Assessment of the security of energy supply in Portugal in 2035-2040 and analysis of possible alternatives

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

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It is my hope that this work is worth the care provided by all, and that it is able to repay some of it by helping point towards a better world, that we can enjoy to the full.

ABSTRACT

The transition towards a decarbonized economy has meant an abandonment of the historical system for electricity production in Portugal, that relied heavily on non-renewable thermal power plants. The national option for decarbonization based itself in building a system highly reliant on intermittent renewable energy sources. This option was not necessarily the best to ensure energy security in the coming decades, as renewable energy sources are not capable of providing a consistent source of electricity to fulfill demand at every hour across the year.

This work begins by simulating the energy system in Portugal for the years 2035 and 2040 on an hourly basis, using various scenarios from the RMSA and historical years as references, and concluding the reality and severity of that crisis. From there, the project moves forward to proposing an alternative energy system that, including nuclear power and a power-to-power hydrogen production system, could provide for a decarbonized energy system and ensure energy security across the year. This solution proves to be promising in terms of economic viability, with the addition of a nuclear baseload greatly improving the hydrogen output in the system.

Keywords: energy security, carbon neutrality, energy sovereignty, nuclear power, power-to-power

A transição para uma economia descarbonizada obrigou ao abandono do sistema histórico para produção de eletricidade em Portugal, que dependia fortemente em centrais termoelétricas não-renováveis. A opção nacional para a descarbonização baseou-se na construção de um sistema fortemente dependente em fontes de energia renováveis intermitentes. Esta opção não foi necessariamente a melhor para assegurar a segurança energética nas próximas décadas, por as fontes de energia renovável não serem capazes de providenciar uma fonte consistente de eletricidade para realizar a procura para cada hora ao longo do ano.

Este trabalho começa por simular o sistema energético em Portugal para os anos 2035 e 2040 numa base horária, usando vários cenários do RMSA e anos históricos como referências, e inferindo a realidade e severidade da crise. Daí, o projeto continua, propondo um sistema de energia alternativo que, incluindo energia nuclear e um sistema de produção de hidrogénio *power-to-power*, que poderia providenciar um sistema de energia descarbonizado e assegurar segurança energética ao longo do ano. Esta solução prova ser promissora em termos de viabilidade económica, com o suplemento de uma base nuclear melhorando bastante a produção de hidrogénio no sistema.

Palavras-chave: segurança energética, neutralidade carbónica, soberania energética, energia nuclear, power-to-power

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AEM: Anion Exchange Membrane (Electrolyzer)
CAPEX: capital expenses
CF: Capacity Factor
EROI: Energy Return on Investment
EV: Electric Vehicle
FCOE: Full Cost of Energy
GDP: Gross Domestic Product
GHG: Greenhouse Gases
LCOE: Levelized Cost of Energy
LCOH: Levelized Cost of Hydrogen
OPEX: Operational Expenses
PEM: Proton Exchange Membrane (Electrolyzer)
RMSA: Relatório de Monitorização da Segurança de Abastecimento (do Sistema Elétrico Nacional)
SMR: Steam Methane Reforming
SOEC: Solid Oxide Electrolyzer Cell

CHAPTER 1. INTRODUCTION

The taming of electricity by Humanity can, as a technology, hardly be compared in its impact to our development and comfort to anything less than the taming of fire, 2 million years before. Although it is a much more recent development, and one that has still to reach the entirety of our species, with 675 million people still lacking access to electricity on a quotidian basis [1], for those of us fortunate enough to have a secure supply of electricity, it is almost inconceivable to imagine life without its presence. Electricity has, in most households, replaced fire in its basic tasks, providing us light, warmth and cooking our food.

If one considers the essential role that electricity has taken for itself in our lives, and how much we have taken it for granted, then one ought to imagine as well the toll that it would take, in our comfort, our prosperity, our livelihoods in general, for it to become constrained and scarce, to be deprived of its use for long periods of time.

Energy security is, according to the definition of the International Energy Agency (IEA), “the uninterrupted availability of energy sources at an affordable price” [2]. Energy security concerns itself with guaranteeing that electricity, but also fuels for transportation or other use, remain accessible to all without any strong limits or deprivations.

In Portugal, energy security has, historically, not been much of a problem, at least when it comes to electricity. The electricity production system, as developed in Portugal throughout the 20th century, was based on two main energy sources – hydropower based on the great hydraulic projects accomplished during the latter half of that century in the Portuguese river basins, and thermoelectric plants, fueled with either coal, oil or, more recently, natural gas [3].

This is, from the standpoint of energy security, a very solid system. Both sources of energy are dispatchable, that is, they can be programmed on demand at the request of the grid operators, although hydropower might have its limitations. But even then, hydropower can perfectly serve as a strong base for electrical production, while leaving the thermoelectric plants to make up for the rest as needed. The only major risk to the proper functioning of the system would be the threat of drought lowering the available levels of hydropower, which was not usually a common issue for most years of the last century and, more pressing, for geopolitical problems leading to a lack of fuel at affordable prices for the thermoelectric plants.

This was a system that proved itself reliable, providing electricity to Portuguese households, services, and industries for decades. However, it has ultimately become necessary to move away from this mode of energy production and, in particular, of its thermoelectric component, as it became ever clearer the impact that this sector has had in inducing anthropogenic climate change, and the consequences that this will have on the future of our species.

1.1 THE CARBON NEUTRALITY TRANSITION

The mechanism and consequences of anthropogenic climate change is a subject so thoroughly discussed in both academic circles and among the general public, that is not worth repeating it in great detail here. In short, human emissions of greenhouse gases, of which the main contributor is carbon dioxide, have been responsible for a rise in global average temperatures, which has had a powerful impact on the climate throughout the world, that have generally been detrimental for Humanity and the wider biosphere.

Combatting this trend, reversing the changes afflicted on the climate by this process or, at the very least, preventing the continued rise of global temperatures that would only exacerbate the already dire effects, has become one of the main policy goals of countries throughout the world, pushed to that by strong grassroots movements.

This means transforming human activity in a way to allow for carbon neutrality, that is, for greenhouse gas emissions to be balanced out by the planet’s ability to capture those gases, maintaining their concentration in the atmosphere balanced throughout time. Reaching carbon neutrality has become one of the main policy goals across the globe.

In Portugal, since the 2016 United Nations Climate Change Conference, commonly referred to as COP22, the Portuguese government has been committed to the cause of achieving carbon neutrality by the year 2050 [4]. More recently, at COP27 in 2022, that goal was pushed forward to achieving carbon neutrality by 2045 [5]. This ambitious feat has become a matter of some pride, as it places Portugal firmly on the forefront of countries promising a fast transition towards a decarbonized economy.

In 2020, Portuguese greenhouse gas emissions were around 57.6 MT [6]. Carbon sequestration is planned to be achieved mostly through the use of forestry and agriculture techniques, which are expected to capture 9 to 13 MT of greenhouse gas emissions yearly [7]. Considering the difference between these values, then transitioning to a carbon neutral economy is certainly quite a feat.

This is already a very ambitious transition plan, and an added hurdle is the commitment to a transition that brings with it economic benefits to the population, including more job opportunities and greater economic growth. This means to reject by default any transition plans that advocate a purposeful contraction in economic production or competitivity, that is, rejecting economic degrowth as an accepted alternative. Energy is, as mentioned before, a vital resource for human life and decreasing it means necessarily decreasing out standard of living. This also means that this transition must be able to not only almost completely replace the existing system, but to end at a greater, more productive place than it was to begin with. All of this presents quite a challenge.

The first step towards moving towards a carbon neutral economy is to recognize the contributions that different economic sectors have towards greenhouse gas emissions. Figure 1 presents a distribution of those emissions by sector, for Portugal in recent years.

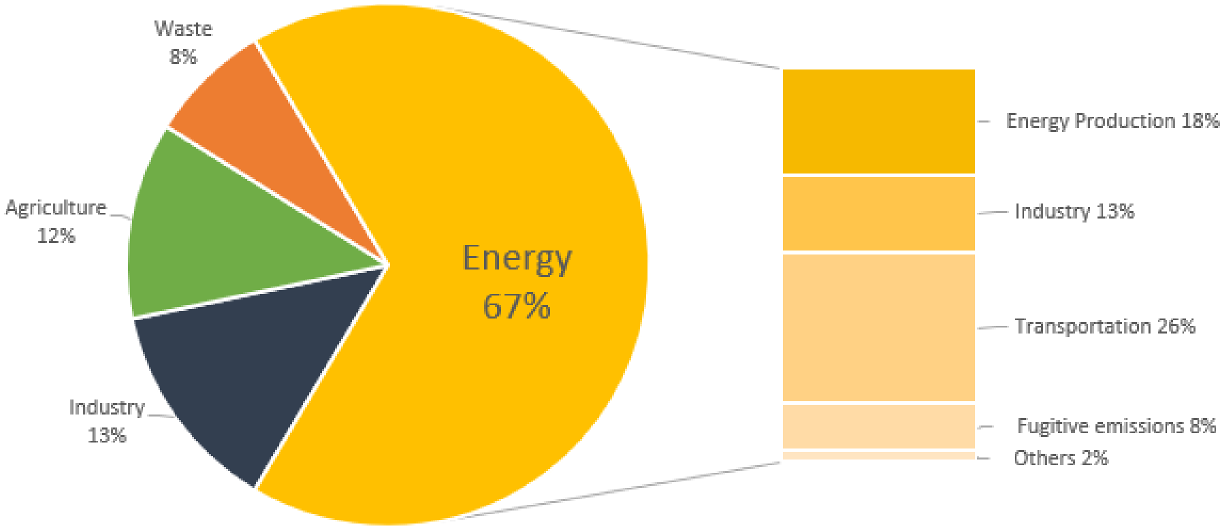


Figure 1 GHG Emissions by Sector, 2020. [8]

Energy takes up a large majority of the sources for greenhouse gas emissions. This is quite sensible, considering that with the exception of some industrial processes, as release from waste products and from some agricultural activities, in particular livestock rearing, most greenhouse gas emissions come precisely from the consumption of fossil fuels as a way to transform their chemical stored energy into useable forms for human consumption.

It should be noted that “Energy” as a sector is somewhat of a broad category. All economic activity, as in “the production, distribution and consumption of goods and services” [9] requires energy. There is no sector of human activity, or even any human activity, that is independent from this energy sector. Looking at its subdivisions is more helpful into getting an insight into the sources of greenhouse gas emissions. “Energy production” refers to, mostly, the production of electricity and its consumption for domestic uses, services, and industries. “Industry”, in this context, refers to the energy used for industrial combustion, so non-electric use of energy in industry. Transportation is the use of non-electric sources for the movement of people and goods, most of it being accomplished through road transportation, but with aviation taking a larger portion of the emissions than its overall share in transportation by distance travelled. Fugitive emissions are caused by several reasons, but are overall inefficiencies of the system, rather than caused by productive activity.

Taking this into consideration, there are some evident sectors that serve as obvious candidates to allow for decarbonization, and those are essentially within the energy sector, namely, being energy production, transportation, and industry. Together, they make up 57% of all greenhouse gas emissions in Portugal and, although certainly not all-encompassing, their decarbonization has been taken as a priority towards achieving carbon neutrality.

At the heart of the decarbonization strategy, therefore, is a two-step process, that tackles the energy sector.

The first step is the electrification of the energy sector, meaning abandoning the use of fossil fuels as the main source of energy in industrial society, to rely more than we already do in electricity. This centers around electrifying the industrial and transportation sectors. The former is achieved by transferring as many as possible of industrial energy needs to electricity, rather than combustion, the latter, by replacing the current fleet of road vehicles, equipped with internal combustion engines and fueled by petroleum-derived products, with electric vehicles. In both sectors, electrification has been ongoing at a promising pace, although there are still blind spots that need to be addressed, namely on how to provide for renewable heat for industry and how to electrify air and sea transportation in the latter.

The second step is to also decarbonize electricity production. The reasoning for electrification as a means to decarbonization goes through assuming that electricity is the easiest source of energy to produce without or at least with limited greenhouse gas emissions. Heat, in comparison, is much harder to produce by most conventional low-carbon sources, with geothermal and nuclear power being exceptions. This makes it one of the energy uses that is currently considered hardest to decarbonize.

The problem then arises that, if the second step is not achieved, and electricity production is not decarbonized extensively, then the first step is not only nullified, but can even be counter-productive, if the energy efficiency using electricity is significantly lesser than that of using combustion. Therefore, decarbonizing the grid has become one the main concerns for achieving the targets of carbon neutrality.

