deepen the understanding, test and verify the impacts that the measures presented in the roadmap for the carbon neutrality (Portuguese case) will have on the Portuguese power system. Through thorough investigation, we were able to question the, viability of the Portuguese Hydrogen project, where as we have shown, is completely based on the assumption that The Netherlands and other European countries will be importing the hydrogen we produce, but at this moment they are still discussing at a national level, if it's more viable to import or produce their own.

We also raised serious questions regarding to the plans for onshore and offshore wind energy, as according to several sources, the roadmap plans to have an installed capacity of onshore wind very close to the theoretical limit of the full potential of the resource, and regarding to offshore wind, a booming technology, and an incredible available resource in Portugal it plans to only have a very small fraction of it can theoretically possibly have. We also analyzed the plans for Hydro power and were very surprised to see that when it is expected to have a lot of scarcity of water, and droughts will be more common, the roadmap plans to build a very limited number of new dams, that can serve not only as water reservoirs but as a means to produce electricity and store water power that can be converted in electricity to help maintain the stability of the electrical system in periods of intermittency are occurring in technologies like wind or solar.

Another conclusion we achieved from the intensive study of the measures is that the European Commission, the individual states, when regarding electrical power, every single one only addresses the issue of power production, but not a single state ever mentions the issues relating to the cross-border interconnections between the member states on their respective roadmaps. As we have mentioned in the document, those interconnections are fundamental to maintain the electrical grids on the European continent stable, and able to help each other fight power fluctuations due to the intermittency, we provided various studies that state the need to increase the total amount of power to 140 GW from the current 60 GW.

When analyzing our simulation, we discovered that our very high voltage system is capable of maintaining its full integrity when applying all the modifications for 2030. We also discovered that without a single modification to the electrical system we can maintain some functionality in 2040, despite having slight overcurrent in some equipment, namely transformers and protection systems, but within operational parameters. Unfortunately for 2050 we can conclude that some modifications are required in order to maintain functionality, as the overcurrent on the transformers and protection systems are too great for the system to converge and operate. Regarding to the lines, they maintained full functionality in all the years analyzed, the only scenario where they had issues was when trying to power the hydrogen electrolyzers through the grid.

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