Impact of carbon neutrality roadmap in Power systems (Portuguese scenario) (2021)

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***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 years of 2030, 2040, 2050. The results obtained can be crucial for planning the next interventions on the grid. We concluded that the grid is prepared for the year of 2030, but some evolutions are 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.

***Index Terms*— Carbon-neutrality, Grid Impacts, Portugal 2050, Renewable energy, Sustainability**

I. Introduction

THE evolution and development of the human being is intimately related to the climate around it. If, in certain periods of history, the conditions climate favored the development of societies, in other periods less favorable led to the escalation of conflicts and even the downfall of civilizations. 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.

Human emissions are responsible of the atmospheric CO_2 concentration increases, which causes a change in Earth's energy balance [1].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) [1]. 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/m2[1]. 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*" [2]. This threshold avoids dangerous climate impacts, governments accepted it and are working to mitigate human emissions. The agreement includes a mechanism to promote National Determined Contributions, which likely are a better tool than the Kyoto mechanisms. In the meantime, clean technologies are developed and geoengineering methods are discussed. 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[3]. From this directive the Portuguese roadmap for carbon neutrality 2050 was born.

Achieving a carbon neutral society is no 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 we will have to transform the way we produce, transform and consume our energy.

II. 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 and 91.3 mm in 2020 when compared to 1993. [4]

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. [5]

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. 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 [1].

Carbon dioxide is by far the most important gas emitted due to human activities, having contributed about 77% to the anthropogenic greenhouse effect [5]. Since the Industrial Revolution, human beings have been destabilizing this natural mechanism, increasing CO2 emissions mainly due to the burning of fossil fuels.

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'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. [6]

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. [3] An impact plan will also be presented to increase the EU's GHG emission reductions target for 2030 to between 50% and 55% compared with 1990 levels.

The plan is to review each existing law on its climate merits, and also introduce new legislation on the circular economy, building renovation, biodiversity, farming and innovation. [1]

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[7] 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

2.4 Portuguese Enrolment 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.

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 [8]. 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)[9] was obtained, which translates to a total decrease of -23.3 Mt CO_2 or -36.06%, these figures are 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.

III. Trajectories to 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 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 objective of reducing GHG emissions requires at least 32% renewable energy in energy consumption, a binding objective at the European level. The directive also provides for a target of 14% renewable energy in transport. It’s in this context that each country in the EU has its own individual strategy and climate plan, which translates into over 25 different plans, this document only covers Spain [10], France [11] and the Netherlands [12] due to proximity and strategical interests, despite all of them being quite similar as they follow the same guidelines.

Nowadays with the rapid cost decline of renewable energy, technological developments and the urgency to drastically reduce greenhouse emissions, are opening up new possibilities. The intermittency nature of renewable sources and the necessity for a renewable energy storage on a European level, 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 agenda to stimulate the roll out of production and use of hydrogen, by building a pipeline of projects. 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 of electrolyzers.

In regard to other energy sources, each country tries to maximize its renewable production in proportion to the availability of the resource. By 2035 France aims to produce 50% [13] of its total electricity needs from nuclear power, a decrease of ~20% when compared to 2020, while this seems a phase out from nuclear, we have 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 [9]. Neutrality is possible 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 we can obtain a carbon sink value of between -9 and -13 Mt CO2.

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.

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.

3.3 Power Systems Evolution in Portugal

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 we can setup a series of plans to maximize their evolution.

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 first thing to be observed is 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.

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.

Some natural gas capacity will be maintained 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.

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[14].

3.4 Hydro Power

The hydroelectric power, currently the heart and soul or our electrical system, as it's our only, and a natural mean of power storage, that we have available to compensate the intermittent nature of the renewable power generation. Currently (2021) there is an installed capacity of 7 086 MW [14], and that it's planned to only marginally increase, by 1500 MW until 2030 and to stagnate at this level until 2050. As of 2021 Portugal has under execution various projects such as the dam in Alto Tâmega that alone will increase the installed capacity by 1766 MW [15], 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, a study[16] 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 we are 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?