1.2 DECARBONIZING ELECTRICITY PRODUCTION

To achieve the proposed strategy towards carbon neutrality, decarbonization of electricity production becomes necessary. Hence why the historical electricity production system in Portugal, that relied heavily on thermoelectric plants fueled by coal, oil, and gas, all of them fossil fuels that produce greenhouse gas emissions, has been progressively replaced.

To build a new system, the plan goes through the installation of large photovoltaic and wind power capacities, wind onshore for the present with offshore projects on the horizon, while phasing out non-renewable power sources. Coal as a fuel for electricity production has been phased out since 2021 and, although the need to keep reserve capacity may limit the abandonment of natural gas, the current plans include severely decreasing the installed capacity for those power plants as well. For comparison, the graphs in Figures 2 through 5 present the installed capacities of different energy sources in the years 2015 and 2022, and, as they are planned, for the Conservative Scenario used in this project, for the years 2035 and 2040.

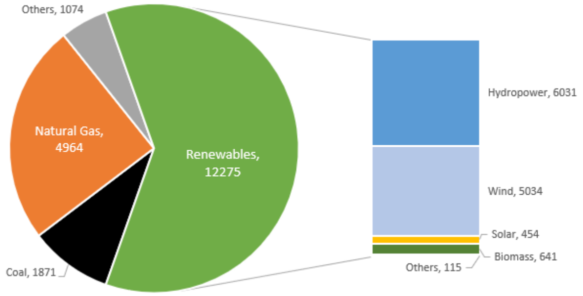


Figure 2 Installed Capacities [MW] for Energy Sources, 2015. [10]

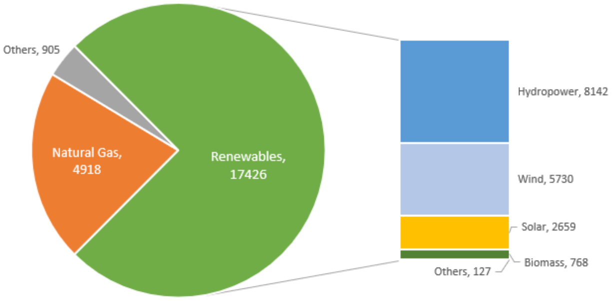


Figure 3 Installed Capacities [MW] for Energy Sources, 2022. [10]

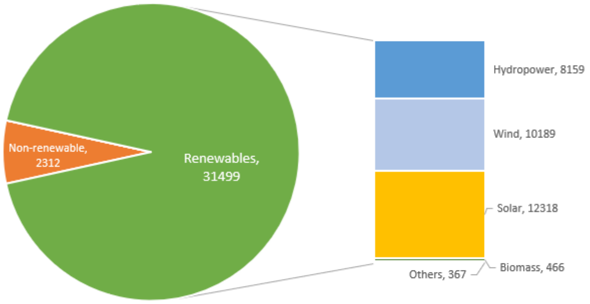


Figure 4 Installed Capacities [MW] for Energy Sources, 2035, Conservative Scenario. [11]

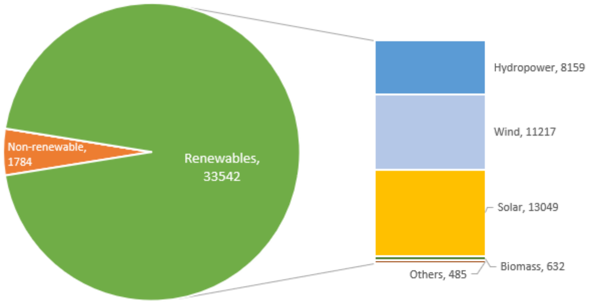


Figure 5 Installed Capacities [MW] for Energy Sources for 2040, Conservative Scenario. [11]

As can be seen in the graphs, the installed capacity of non-renewable energy is supposed to decrease by more than half, while that of renewable energy sources are meant to almost double in the next 20 years. More precisely, the bulk of this growth is in wind power and solar power, the latter of which is meant to face a veritable explosion in installed capacity and become the leading installed energy source in the country.

Looking only at the installed capacities of the system as a way to assess its decarbonization, however, can be misleading. The graphs on Figures 6 and 7, for 2015 and 2022, display the distribution of sources for actually produced electricity for the same historical years.

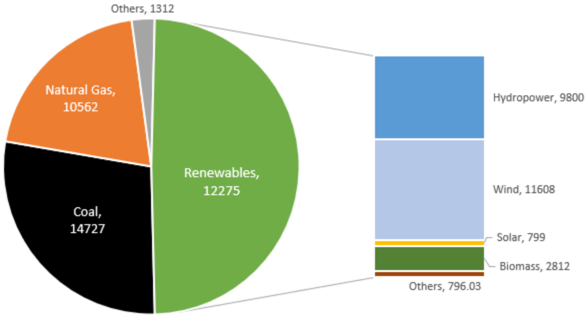


Figure 6 Electricity Produced by Source [GWh], 2015. [12] [13]

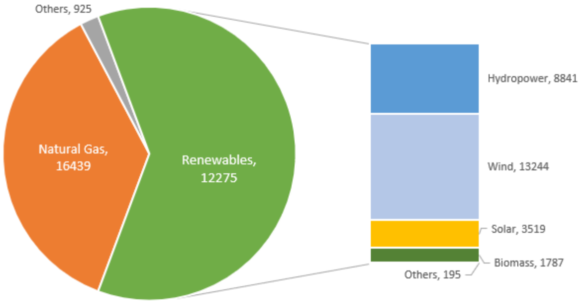


Figure 7 Electricity Produced by Source [GWh], 2022. [12] [13]

In these graphs, the share for nonrenewable energy is rather more important than in those of installed capacity. That has to do with the capacity factor for each energy source. The capacity factor (CF) of a unit is the ratio between the electrical energy that it produces over a given period of time to the electrical energy that could have been produced at continuous operation at full power over the same period. In the case of coal in these graphs, for example, its capacity factor in 2015 was 90%, meaning that, if the coal-powered plants had been working at full capacity year-round, they would have produced 10% more power.

In both years, wind power had a capacity factor of around 26.3%, while solar power had in 2015 a capacity factor of 20% and in 2022 of 15%. Unlike coal, while the limiting factor to its capacity factor mostly has to do with fitting it to the grid demand, or otherwise technical issues at the plant, in the case of wind and solar power is that their energy production capabilities are dependent on the output of the natural energy source that they use, meaning wind and sunlight. Wind power only approaches full capacity when the wind is blowing particularly strong, while solar power is deprived of producing altogether during the night and only approaches full capacity when the sun is at its maximum position in the sky, and even then is dependent on atmospheric clarity. Hydropower, of course, is also dependent on the natural water flow in the case of run-of-river power plants, and even in the case of hydropower plants with reservoirs, on the amount of water that is present in the reservoir and is possible to be discharged.

To the energy sources that have fluctuating production, relying on natural conditions, is given the name *intermittent* sources. These sources are also *non-dispatchable*, as they cannot be programmed to operate on demand for the needs of the electric grid, but rather produce energy on the basis of the availability of the natural resource from which they extract energy. By contrast, most non-renewable energy sources used for electricity production are extremely dispatchable and flexible in their operation, with their power plants being capable of producing the exact amount of energy required to fulfill the needs of the electric grid.

And this now presents a problem. Unlike dispatchable energy sources, intermittent sources cannot, by themselves, fulfill demand requirements. When relying on intermittent sources, one cannot assume that energy production will rise to the challenge of fulfilling demand. The question of energy security, that under the former system was less prominent of an issue, now becomes a very pertinent question.

1.3 AN ENERGY SECURITY CRISIS?

The commitment to reaching carbon neutrality has meant sacrificing the dispatchable energy sources that, for decades, ensured energy security in Portugal, phasing it out and replacing it with renewable energy sources, mostly based on wind turbines and photovoltaic panels.

From an energy security perspective, there are certain benefits to these energy sources, namely that, once installed, they produce energy domestically through resources available in situ, rather than demanding the importation of resources in what can become a volatile international market. However, those benefits can be vastly outweighed by the disadvantage that their non-dispatchability presents. Unlike thermoelectric plants, renewable sources are not capable of making up the necessary energy required to fulfill demand as needed, but rather produce energy as it becomes available.

This means that, in a system dominated by renewable energy, even if built over capacity, there will be moments when the system's production will not fit consumption demand. Rather, for some hours, there will not be enough production to cover demand, and there will be a deficit, while for other hours, electricity production will exceed demand, creating an energy excess for the system, leading to curtailments in production. Both situations can be problematic for the proper functioning of the system.

The electricity grid can be said to work under a "Goldilocks principle", an interdisciplinary concept that refers to a situation in which conditions must be "just right" for a complex system to function. In this particular case, it means that the electricity grid must have a balance between electricity production and electricity consumption to properly function [14]. This balance must be kept, not just on a yearly basis, but at all times, with that being the most challenging aspect of this problem.

This project deals with the question of whether an energy security crisis threatens Portugal in the coming decades, and what can be done to prevent it without abandoning the goals of decarbonization.

Chapter 1 has been this introduction, that will still be completed with some observations on different topics, presuppositions and choices used throughout this project, such as the choice for following a principle of energy sovereignty for Portugal, the choice not to use or explore in depth batteries as a method for grid storage, the choice to not assume a great ability for demand to become flexible, and the choice to study a nuclear power system as a proposed solution.

Chapter 2 deals with the methodology and materials used, explaining what was accomplished, using what software and what data, and explaining the data that was extracted from the simulation to analyze the model that was constructed.

Chapter 3 regards the simulation of the energy system for the years 2035 and 2040, as is being currently predicted. It analyses the various components of the simulation, and ends with a full-system analysis, concluding whether there is a real threat of an energy security crisis for the coming decades.

Chapter 4 deals with adding a nuclear baseload to the system, studying the impact of different sized baseloads and analyzing the results for the system's energy balance, finishing by giving a recommendation on how to proceed to improve the energy security of the Portuguese energy system in the near future, considering the data obtained.

Chapter 5 is about adding a power-to-power hydrogen production system, interacting with the grid through electrolyzers and fuel cells, and determining its impact for different nuclear baseloads. From this, a corrected recommendation is given for a nuclear baseload to be installed, considering its impact on the hydrogen system that is simulated.

The final chapter presents the conclusions of this work and what further research should be carried out to fully assess what should be done to prevent an energy crisis in Portugal and maximize the energy resources available for Portugal.

1.4 ENERGY SOVEREIGNTY

Energy sovereignty can be defined as "the ability of a political community to have the authority to control, regulate and manage their own energy" [15]. In recent publications, this terminology has been mostly associated with a European Union-wide attempt to gain some authority over its energy sector in the aftermath of the war in Ukraine, when the dependency of several European countries to Russian natural gas was exposed as a geopolitical liability.

For this project, however, "energy sovereignty" is used at a national level for Portugal. It means the ideal of the Portuguese energy system being capable of fulfilling its needs, rather than relying on external energy links to achieve some balance. In practical terms, this means Portugal's only continental neighbor of Spain and it means thinking the system that will be modeled in this project in an isolated manner, without accounting for the connections to the Spanish electrical system and the shared Iberian market.

This is clearly a point of the simulation that stretches credulity. Most other simulations of this type would certainly account for the ability to access, on equal terms, to the Spanish market as an important part of their accounting of the situation. And it certainly is. Nevertheless, this choice was done deliberately.

The main reason for this choice is that the Spanish energy system is set to, in the same years as the Portuguese one, to undergo a push towards decarbonization, one to rival that of Portugal, with non-dispatchable renewable sources set to take the bulk of Spain's energy production. The graph on Figure 8, taken from a report by BloombergNEF and ACCIONA on the topic of the Spanish energy transition, confirms that statement.

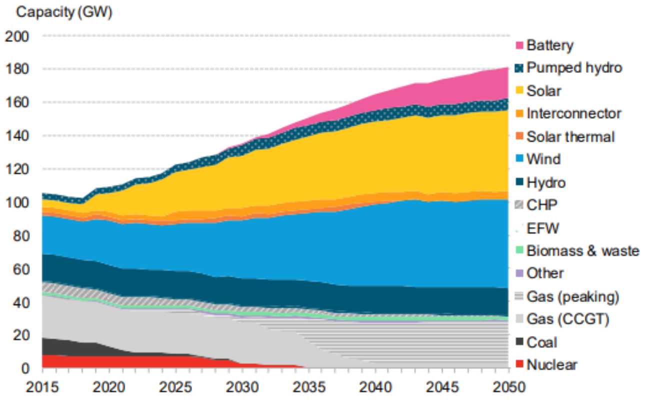


Figure 8 Evolution of Spanish generation capacity according to the report. [16]

As in the Portuguese case, Spanish decarbonization involves installing a very large capacity for solar and wind power, and become reliant on the energy those sources provide, while dismantling its nuclear fleet. The main difference between the two plans, in fact, seems to be Spain's investment in a large 25 GW of peaking gas powers, certainly to be used during the hours when there is a deficit to the energy balance. Portugal could also make use of this investment, but this doesn't quite constitute decarbonization.

The same problems that are being studied for the Portuguese system will, certainly, reflect themselves in the Spanish system as well. Moreso, given that many of the natural resources found in Portugal and Spain roughly coincide – sunlight hours are not very different between the two countries, nor is the water flow, considering they are, for the most part, the very same rivers – it could be reasonably expected that the hours when energy deficits happen and when energy excesses happen to also coincide. As will be seen in the following chapter, there is a strong relation between hourly and monthly energy production and consumption, relations that should be expected to emerge as well in the Spanish system.

Confirming all of that, however, would require repeating the work of this project for the Spanish energy system. This was not possible to be done with the data provided. Nonetheless, there is a strong reason to assume that shared deficit hours, and shared excess hours, could be a problem for the Iberian market.

Finally, wanting the Portuguese energy system to be mostly self-sustaining, and having the connections with Spain to be more of an extra layer of added energy security, rather than a crucial part of the system's survival, is not at all an outlandish demand, especially as imports seem to exceed exports significantly in Portugal, and it is one that can be felt in the government pledges during the decarbonization process [17], as a dependence on Spanish energy would have a negative impact on the Portuguese debt issue. Energy sovereignty as a study principle allows us to test just how capable of this the energy system will be of guaranteeing its basic needs.

1.5 LIMITATIONS ON CONVENTIONAL STORAGE

A possible solution to the problem of energy intermittency would be to arrange a system for energy storage in the grid. That would mean that, as long as the non-dispatchable renewable sources produce as much energy, over the year, as that which is required for consumption, the energy from the hours with a surplus could be stored to be used for the hours with a deficit.

That is not, in itself, a bad idea. In fact, the hydrogen part of the proposed solution, on the third chapter, functions partially as an energy storage system, using hydrogen as a method of chemical storage of energy that is later transformed back into electricity. However, as it will become clear while studying that chapter, using hydrogen in such a manner can easily become, if not economically unfeasible, at least costly, due to the energy lost during the back-and-forth transformations. This has led to more attention being placed into other methods of energy storage that are more efficient and more technologically mature, those being batteries and hydropower reservoirs through pumping.

Storage is also differentiated regarding the timespan that is discussed, with there being daily storage systems, meant to store energy for hours at most, and those meant to store energy for months. Both of those systems have their own issues and concerns to be considered.

Therefore, it becomes necessary, before presenting a hydrogen-based solution, to explain why those methods do not present viable alternatives.

Regarding conventional batteries, the answer is quite straightforward. They don't have enough capacity to make a significant difference in the system. The current plan for battery storage by 2050 in Portugal involves an installed power of 500 MW [18], with no given actual installed capacity. However, just from the data point of installed power, meaning how much power the system could discharge to the grid at a given point, the inadequacy of this system becomes evident. 500 MW is not nearly enough to satisfy the needs of the grid, that at times faces deficits 20 to 30 times that value.

As for battery storage, BloombergNEF predicts, for 2040, a global installed capacity of 2850 GWh [19]. In comparison, the two scenarios used to model the year 2040 expect an electricity consumption of either 62.843 GWh or 75.608 GWh for Portugal alone, so the worldwide battery capacity would be only 3 to 5% of the Portuguese electrical consumption. It will become clear, from observing the graphs from the balance of power when modelled for that year, that not even this value would be enough to cover the needs of the grid. This technology simply does not seem promising for this role.

Regarding the storage of energy through water in reservoirs, they can indeed provide a sizeable storage for water, and they are accounted for in the model. The way this was modelled is further explained on the next chapter, in section 3.4, dealing with Balance with Hydropower. What must be noted, however, is that the storage capacity existing within the hydropower system is at around 3080 GWh which, although certainly more significant than the case for batteries, is still a relatively small amount of the overall needs of the grid, and so, the impact is also limited. Reservoir interdependence also means that the real value of storage is more limited than it would appear.

Further limiting the impact that the water reservoir system can have, is the fact that water resources must be managed in a sustainable and responsible manner. Although often called “natural batteries”, the truth is that hydropower systems don’t work quite like batteries do. This question is elaborated upon in the section 3.4, but ultimately, one cannot think of hydropower as equivalent to a conventional storage system.

And finally, the major limitation for the potential of hydropower reservoirs for energy storage is the geographical limitations of this resource. There is a physical limit to the amount of water the landscape can withhold, and to expand it beyond current levels would be quite challenging and is generally not expected to happen. Hydropower is the one energy source that remains static in installed capacity for each scenario and each year that will be modelled. If anything, given the threats of drought facing the Iberian Peninsula in the coming decades, hydropower as a resource is quite more likely to become less reliable than anything, and expanding the infrastructure would probably have a negative impact on that.

1.6 ON DEMAND FLEXIBILITY

Another proposed solution to help balance the system is to make the energy consumption more flexible, shifting energy needs to accommodate for energy production, rather than the other way around, as was done historically. Similar strategies, such as load shedding, switching off the distribution of energy to certain areas during hours of peak demand, have also been proposed and even used in some situations when the grid could not fulfil demand fully and it became necessary to cut back power to certain areas to safeguard the proper supply of others.

While there are certainly interesting things that can be done with smart systems with flexible energy consumption to lower energy costs, usually the scale at which those systems work is not significant for the grid as a whole, and are applied more at the scale of residential buildings or individual factories. In global terms, it becomes much more difficult to achieve, in particular because the severity of the deficits is often too large to be shifted easily, as that would demand, at certain time periods, for a major pause in energy consumption on all sectors, which would be impossible to achieve.

Another issue is that, as will be further studied in the next chapter, electricity demand is very tied to daily and seasonal patterns of human life and habits. Asking to shift energy consumption away from the early evening, when most people are used to have dinner, enjoy their household devices and bathe, would be very difficult to achieve, as would be to ask for residences to consume less energy during winter and summer months, as the need for home heating and cooling increases, a need that should be expected to increase in the near future, as a result of such systems becoming more commonplace and as climate change makes weather extremes harsher during those seasons.

In terms of industrial needs, it is worth pointing out that, for many industries, curtailing energy consumption means decreasing their productive hours and, therefore, decrease their productivity and profits. It is a similar concept as that of capacity factor – the less time an industry is able to function at full power, the less it will produce and, should capital and operational costs be important contributors to the cost of its product, then the industrial production will become less efficient and less profitable. And this means, ultimately, making Portuguese industries less competitive in the world market.

This would also create the question of deciding which sectors, which areas, should be considered priority over others when load shedding. While it might be generally agreed that sectors such as healthcare, water supply and other basic needs should take some priority, is it more important for a factory to work or for households to have heating and cooling? Should a commercial hub be given priority over a residential neighbourhood? And how forceful should these policies be implemented? This is not to mention the socioeconomic differences between communities, with poorer communities certainly bearing the brunt of higher energy prices, increasing energy poverty and decreasing standards of living across the country. These sorts of questions are not only difficult to answer, but to consider them as viable would go against the commitment to a socially beneficial, economically enriching energy transition. It is necessarily creating a poorer, more regimented society.

Ultimately, for all those reasons, demand flexibility was not explored in this work. On the other hand, it must be said that possible changes to the electricity consumption patterns that might exacerbate the questions of energy balance were also not introduced, such as the aforementioned increases in electricity consumption for heating and cooling, as those devices become more prevalent and as the Portuguese climate becomes more amenable. The sole exception was the introduction of the electricity requirements for the EV fleet in Portugal.

As will be explained in the next chapter, energy consumption will be regarded as mostly reflecting the patterns seen historically, throughout the last few years. This might be an inexact assessment, but in broad strokes, it can be expected to follow through, if only because, as will be seen, energy consumption is impacted the most by the common daily and seasonal habits of the Portuguese population.

1.7 NUCLEAR POWER AS PART OF THE SOLUTION

Nuclear power is a conspicuous absence in the current plans for decarbonization. The Portuguese strategy doesn’t envision the use of nuclear power at all, while in the Spanish plans, nuclear power is expected by phased out much more thoroughly and earlier than non-renewable sources. This is curious, since nuclear power is a technology capable of producing massive amounts of energy while producing no greenhouse gas emissions during production.

There is an existing prejudice against nuclear power that is reflected in that unwillingness to consider its benefits for the energy transition. This prejudice is decades-long and rooted in public opinion more than government policy on the matter, and is often based on incorrect presuppositions about nuclear power, its safety and its economic viability. Regarding the latter point, the economic concerns of nuclear power will be discussed in section 4.1. As for safety, it is enough to say that, in terms of deaths per energy produced, nuclear has the lowest mortality rate, as the graph on Figure 9 displays.

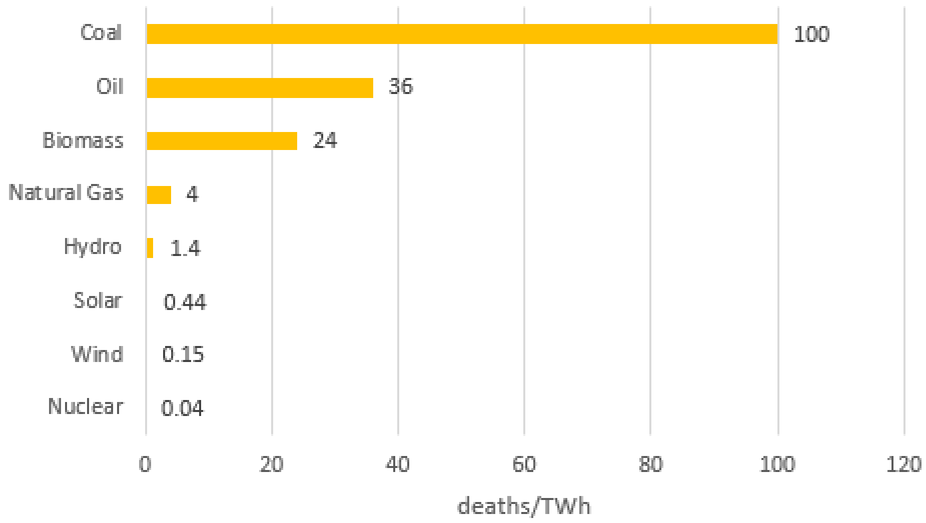


Figure 9 Deaths by TWh of energy produced by source [20]

It should also be noted that the deaths attributed to nuclear power include those from decades-old disasters and from older generations of reactors. Decades of nuclear power research have been dedicated to increase the safety of its operations to a degree of thoroughness that is not found in any other branch of industry. Generation III and above nuclear power plants, which will the ones being discussed for installation, have security apparatus they make the risk to either its workers or to the surrounding population almost null, compared to other energy sources for which safety has not been a decades-long cause of paranoia.

Nuclear power also offers more employment opportunities, creating 25% more employment opportunities than wind power, and with its workers being the best paid in the energy sector, receiving wages 25-30% higher than in the renewable sector. These are also more lasting jobs, as nuclear power demands a sizeable operating workforce, while in the case of renewables, those jobs are mostly geared towards installation, and decrease once the plant is in place [21]. In terms of the commitment to a fair and enriching transition, nuclear power could make a very important contribution.

In practical terms for this project, nuclear power mostly functions as a baseload energy source. This means that, unlike the non-dispatchable renewable sources, that function at the capacity factor its resource allows them, and dispatchable, most non-renewable sources, that function at the necessary capacity factor to achieve an energy balance, nuclear power functions almost constantly at full capacity, with its capacity factor nearing 0.9. Nuclear power does have some greater flexibility than that, with modern power plants being able to, through methods such as frequency regulation, to decrease their energy output to match the needs of the balance of energy [22]. However, such methods based on artificially decreasing energy production usually result in proportionally increasing the energy cost, so their economic viability is concerning. In whatever case, that flexibility was not considered in the simulation, with nuclear power being treated as a simple baseload, and the problems this creates being addressed in the chapter on adding a nuclear baseload.

To finish, it should be noted that, while in Europe and North America, nuclear power is often treated as a “dinosaur”, on its way to extinction, this only holds true of a select number of countries, and is not even prevalent throughout the entire region. Germany is a famous example of a country that recently shut off its nuclear fleet [23], with the consequences of this action seeming less than positive as coal extraction rises to replace it [24], while France remains committed to its nuclear-heavy energy system, which often results in enviable energy prices compared to the rest of Europe [25], and Poland continues committing ever more seriously to build a nuclear fleet of its own [26]. Outside Western Europe, Russia remains a strong champion of nuclear research [27], while countries like China [28], South Korea [29], India [30] and the United Arab

Emirates [31] invest in nuclear power, with results generally outdoing those of a crippled European and North American system.