3.5 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 [17] it is possible to utilize floating devices that can be an important future source of electricity for Portugal. As for comparison in 2020 countries like Netherlands, Denmark and Belgium, have an installed capacity of 2.6GW, 2.26GW and 1.7GW respectively [18]. This number is expected to grow as per their respective roadmaps for carbon neutrality, the Dutch government is planning an installed capacity of 11 GW for 2030 [19].

With the emergence of the floating wind power, and despite Portugal having a large coastline with a potential of over 40GW for the floating systems [20] and [21], the planed capacity is only 0.2|1.3GW for 2050, 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 is proving to be a reliable and resilient technology with 4000h of power availability, capable of surviving storms of 140km/h and 14m waves [22].

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 [23], plans to more than double its installed capacity from 5 GW to 13 GW. It sounds good on paper, but a study carried by LNEG [21], states that if Portugal were to install wind turbines with an average nominal power of 3 MW, it estimates that the sustainable wind potential in Mainland Portugal would be 13,7 GW.

While technological advances can allow the use of turbines with a nominal power higher than 3 MW, this still requires to utilize almost all the land with high wind potential. As of 2017, the average installed capacity was 2,3 MW [24]. To add to it, we also have 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 [25].

3.6 Photovoltaic Power

The roadmap puts a lot of focus on solar PV capacity building due to competitive prices and abundance of the resource. 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. [8]

Solar resource assessment is essential for the different phases of solar energy projects, and as such we will start by analyzing the availability of the solar power in Portugal. 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) [26]. Portugal also possesses an average of over 200 days per year without rain [27], 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 [28]. 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.

3.7 Hydrogen

Regarding Hydrogen, the analysis starts with an overview of the established goals by the EN-H2 (Estratégia nacional para o Hidrogénio), to be met by 2030, they are the following [29]:

- 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.

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: [30]

- 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 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 comprises the production of hydrogen. 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 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 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.

3.8 Natural Gas

With regard to the installed capacity for electricity production, Portugal, in 2018, had a total of 5 GW [30]. The roadmap [8] plans to keep using natural gas as a backup system to mitigate the intermittency of the renewables up until 2040. While we 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 [30], 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. 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) [31], 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. [30]

3.9 Critical Analysis

We observe that this part of the roadmap has some slight contradictions and big constrictions, as we've seen, we start 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 proposes in 2050 a hydrogen installed power production capacity ranging from 12.99 GW to 21.49 GW, in addition to this capacity, from the EN-H2 we know that 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 peaks at 10 GW, a value that will overload the majority 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 some wind turbines, this also presents us with a big technical challenge since, if we try to match this load requirement with only solar panels, with a yearly daily average solar irradiance of 600W/m2 and a panel efficiency of 15% it would require us a surface area of 23.14km2 of Solar panels just to match the entire peak production of H2 in 2030. As a comparison, the total surface area of Lisbon metropolitan area is 100km2. 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 almost at its full available potential. 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 [22]. But the issue here is that offshore wind technology is being ignored by the roadmap, only foreseeing an installed capacity of 1.3GW [1].

Another issue with the EN-H2 is stated that basing the entire value chain of hydrogen production [29], 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 [32]. 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 [19], 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 [2], with the current average being 2,3 MW [24], it comes into question it's feasibility. Not only it's required to either install bigger generators, the ancient ones need to be replaced, and even if the average of 3MW is attained, we require to use all the land with theoretical potential for wind power. As we know, not all of these lands are not suitable for construction for being located in tops of mountains, inaccessible sites, etc, a further technical study is necessary to plan a value of 13 GW of onshore wind.

In hydro, as mentioned in the section 3.4 the roadmap plans for 2050 is to increase the total installed capacity by only 1500 MW, it's quite strange that no further plans exist to explore this resource, since, when analyzing the hydroelectrical potential, a study [16] 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/m2 with a 15% efficiency we would need 120 km2 of just solar panels, it would occupy a land greater than Lisbon metropolitan area. (100 km2). The centralized seems more attainable since it would be installed mostly on top of the houses roofs and wouldn't have much impact in land usage.

As far as we've seen all of the roadmaps 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 [33]. 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),*" [34]. 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 found from the European Commission from 2018 with an interconnectivity target of 10% of its total production, a target that was already met by 17/27 member states at the date of conception [35].

IV. Experiment

To create this model, we need to catalog the existing equipment on the substations and the respective cables. For the transformers the software requires to work on a power base power of 100MVA, since REN gives the information on the base of power of the transformer, we need a simple calculus to convert to the base of 100 MVA.

$$R_{100} = R_{SbaseT} \times \frac{100}{S_{BaseT}} \quad (1)$$

$$X_{100} = X_{SbaseT} \times \frac{S_{BaseT}}{100} \quad (2)$$

$$B_{100} = B_{SbaseT} \times \frac{S_{BaseT}}{100} \quad (3)$$

Using the equations 1, 2 & 3 to calculate de values for, R_{100}, X_{100}, B_{100}, G_{100} are the values of the resistance, reactance and magnetic field, in the base of 100 all in pu (*per unit*). The data was analyzed, and a 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 together using a pivot table and calculated the average, this process reduced the number of the catalog entries from 200 to 29.

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.

$$R = \left(\frac{\left(R_{base} \times \frac{S_{base}}{V^2} \right)}{d} \right) \times nºlinhas \quad (4)$$

Aside from the resistance and reactance of the cable we also need to know it's maximum current, fortunately REN [36] provides us with the S [MVA] of the cable, from here and knowing its voltage is a very straightforward calculation.

$$I_{max} = \frac{S}{V \times \sqrt[2]{3}} \quad (5)$$

With all the data processed, the process of introducing all the necessary equipment in the program began, in order to create the model of the Portuguese electrical grid.

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.

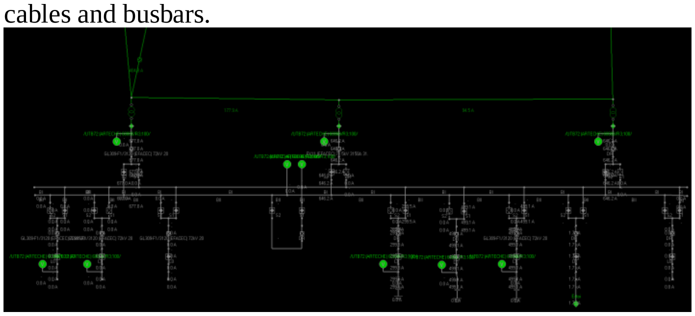

Fig 1. Example of substation (ESTOI)

With all the equipment inside the substations, and powerplants they were connected according to the data from REN. In the next coming years a few modifications to the grid are being made, since as of 2030 they should already be completed we decided to include them in our model. However, since we do not have the information of the cables and transformers to install, we simply added the lines and assumed the most common type existing on the 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 Tâmega dam complex.
- New 400kV lines in the interconnections with Spain in Brovales and Puebla de Guzman.

Then, to carry out the experiment, the next step was to estimate the increase in electricity consumption for 2030, 2040 and 2050. From the Portuguese roadmap [8], 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 1 – Calculus of the increase in energy consumption

Ano	2020	2030	2040	2050
Energia (PJ)	173,59	199,41	269,7	316,72
Aumento (%)	0	14,87	55,36	82,45

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

Regarding to the production, we know 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 knowing that we have around 10% of the load as reactive power, a series of scenarios can be 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.

With all the parameters for the experiment defined we pulled data from REN electrical substations, present on their annual report on the grid for January and August to, create the scenarios for an average summer and winter day. In each substation we increased the load in the amounts calculated in Table 1 in each decade. Below we can see the proposed scenario with the sum of electricity on a winter day.