The claims that the future does not have room for nuclear power are highly exaggerated and very much Eurocentric, and even then, limited to a small group of European countries.

CHAPTER 2. METHODOLOGY AND MATERIALS

In this project, a simulation of various scenarios for the future of the Portuguese energy system, specifically for the years of 2035 and 2040, is carried out. This simulation was created using Python script and inputting historical data relevant to energy production and data from prediction model for the aforementioned future years. From this, an output of data, in both numeric form and in the form of graphs, was obtained, that was used to give an analysis of the results of the study and to reach the project's conclusions.

2.1 THE PROGRAM

Rather than use preexisting energy simulation software, in order to have full control over the results and the logic of the system, the simulation was run on a Python script written for this specific project and using a Spyder environment.

The program mostly consists of a series of functions that simulate the functioning of a particular energy system. There is a function for energy consumption, for non-dispatchable renewable energy production, for hydropower, for non-renewable thermal power, for nuclear power and for the hydrogen system.

In these functions, the main mechanism is a while cycle, that goes from hour to hour in the input data, changes it as is required for simulating the impact of the given system it is on, and proceeds, doing so for the more than 8 thousand hours that are required for completing a year, and repeating it for each year being simulated. Depending on the system, within the while loop there will be a series of conditionals to follow, in particular if the system has different behaviors for different situations, such as hydropower not producing energy if its reservoir is below a certain limit. The output of those functions is an array corresponding to the hours across a year, each line having the month, day, hour and energy load after a particular system.

In the functions, some data might be collected beyond energy balance, such as the amount of hydrogen produced or consumed in the program, or the greenhouse gas emissions that are simulated in it. This is helpful to obtain further data for analysis.

Upon being outputted from the functions, the data will be treated in a number of ways, being organized in different arrays with average hourly and monthly values, or being organized in a descending order. This processed data will be used to make graphics, as explained in section 2.3.

2.2 THE INPUT DATA

Creating a simulation of the energy system for 2035 and 2040, for each hour of the year, is a challenging task. Rather than doing a single possibility, it is wiser to use a range of possible values and, through studying their differences and their similarities, arrive at conclusions about the choices to be made.

That logic was applied for this project. As such, for each of the two years being studied, two different scenarios were taken into consideration, one Conservative and one Ambitious and, for each of those scenarios, seven different distributions were used, each representing a historical year, between 2015 and 2022. This left each proposed solution with 28 possible outcomes to be explored.

The historical data for the years 2015 and 2022 encompass a number of different information pieces.

- Electricity consumption data: obtained from the ENTSO-E Transparency Platform, this data is an array for each of the historical years, yielding the consumption of energy from the Portuguese grid for each hour of the year, alongside the year, month, day and hour in question for easier navigation. The load appears undifferentiated and is given in MWh

- Electricity production data: obtained from the ENTSO-E Transparency Platform, this data is an array for each of the historical years, yielding the production of electricity by source to the

Portuguese grid for each hour of the year, alongside the year, month, day and hour in question. The production data appears differentiated by energy source, including renewable and non-renewable sources, and is given in MWh

- Installed Capacity data: obtained from Ren Data Hub, this data is an array for each of the historical years, yielding the installed capacity for wind, solar, run-of-river hydraulic, hydraulic pumping and biomass, for each hour of the year, alongside the year, month, day and hour in question. The installed capacity data, although appearing for each hour, is updated monthly, and is given in MW

- Water inflow data: obtained from REN Data Hub, this data is an array for each of the historical years, yielding the water inflow, in amount of potential energy, to the water reservoirs. This data is only obtained on a daily basis, and for ease of navigation, appears alongside the year, month and day to which the value is associated. The value is given in GWh

As for the scenarios for 2035 and 2040, those were taken from the Report on Monitorization of the Security of the Supply of the National Electric System for 2023-2040, more commonly known as RMSA 2022 [32]. This report works with three distinct scenarios, a Conservative Scenario, an Ambition Scenario and A Stress Test Scenario. As the latter is only carried out until 2027, it was not considered for this work. It is also worth mentioning that the RMSA diverges significantly from other perspectives towards the near future, namely the PNEC 2030. Extending those perspectives to the future would also be interesting.

The difference between the two is based on macroeconomic indicators, with the Conservative Scenario taking a more pessimistic outlook on the economic growth of the Portuguese economy, and the Ambition Scenario taking a more optimistic outlook predicting greater economic growth. In terms of impact to the energy system, it means that, compared to the Conservative Scenario, in the Ambition Scenario Portugal is farther along in its energy transition, with greater renewable installed capacity, and a reduced non-thermal capacity, but also with a greater energy consumption.

For both scenarios, it is expected to exist economic growth, and therefore an increase in energy consumption, between 2035 and 2040. In each scenario, by 2040 the goals of the energy transition plan are also further along, with more installed renewable energy capacity and a reduced non-renewable one.

The main data points used across the different years and scenarios, referred through the report, are described in Table 1.

Year and Scenario	Installed Capacity [MW]					Consumption [TWh]
	Wind	Solar	Hydropower	Biomass	Non-renewable thermal	
2035 Conservative	10189	12318	8159	466	2312	60.261
2040 Conservative	11217	13049		632	1784	62.843
2035 Ambition	10446	12565		508	2180	71.087
2040 Ambition	11731	13543		715	1520	75.608

Table 1 Installed Capacity of Energy Sources and Energy Consumption across RMSA Scenarios

By using these various scenarios, and repeating them for seven distinct historical years, it becomes more plausible to believe that the future years being studied fall within the range of options that is found, especially when it becomes clear, from observing the results in graphic form, that the similarities between the various years are distinct enough to take some encompassing conclusions.

2.3 THE GRAPHS

Graphs are one of the main outputs of the program, allowing to visualize the results of the various scenarios and have a decent understanding of the results obtained. Three types of graph were created by the program from its treatment of the data, for hourly load, monthly load and for the load monotone curve.

Those graphs and the reasoning for their study are explained in this section. In common to all the graphs produced by the program is them being composed of seven lines, differing by color, each representing a different year among the historical sample between 2015 and 2022.

An example of the hourly load graph is presented in Figure 10.

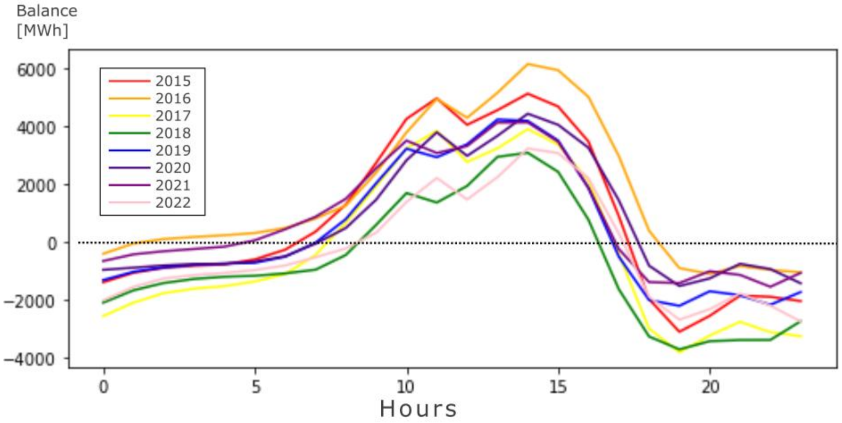


Figure 10 Hourly Load of Non-Dispatchable Renewable Energy Balance. Conservative Scenario, 2035

To produce this graph, a load array goes through a while cycle, in which the value of the hour for each line is taken and, sorted through that, its individual value is summed to the existing value in a corresponding position in a 24-value array, one for each hour of the day. At the end of the cycle, once the year array is over, the average value for each of the positions in the 24-hour array is calculated.

The graph is then designed by imprinting the values for the hourly arrays of each of the historical years, to give a sense of the range of differing possibilities throughout the scenario. In this case, hours with a positive value represent hours where, in average during the year, there was an excess of electricity in the simulation, while those with a negative hours represent hours that, on average, had electricity deficits.

This graph is quite useful to have an idea of the distribution of power throughout the day, and to study which hours would be most affected by the problems of energy security. It also gives a good idea of how those patterns change, or remain the same, throughout the years.

Another graph used to illustrate the behavior of the energy system throughout time is that of the monthly load, which is presented in Figure 11.

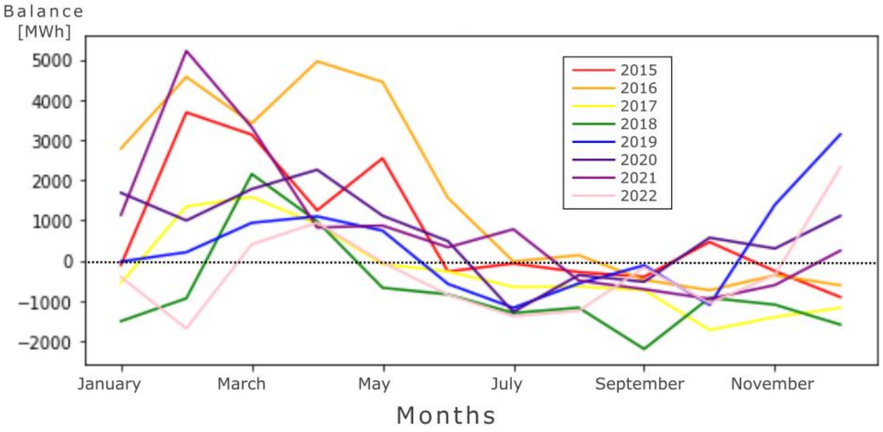


Figure 11 Monthly Load of Non-Dispatchable Renewable Energy Balance. Conservative Scenario, 2035

The process to produce this graph is similar to that of the hourly load one, except that instead of a 24-value array, it is a 12-value one, and care must be taken since there is no month 0. The rest of the process is rather similar, with the values being summed and, at the end, averaged to give the final result.

These graphs also imprint the various years on the same graph, to give a sense of range, and the positive and negative values also represent hours averaging at excess and averaging at deficit respectively.

The final graph that the program creates is the load monotone curve. This graph is presented in Figure 12.

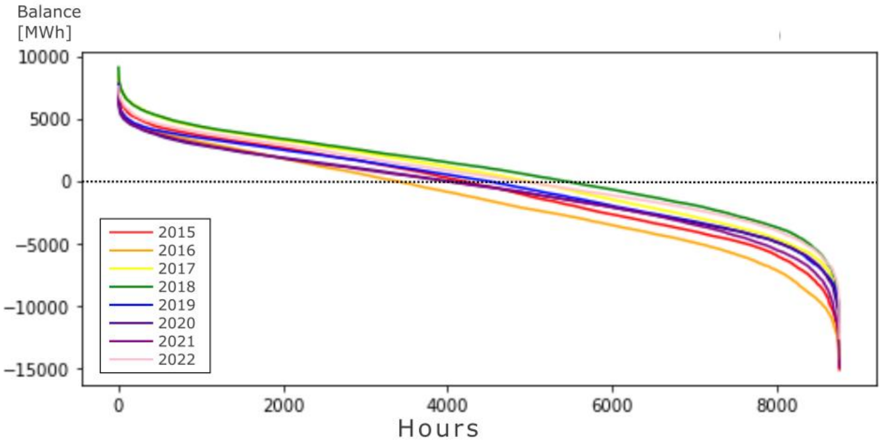


Figure 12 Load Monotone Curve for Energy Balance with non-Dispatchable Renewable Sources. Conservative Scenario, 2035

Load monotone curves orders the load for each hour of the year from largest to smallest. They are often used to study energy systems, providing an idea of the maximums, minimums and preponderances of different values across the span considered.

Following convention, and unlike the other graphs in the project, the positive values of the curves indicate deficits, while the negative values indicate hours with excess energy. Using load monotones, it is possible, by locating the point when the line crosses from positive to negative, to determine the number of hours in the year when the system is in deficit, and when the system is in excess, a useful tool for observing the impact that changes to the model can create on the energy situation of the country.

CHAPTER 3. 2035 AND 2040 SIMULATION

This part of the project dealt with simulating the electricity balance in Portugal for the years 2035 and 2040, on an hour-to-hour basis. This was accomplished by working from historical data, from the years 2015 to 2022, obtained through the ENTSOE database and providing detailed accounts of electricity consumption and production.

The historical data allows to account for the fluctuations and irregularities across different years. Energy production and consumption can be affected by an incalculable number of changes, both due to natural particularities – such as the weather affecting solar, wind or hydroelectric production – and human matters – such as massive lockdowns due to pandemics. Through modelling 2035 and 2040 through seven distinct sets of data, each one encompassing a year between 2015 and 2021, it becomes possible to establish a range of possibilities that is not liable to the particularities of any given year.