Table 2 – Total 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 we simply added the new hydro power under construction, such as Gouvães, Daivão, Alto Tâmega. 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, the wind turbines will be more in the mountainous areas of the north and center of the country. To reduce complexity issues, we decided to group all the new powerplants per region and connect them to 3 nearby major substation of the region, this allows us to have just 5 powerplants per technology instead of hundreds of small PV or wind powerplants. To reduce the impact on the functioning of the grid we defined this power plants as a PV node, in order to control the Voltage and prevent the grid to "use" the additional lines as an extension of the current network.

We ended up to decide to follow the ratio of what already was installed and simply increase on the same proportion to match the capacity to install.

Table 3 – Wind Power distribution per region

Pinst [MW]	Algarve [%]	Alentejo [%]	Lisboa [%]	Centro [%]	Norte [%]
5306.9	6.15	1.53	12.47	36.8	43.02

Table 4 – Wind Power to add per region in each decade

Decade	Padd [MW]	Algarve [MW]	Alentejo [MW]	Lisboa [MW]	Centro [MW]	Norte [MW]
2030	2693.1	165.62	42,44	335.91	991.24	1158.7
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

In order to facilitate the testing process, a series of files was 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 decade and for each resource availability, in this way we can mix different availabilities of different resources to observe the impacts on the network.

V. Experiment Results

1. Energy Transition 2020 – Baseline Scenario

To validate the model, we began by applying the load and production of the peak days of various seasons and observed if any fault would emerge, or if, the reference of the grid would be over or under pressure.

With all the values inserted we went on to verify them first, if the line 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 line to work 100% correctly). Without any faults in the model, we proceeded to confirm that the reference was not under pressure (being it overcompensating an excess or lack of production).

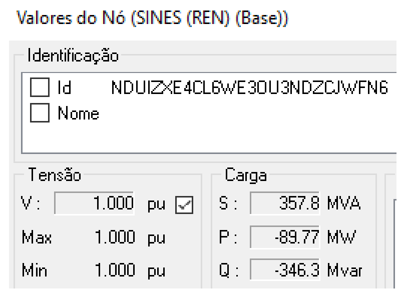

Fig 2. Data obtained from the reference node

In Fig. 2 the validation of our model was obtained, as these values needed to be equal or close to 0. The excess of about 89 MW 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 [36] not having the actual value from the reactive power production, it only provides the produced active power so there's some assumptions to be made, using "typical values" of the power factor from the synchronous machine, and chose strategically some generators in P-V mode, by fixing the value for the voltage and the active power, to balance the excess of reactive power on the electrical grid, within a certain limit. With all our premises verified, it was concluded that the created model was a close approximation to the real grid, and proceeded to simulate the grid for 2030, 2040 and 2050 with the expected increases in production and consumption of the national system.

Additionally, to further validate the model an analysis of the contingencies of the system. According to Diário da República[37], 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" [37]. This means that whenever any element of the grid is, faulty, removed or shut down the grid must maintain its full functionality without any violation of voltage criteria or overload, without reconfiguring the system.

The software is equipped with a function, that helps us with this analysis, and shows which lines don't follow the n-1 contingency rule. 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 we are in the presence of a radial line, where there is no contingency, these situations only appear in the connection of some electrical producers to substations.

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.

Fig 3. Contingency analysis of the system

2. Energy Transition 2030

The testing for the 2030 hypothesis, kept the same values from the thermal production, since on our example we don't have any production from the coal powerplants, but natural gas and co-generation will still be in full operation. As with the previous simulation, it started by checking that all the data was inserted and loaded correctly. Next step is to verify if there's enough supply of electricity from the created scenarios.

Table 5 – 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

On the table 5 is the example of one of the cases for wind energy, for each technology was created a case where the availability of the respective resource is either very abundant, average or scarce. This table was obtained by multiplying the value from Table 4, with an arbitrary percentage of production related to the availability of the resource.
By adding all of these scenarios together we obtain our global available power supply. To adjust the grid, as the supply needs to meet the demand plus the losses, on this case we can either import/export electricity through the interconnections available 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 or consume.
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 [38], the electrical grid was designed by considering Sines as it's reference, not only that, with the plans to produce, consume and export hydrogen as explored through this dissertation, consider Sines its main hub, as thus it will likely still be used as a powerplant in the future. On the reference node we can see the compensations being made by the system, with one look it can be seen if there's either too much or too little power, just like at a control center. With this information it's 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. 4, 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.