The logic through which this model was built from there can be visualized through the flowchart on Figure 13, and will be explained in greater depth throughout this section.

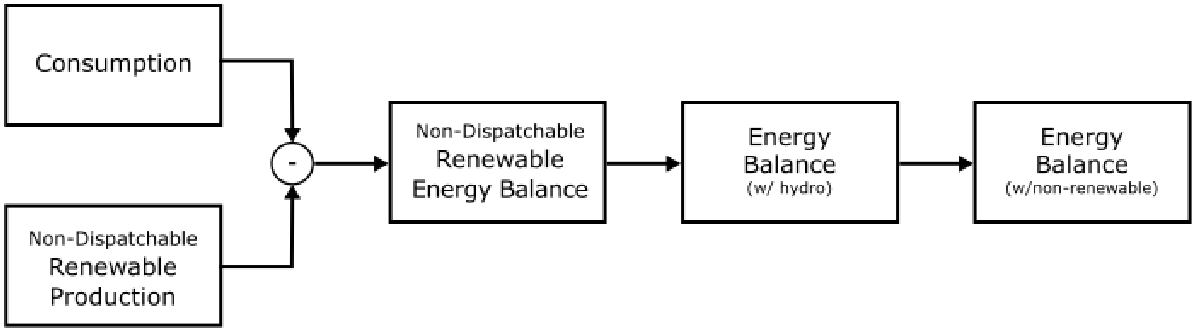


Figure 13 Energy System Model Flowchart

The model for energy consumption for 2035 and 2040 takes into account two distinct consumption outlets. One is the general consumption, as electricity is consumed nowadays and uses as its input the historical data. The other is the impact that the electricity consumption by electrical vehicles will have for those years. How this is achieved is described in greater detail in section 3.1.

Parallel to this, historical data is also used to compute an array for the production of renewable energy that is non-dispatchable, specifically wind, solar, run-of-river hydroelectric and biomass energy sources. This study uses both historical data of energy production and installed capacity to achieve its results, as is elaborated upon in section 3.2.

Through subtracting to the non-dispatchable renewable energy production array the values of the consumption array, it then becomes possible to obtain an array with the renewable energy balance, that is, the values of the electricity excess or deficit, from those sources alone, for each hour of any given year. The results obtained from this array are discussed in section 3.3.

For the model that simulates the electricity balance as it is currently planned, the next step is to add the impact that hydroelectric dams, and their pumping systems, have on the system. With this being a system that allows for the storage of energy and the use of energy surplus to increase that storage, it demands a more complex system than that of the non-dispatchable energy sources. This system, rather than use historical hydroelectrical production directly as data, instead uses historical energy inflows into reservoirs. How this system was modelled is therefore explained in section 3.4.

The last source of energy to be considered for this system is non-renewable thermal energy, essentially meaning, in the Portuguese context, natural gas. This energy, being both non-renewable and greenhouse gas emitting, is at odds with plans for decarbonization, and so its use should be limited to the minimum, which is what is attempted by placing it as a last option in the model. No historical data is used for this part of the model, as this source of energy is only dispatched when required. This model is further described in section 3.5.

Through the modelling of each of those sources and their impacts, we can then establish a perspective of what the energy security situation would look like, in Portugal, in 2035 and 2040, using the parameters that have been chosen for this model. The analysis of those results is given in section 3.6.

3.1 ENERGY CONSUMPTION

Energy consumption for the years 2035 and 2040 is modelled through two distinct consumption outlets. The logic for this part of the model is displayed in the flowchart in Figure 14.

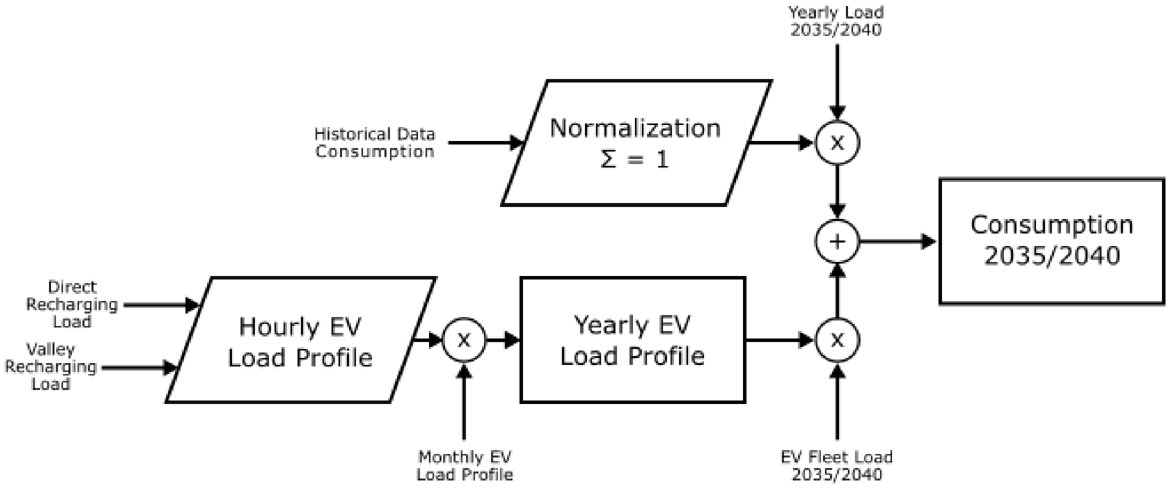


Figure 14 Energy Consumption Model Flowchart

The first, and most relevant of the two, is general consumption. This regards the energy consumed, as it is today, for various sectors of the economy, namely industries, commercial and public sectors, and in residences, with these three sectors nowadays making up the bulk of energy consumption.

From the historical data, the value of this energy is obtained undifferentiated, in an array from hour to hour for each of the years between 2015 and 2022. For each hour in the year, a value in MWh for energy consumption is obtained. The first step in handling that data is through normalizing the energy values across the year, that is, dividing the value of each hourly consumption by the total for the entire year, thereby obtaining a new array for each hour whose sum would equal 1.

This array is then multiplied by the value of the yearly electricity consumption, excluding the energy allocated for the consumption of electrical vehicles. This, then, allows for the simulation of hourly electricity consumption in the future, in the same sectors that are major electricity consumers nowadays. It is assumed that the patterns of consumption throughout the year will not change significantly in regards to those. However, it should be noted that, with the rise in electrification in domestic acclimatization systems, and the rise of more extreme temperatures due to climate change, it is quite possible that consumption behaviors change significantly. Further deindustrialization, and changes in societal routine, such a more permanent shift towards working at home in a considerable section of the population, could also impact this in unforeseen ways. These considerations, however, were not taken into account in this study.

The value for the energy consumption in future years is drawn from the RMSA report, which provides several scenarios, which are based on macroeconomic considerations and the technical evolution of energy efficiency of electrical systems. There is a strong correlation between GDP and useful energy consumption in a society [33], and therefore, by evaluating GDP evolution and the improvement of energy efficiency in the coming years, it is possible to estimate the total energy consumption for society in a future year. This is obviously not a method without its faults, but the existence of distinct scenarios also allows to test across a range. Even then, all current models predict a substantial increase in electricity consumption, due to both GDP growth and due to an increased electrification of industries, services and residential energy uses. In the RMSA report, energy consumption by 2040 is expected to rise between 10 and 32% compared to the present.

Besides the electricity consumed in the sectors that now make up the overwhelming majority of consumption, a significant change is taken into account, that of electrical vehicles becoming more prevalent and therefore transportation as a sector becoming relevant for electricity consumption behavior.

Unlike general consumption, whose behavior throughout the year can be assumed to be similar to that of the historical record, although with the caveats mentioned above, it is necessary to model the behavior of electrical vehicles' energy consumption without recuring to historical values. As it stands, research on electrical vehicle charging behavior models is still quite limited, in particular when it comes to wider studies, with most analysis being made on a small scale, usually limited to single stations and subject to their own geographical characteristics (namely whether such a station is in a residential or commercial area.

However, a simple model can allow for some variation to be accounted for.

Hourly variation across the day of the EV recharging profile has certainly been the most discussed aspect of this topic. A myriad of studies can be found proposing both the impact of this new sector and strategies to avoid the disruption that it could provoke. Namely, the RMSA report considers two recharging strategies, direct recharging, where this recharging is done whenever necessary, in accordance with studies made about the behavior of EV users, and valley recharging, in which periods of surplus power are privileged over those without them. This mostly means not charging EVs during the peak of demand, in the late hours of the afternoon, and charging it instead during the night.

The RMSA further proposes that, rather than consider any of those two strategies to be employed by itself, to instead consider two scenarios, with different weights for each strategy, specifically one where 20% of vehicles employ a direct recharging strategy and 80% a valley recharging one, and another where the weights are 60% for direct recharging and 40% to valley recharging. Each of those scenarios gives a normalized load as displayed in Figure 15.

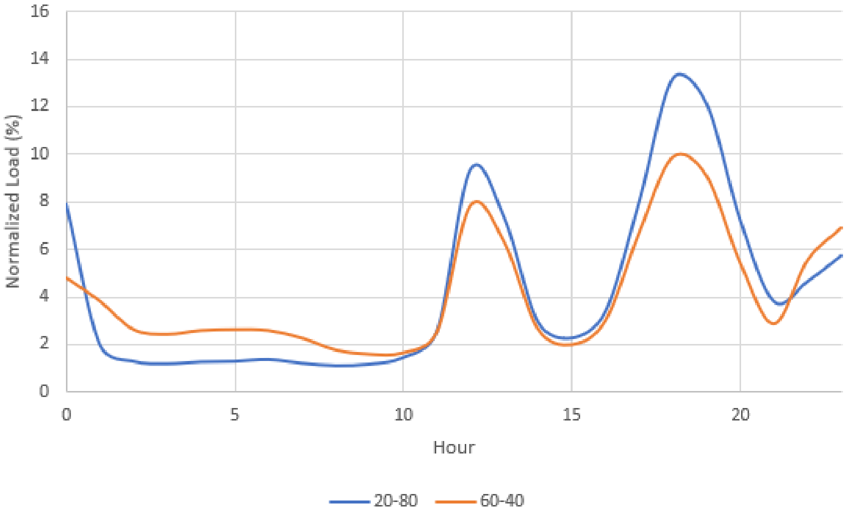


Figure 15 Normalized Load (in percentage) for EV recharging by Hour for each Strategy Mix

These strategies were employed in this model. However, after testing with both of the scenarios employed above, and with some other, more extreme scenarios, it soon became clear that the impact that these different strategies have on the system is quite negligible. This is mainly due to two reasons. For starters, the size of the EV fleet on the whole electrical load is still small, accounting for roughly 10% of the total. And ultimately, the two recharging profiles, or most other combinations of the two scenarios for that matter, are not dissimilar enough for, at that volume of electrical consumption, to make much of a difference.

In fact, if anything, the load proposed by the RMSA report for valley recharging, that is supposed to alleviate load stress, seems to do more harm than good, from the tests that have been run using the model. Nevertheless, the impact is quite too small to be significant.

Another load variation whose impact could be significant, but that receives much less attention or focus than the hourly one, regards monthly variation of the EV recharging profile. Although few studies have been conducted studying this variation, it can perhaps be assumed that month-to-month variation of EV energy consumption should not differ significantly from that encountered in conventional vehicles, and that the monthly profiles for electricity for the EV fleet should not differ considerably from the monthly profiles for road fuels (normalized, of course). In fact, it raises the question whether differences between those two profiles reflect technical, and therefore likely more lasting, differences between the vehicles, or rather socioeconomic differences between its users, which would likely be erased as an expansion of the EV fleet brings a wider, and therefore more mainstream, part of society to the fold.

Ultimately, the load profile displayed on Figure 16 was used, created using a normalized monthly profile of the consumption of road fuels adapted from values for the years 2018 and 2019, to avoid contamination from 2020, due to the lockdown measures having a striking impact in the profile [34].