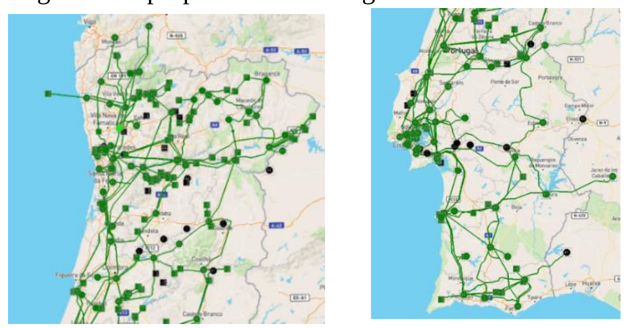

Fig 4. Voltage and current analysis 2030 a) North of Portugal b) South of Portugal

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 5, we can immediately 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.

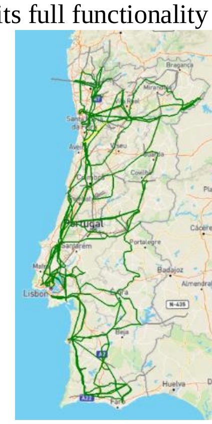

Fig 5. Contingency analysis 2030

3. Simulation Results - Energy Transition 2040

On the decade of 2040 the situation becomes more complicated. The experiment starts by repeating the same process of data checks, followed by the addition of the production values.
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. Afterwards by observing Fig 7 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.

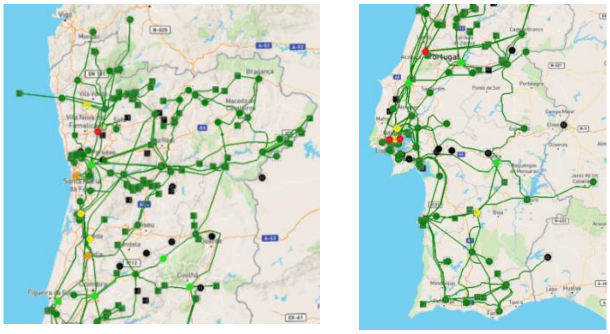

Fig 7 Current and voltage analysis 2040 a) North of Portugal b) South of Portugal

Aside from this analysis, it's also possible to analyze the contingencies in n-1. As it can be observed in Fig 8, 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 8. Contingency analysis 2040

4. Simulation Results - 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, there is a need to have a decentralized electrical system in order to not overload the electrical grid. 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%[8] 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 2) due to decentralized domestic power production. Afterwards the additional production values of hydro and wind were added.

On the Figures 9 & 10 below the first thing that can observe is that all the lines held the required load, but when analyzing the substations, 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.

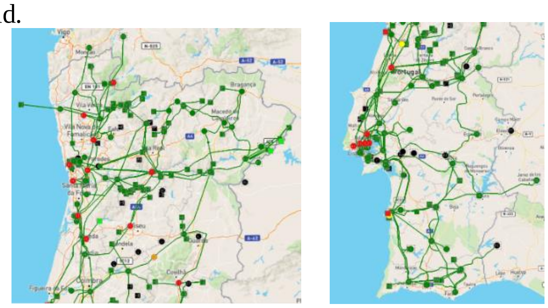

Fig 9. Current and voltage analysis 2050 a) North of Portugal b) South of Portugal

VI. Conclusion

The research presented was intended to deepen the understand, test and verify the impacts that the measures presented in the roadmap for the carbon neutrality (Portuguese case) will have on the Portuguese electrical system. Through thorough investigation, we were able to question the financial, 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's 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 electrical power to help maintain the stability of the electrical system when 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, nobody ever mentions the issues relating to the cross-border interconnections between the member states. As we've 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 some modifications are needed 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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