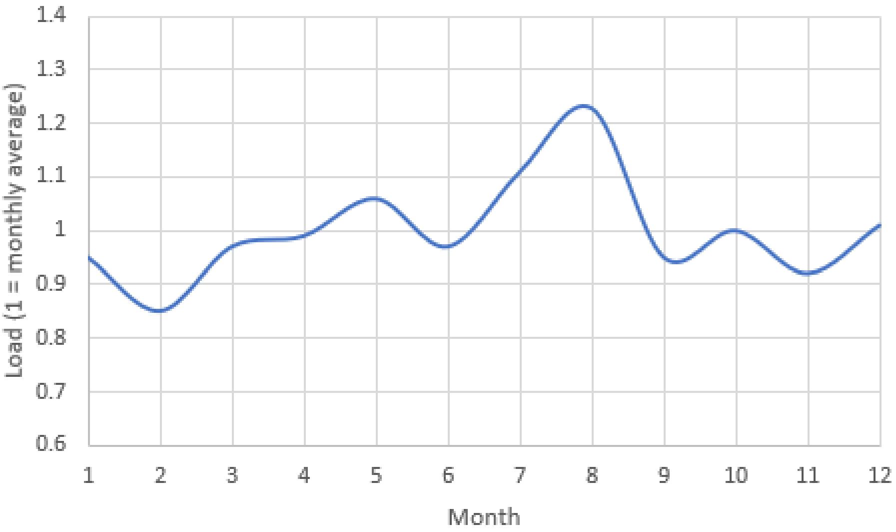


Figure 16 Monthly Load considered for the EV fleet

Through combining both hourly and monthly variation, it allows for an array of values that are spread unevenly across time, which gives a greater proximity to reality. Of course, that the absence of variation across the days of the month means there is quite a lot of repetition, however, in that regard, the most that could be done would be to differentiate weekdays from weekends, although even then, finding good data would be difficult and, ultimately, have very little impact.

In fact, this whole exercise has been characterized by having very little impact for the load, especially when one accounts for the complexities required to achieve this. Although certainly the increase of the EV fleet has an important impact on the electrical sector, by 2035 and 2040, one shouldn't expect that impact to be so great as to give much of an influence on matters such as recharging strategies.

With both arrays, for general consumption and EV consumption, calculated, it is a simple matter of adding them to have a single array with hour-to-hour electricity consumption, in MWh, predicted for a given year and based partially on the historical data of one of the years between 2015 and 2022. This can be repeated using different historical years, different years to be modeled and different scenarios. In fact, there are a number of different aspects that can be tweaked significantly to achieve different results.

There are, however, some important results that do not differ greatly between each scenario. For example, the hourly and monthly distributions of electricity consumption obey to a general pattern that can be observed in the graphs of Figure 17.

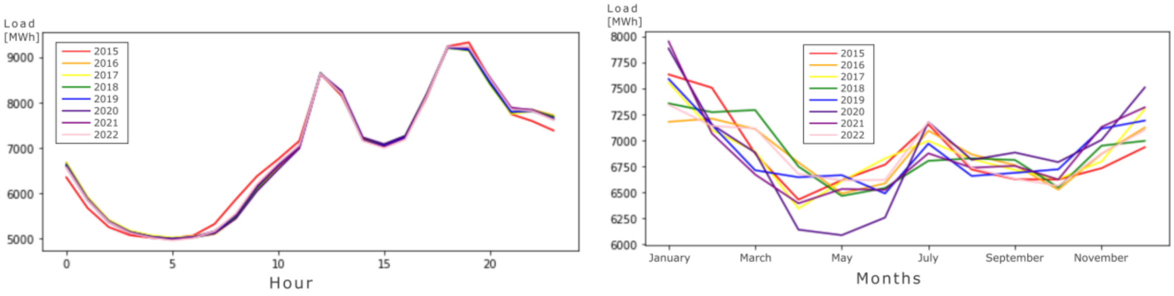


Figure 17 Hourly and Monthly Energy Consumption. Conservative Scenario, 2035

The graphs are specifically from the Conservative Scenario for 2035. However, since the distribution of energy consumption comes from historical data, the curves remain identical in shape for the other scenarios, suffering only the overall consumption value depending on the yearly energy consumption.

From the hourly graph, we can see that there are two peaks of power consumption, one around 12 and the other at around 18 to 20. Those are the ones we encounter presently, and there is very little reason to believe they will change, since they correspond to meal times, when energy is needed for cooking. The hours of valley consumption, during the early morning, are also sensible, considering it is the time most people spend sleeping. No major changes to any of these is expected.

On the monthly graph, there are two main things to note. The first is an odd deviation, for the months between April and June of 2020. This is due to the lockdown procedures happening due to the covid-19 pandemic, that led to a significant economic shut-down. Although this creates an outlier, but it is nevertheless interesting at the very least to see the impact that such pandemic events, other economic crisis, or even shifts to work from home, could create in a future scenario. Notably, even then the monthly consumption difference is only around 10%.

The other notable characteristic of the consumption curve is its W shape, with peaks during winter and summer months. This is due, in great part, due to the need of heating and cooling. With both the increase of electrical heating and cooling systems in residences, and the greater need for them due to the impact of climate change, it could be considered whether their impact won't be even greater in the future. This, however, was not implemented for this model.

A monotone curve of the consumption of electricity by hour across the year, for the various years, also helps to better understand the challenges ahead. The explanation for how this curve is obtained and its meaning is provided in the chapter on Methodology and Materials, in section 2.3.

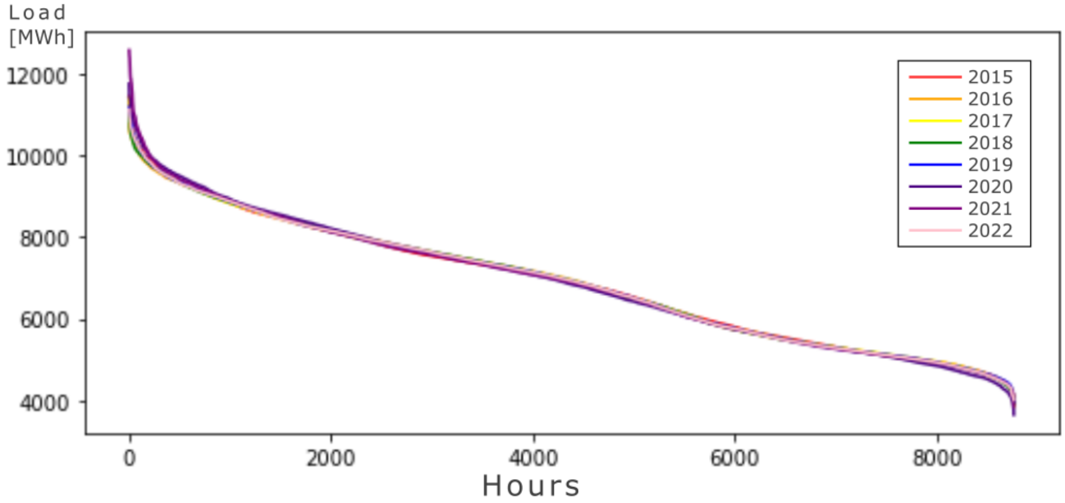


Figure 18 Load Monotone Curve for Consumption. Conservative Scenario, 2035

The graph in Figure 18 is again from the Conservative Scenario for 2035. Nevertheless, its curve is identical to that of the other monotones for consumption, for the same reason as explained before. From the graph, we can see that consumption by hour rarely dips below 4000 MWh, and also, at most, goes above 12 thousand MWh. In the Ambition Scenario, this upper value goes above 14 thousand MWh, and as a minimum, goes slightly above 4000 MWh. This helps us have an idea of the sort of fluctuations that can be expected for demand, that is always within this range of values. It is also notable, in the graph, just how similar the load monotone curves are for the different years, implying some constancy.

3.2 NON-DISPATCHABLE RENEWABLE ENERGY PRODUCTION

Energy production for the years 2035 and 2040 is obtained through the use of historical data to extrapolate between the years from 2015 to 2022 and those being modelled. The way in which this is accomplished is explained in the flowchart of Figure 19.

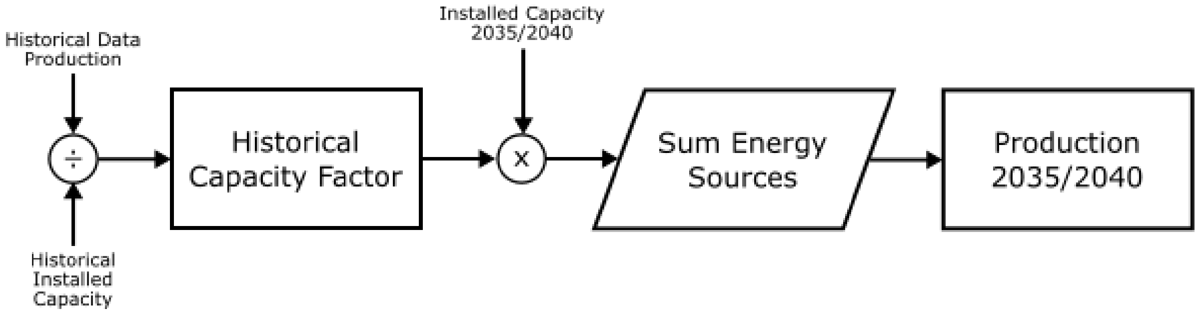


Figure 19 Flowchart for Non-Dispatchable Energy Production Model

The historical data for this electricity production divides it among the sources. Of particular interest to this model are wind, solar, run-of-river hydroelectric and biomass energy sources. Although biomass is not exactly non-dispatchable, the economics of its use, given the need for sustainability and ephemeral nature of its fuel, and its limited size, makes it simpler and not particularly problematic to include it in this section.

These renewable energy sources have seen the largest growth in past years, in particular during the historical years which are used for data and are expected to keep growing in installed capacity at an ever-greater pace up to 2040. This is particularly true for wind and solar power, which are the main recipients of investment dealing with decarbonization.

Because of this, it is very important to account for the change in installed capacity when modelling energy production. To accomplish this, the first step in this model goes through dividing the array of historical values of energy production by source for each hour, with an array of installed capacity by each source. Although this array of installed capacity is also divided by hour, to facilitate the division, in reality these values are only obtained for each year, providing a less detailed, but still useful approximation.

Through dividing these two arrays, one obtains an array that gives, for each hour of a year, the capacity factor of a given energy source. This already has the benefit of being normalized. Therefore, it is afterwards only necessary to multiply this value with that of the installed capacity for the year and scenario being run.

This gives us an array with the energy production, hour by hour, for the various non-dispatchable renewable energy sources being considered. From there, it is only necessary to sum those various arrays to obtain for a final result the non-dispatchable renewable energy production, hour-by-hour, for each of the historical years being considered and adapted to 2035 and 2040.

Once again, from the hourly and monthly distributions of the production of non-dispatchable renewable power, some patterns can be observed, as demonstrated by the graphs of Figure 20.

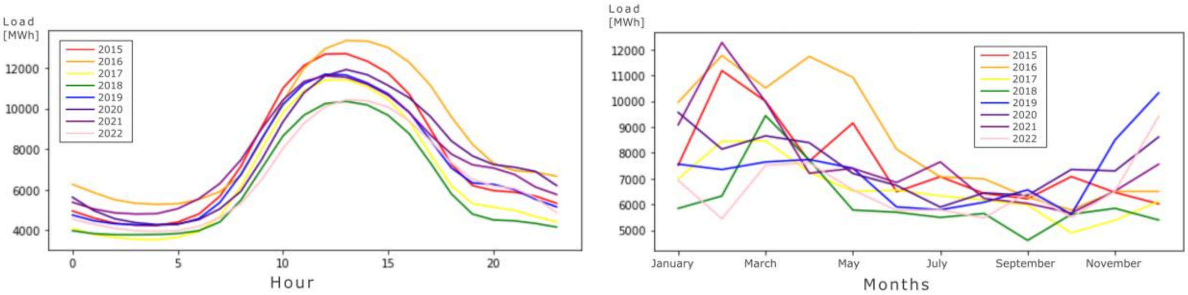


Figure 20 Hourly and Monthly Non-Dispatchable Renewable Energy Production. Conservative Scenario, 2035

Once again, the graphs from the Conservative Scenario for 2035 are used. Although those curves are not identical to the ones from either the Ambition Scenario or for 2040, due to changes in the mix of installed capacities between different scenarios, the difference is barely visible on the graphs, due to the overall similarity of the conditions that can be predicted reasonably.

An interesting note across the graphs, however, is how, on the hourly values, the impact of solar power, that reaches its peak during the most sunny hours in the middle of the day, is most felt, while in the monthly values, it is the impact of wind and hydropower, strengthened during the winter months, that gives the graph its peak, while the summer, despite greater solar energy production, is a valley. And quite a significant valley, it must be noted, with some months having barely half the energy production of others.

3.3 NON-DISPATCHABLE RENEWABLE ENERGY BALANCE

The array for the excesses and deficits obtained from using non-dispatchable renewable energy sources alone is quite easy to accomplish. It is essentially only subtracting that energy production from the electricity consumption for each hour of the year.

The results are, however, quite interesting, and deserved to be discussed more profoundly. With these renewable energy sources, especially solar and wind power, facing the largest growth and investment for the coming years, understanding their impact on the energy balance is quite important.

Firstly, the way these renewable energy sources impact the electricity balance across the day and across the year can be studied through observing the graphs for hourly and monthly distribution of the energy balanced, as displayed in the graphs of Figure 21.

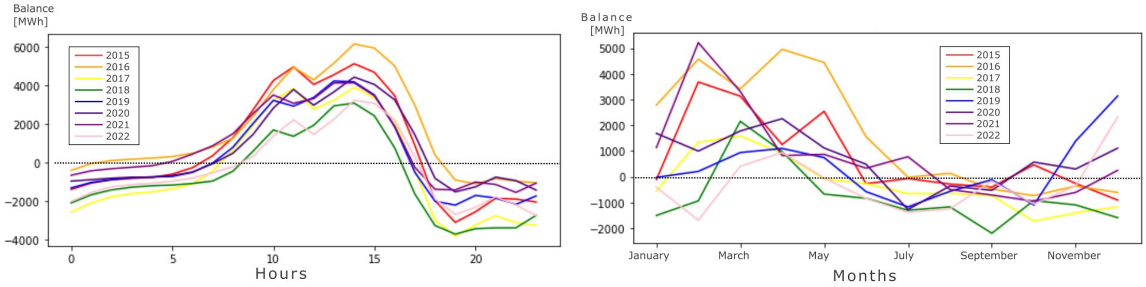


Figure 21 Hourly and Monthly Non-Dispatchable Renewable Energy Balance. Conservative Scenario, 2035

From the graphs presented above, some interesting things can be noted. Namely, that the hourly energy balance is particularly negative during night hours, even though most of those are, in terms of consumption, very much a valley. Nevertheless, the lack of solar production during the night ultimately means that there is an energy deficit during this period that cannot easily be overcome. Considering this, the valley recharging strategies for the EV fleet, considered above, do not make sense whatsoever, and are in fact detrimental to the grid. If anything, the EV fleet should be getting charged during the day, when the energy surpluses are in peak value.

As for the monotone curves, those are quite interesting to study, not just for the overall energy balance, but for the one that can be achieved using only solar power (the most invested-upon of the energy technologies), the combination of solar and wind power, and the four non-dispatchable sources. Combining those three monotone curves with that of the consumption, the graph of Figure 22 is achieved.

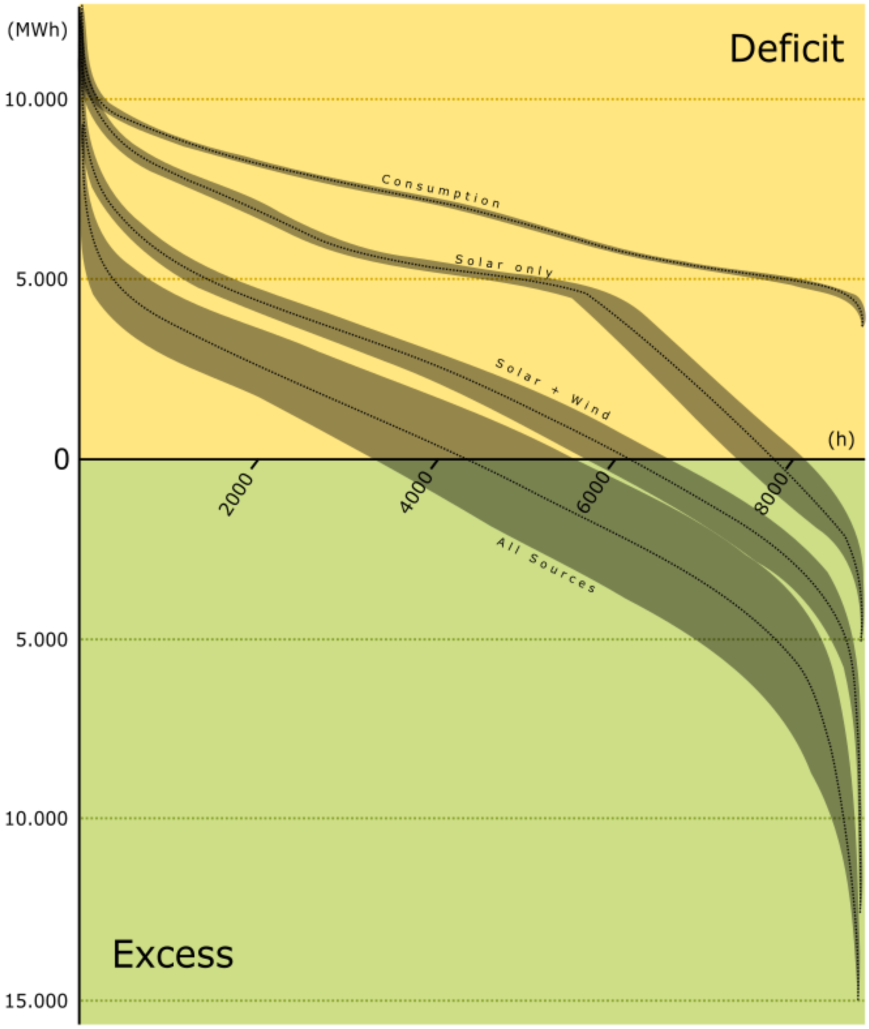


Figure 22 Load Monotone Curves for Consumption and Various Renewable Energy Balances. Conservative Scenario, 2035

From the curves, we can see the impact that the various renewable source combinations have on the balance of power throughout the year. It can be observed that solar only meaningfully impacts less than half of the hours of the day, which is to be expected, while leaving night hours still with rather high deficits. And although wind power and the other non-dispatchable sources help create a more balanced curve, two issues can be noticed right away. The first is that, even with all renewable sources, only around half of the hours each year are actually left without deficits, some of them quite significative as well. And the second issue is that, for those hours without electricity deficits, they face excesses instead, which can also be problematic. Non-dispatchable sources don’t really allow for hourly balances.

From the monotone curves in particular, the main issue with attempting to solve the energy crisis through mainly investing in non-dispatchable renewable energy sources is laid bare – they greatly increase the gulf between the values of excess energy and deficit for each hour. Attempting to solve this issue simply by investing in greater installed capacity for these sources would have little impact by itself, and only continue to increase the surplus of energy during excess hours, while barely impacting its deficit.

3.4 BALANCE WITH HYDROPOWER

Hydropower dams have the ability to retain water in their reservoirs and, through that, to store potential energy to be later transformed to electricity, rather than release it immediately to the system, as the non-dispatchable sources. Furthermore, by using pumping systems, water can even be brought up to the reservoirs, with surplus electricity being used to create potential energy that can be later, with a given efficiency loss, of course, be redeployed as electricity. This means that, rather than to have to release energy as it is captured, the dam can instead release electricity when it is needed, withhold it when it is not, and even transform surplus power into potential energy for later use.

From a control perspective, such a system could allow for a very good solution, essentially serving to mutually cancel the excesses and deficits and flattening out the balance curve to perfect zeroes throughout. However, that is only true from an abstract perspective. In reality, constraints such as the need to keep water management sustainable and avoiding too much machine wear to the dam systems means that the system works best by choosing a regular water flow, that is respected as long as it does not interfere with the reservoir limits or with the energy balance.

How this is achieved is displayed in the flowchart of Figure 23.

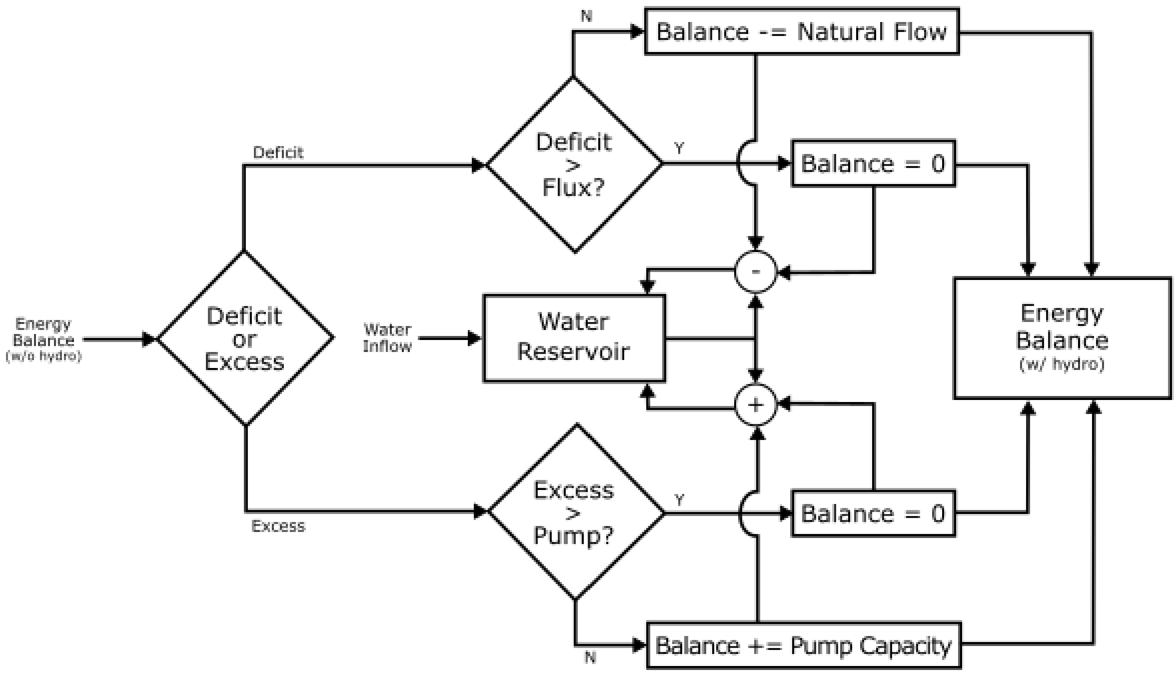


Figure 23 Flowchart for Energy Balance with Hydropower

Since hydropower allows for a more flexible dispatching of electricity, using the historical data of hydroelectric production is not particularly useful. Instead, by using historical data for the affluence of energy to the reservoirs, one can still have some variance between the years. These data were obtained from REN Data Hub, and give the affluence of energy, in the form of potential energy from accumulated water to the reservoirs. The data that REN provided, however, were on a daily basis, rather than hourly. This forces us to use a less exact approximation, but it is still sufficient. Instead of having an hourly inflow, it is instead considered that each day, at midnight, all the daily inflow arrives at once.

Another limitation to consider in regards to the historical data for water affluence is just how much does the historical hydrological behavior resemble that of the future, even only a few decades forward. Drought in the Iberian Peninsula has already compromised some of the years in the historical record in regards to hydroelectric production, and with the ongoing threats of desertification, it is not an undue question whether such drought conditions won’t become the general behavior of the system, in which case relying on the historical data could present an overly-optimistic picture of the future. Despite these considerations, the historical data was used.

The reservoir itself has constrictions that must be respected. Namely, there is a maximum amount of energy that can be stored. This is quite sensible, after all, there is a physical limit of water that can be stored in the reservoir. For the years considered, this value is around 3080 MWh of potential energy. Then, there is the minimum amount of energy that can be stored. Obviously, zero would be a strong physical limit to this value, but strategic and ecological considerations impose a legal limit for this value that is much above that. In the model, this was considered to be at 1000 MW.

From the state of the energy balance obtained from non-dispatchable renewable sources, a decision must be made. If the balance is at a deficit, then hydropower can be released to the electricity system. If the value of the deficit is under that of the regular water flow, then the system should only release enough energy to cover the deficit. If the deficit is greater than that water flow, then the regular water flow should be dispatched, with the deficit only being partially covered. If the balance is at excess, then rather than release energy, the system should take the opportunity to pump water, therefore storing some of the excess energy. There is a maximum pumping flow, whose considerations are more around sustainability rather than technical capacity, that must be considered in determining how much of the excess power can truly be covered through this process.

Through all of this, the reservoir conditions cannot be forgotten. If the request energy release would put the reservoir below the minimum limit established, then it should not be fulfilled. And if pumping water into the reservoir would put it above its maximum capacity, then this pumping shouldn't happen either.

This way, a simple and verisimilar model for hydropower can be designed. A reflection to take from this is that, despite hydropower dams with reservoirs being often called "natural batteries", due to the limitations imposed on them by mechanical and ecological necessities, it is much more adequate to think of them as energy stabilizers – they allow for the energy flow of water, rather than be taken as it reaches the dam, be used more regularly, at a steadier flow. This is, of course, already helpful, especially if the strategy followed in this model, that allows for the flow to be diminished or curtailed to avoid energy excesses, is followed. But it also shouldn't be thought as a save-all, as the following graphs will demonstrate.

Starting with the graphs for the new energy balance on a hourly and monthly basis, it can be seen in Figure 24 how the inclusion of the hydropower dam system impacts the balance of energy.

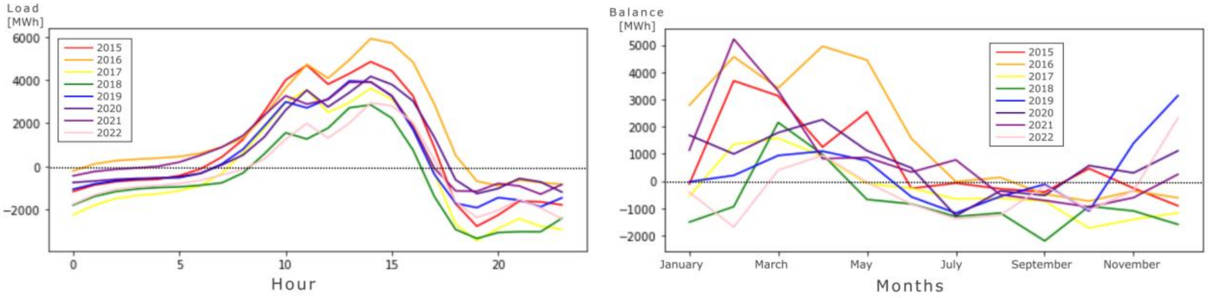


Figure 24 Hourly and Monthly Balance of Energy with Non-Dispatchable Renewable Energy and Hydropower Production. Conservative Scenario, 2035

As could be expected, considering that hydropower works as a sort of stabilizer for energy, the curves only change slightly from previous graphics, with less pronounced deficits, especially noticeable on the hourly graph. An improvement, but not a ground-breaking one in the slightest.

The monotone also allows us to see how the system has evolved with the addition of the hydropower module, which has a significant impact on the very shape of the curve.

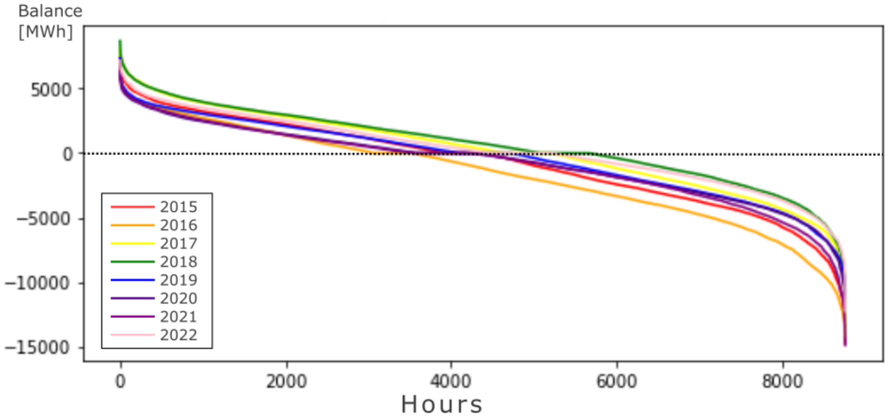


Figure 25 Load Monotone Curve for Balance of Energy including Hydropower. Conservative Scenario, 2035

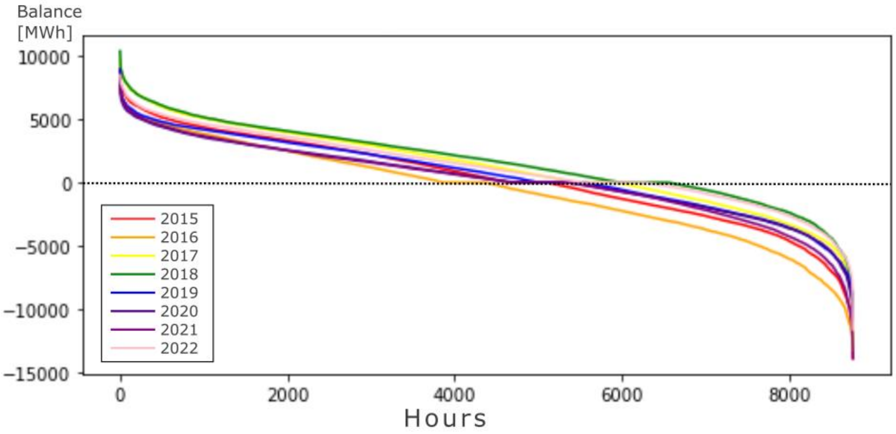


Figure 26 Load Monotone Curve for Balance of Energy including Hydropower. Ambition Scenario, 2035

From the monotone curves for each scenario, displayed in Figures 25 and 26, similarities and differences can be observed. First of all, a clear difference between these monotone curves and previous ones can be noted, with both curves possessing, in the middle, a straight line across 0 MWh. This line represents the hours at which, through the use of either the release of water to match the energy deficit, or the pumping of excess energy, the electric grid is perfectly balanced. It can be also noted that, for the Conservative Scenario, this line generally goes from the 3000th to the 5000th hour of the monotone, while for the Ambition Scenario, it generally goes from the 4000th to the 6000th. This is already a significant difference, but most notably is that, whatever the case, thousands of hours, for whatever year, for whatever scenario, are left with energy deficits, for which a solution must still be found.

From these graphs, the impact of the hydropower model on the whole system can be observed. It is significant, but not quite all-encompassing. This limitation can also be understood if one puts into perspective the amount of energy inflow, in the form of water, to the reservoirs, on an yearly basis, and compares it to the energy consumption that is expected for the years being modeled, as shown in Table 2.

	Water Inflow [GWh]	**Consumption**			
		2035 Conservative [60621 GWh]	**2035 Ambition** [71087 GWh]	**2040 Conservative** [62843 GWh]	**2040 Ambition** [75608 GWh]
2015	2224	3.7%	3.1%	3.5%	2.9%
2016	5845	9.7%	8.2%	9.3%	7.7%
2017	2108	3.5%	3.0%	3.4%	2.8%
2018	5163	8.6%	7.3%	8.2%	6.8%
2019	4527	7.5%	6.4%	7.2%	6.0%
2020	4214	7.0%	5.9%	6.7%	5.6%
2021	4184	6.9%	5.9%	6.7%	5.5%
2022	3741	6.2%	5.3%	6.0%	4.9%

Table 2 Table for the Water Inflow compared to Energy Consumption

From the table, it becomes clear that hydropower composes a substantial, but certainly limited, part of the energy system. Even with pumping, it can’t be expected to cover the entire needs of the grid and unlike other renewable sources, it can’t be expected for its installed capacity to increase enough to change that. Water resources are limited, are volatile, as comparisons from year to year demonstrate, and are also in risk of diminishing due to climate changes making the Iberian environment drier [35]. All of that means that caution must be exerted when considering hydropower as an important pillar of the future energy system in Portugal.

3.5 BALANCE WITH NON-RENEWABLE THERMAL POWER

Traditionally, thermal power plants, using coal, oil or natural gas as a fuel, were dominant sources of electricity production, competing only with hydropower. Even nowadays (2023), natural gas is the single greatest source for electricity generation in Portugal. However, due to concerns for the impact of greenhouse gas emissions, its non-renewable nature and geopolitical concerns, energy policy in Portugal, as in much of Europe, has focused on decarbonization, meaning a shift from those energy sources into renewable and non-greenhouse gas emitting ones. Due to this, all models for the future years must account for a decrease, and possibly an eventual disappearance, of those thermal power plants.

For the scenarios laid out in the RMSA report, and whose cues were followed in this work, the installed capacity for non-renewable power plants in 2035 and 2040 were 2312 GW and 1784 GW, in the conservative scenario, and 2180 GW and 1520 GW, in the ambition scenario. Ultimately, these values are the main limitation for this system. Thermal power plants are incredibly flexible and their energy very dispatchable. They can be turned on and off and run at the needs of the grid. This is the main advantage of thermal power, that it can operate with so much flexibility and cover the various deficits that may occur without causing excesses.

This also means that the model for this input is also quite easy to achieve, with no historical data being needed. Rather, it is only the matter of subtracting from the deficits in the existing balance up to as much as the installed capacity from thermal power plants, while leaving the excesses untouched.

The impact that the thermal power plants have on the grid as a whole can be observed through the graphs in Figure 27, first depicting the hourly and monthly loads of the new balance of power.

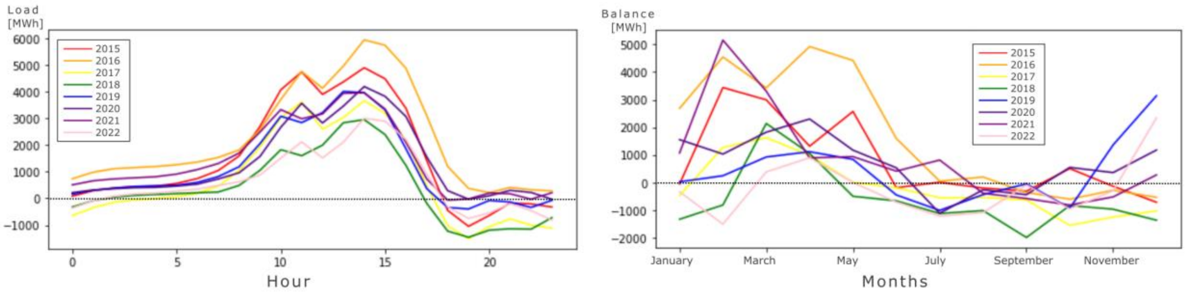


Figure 27 Hourly and Monthly Balance of Energy including Non-Renewable Sources. Conservative Scenario, 2035

It is noteworthy that, even at this point, there are hours of the day, and certain months across the years, where the ultimate balance of power is still negative, meaning that the total deficits of energy exceed the surpluses across the year.

As for the monotone, it shows the final line that is achieved through the model for the years of 2035 and 2040, as currently planned. The contribution of the thermal plants, and their limitations, are quite visible through its study.

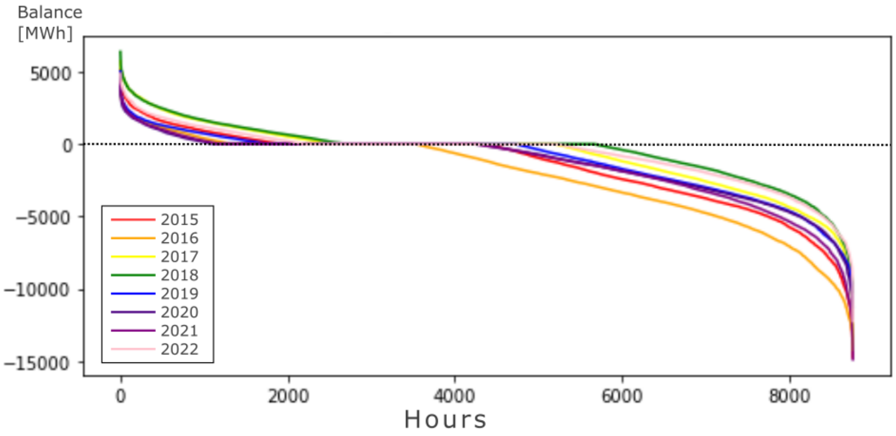


Figure 28 Load Monotone Curve for Balance of Energy including non-renewable sources. Conservative Scenario, 2035

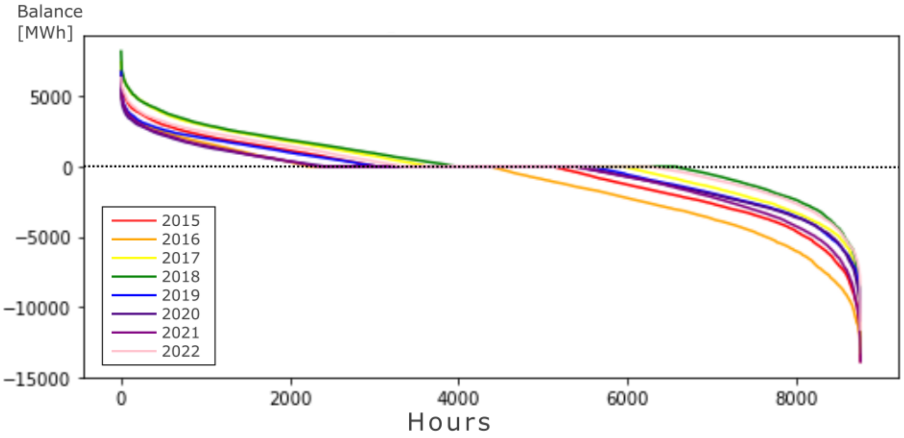


Figure 29 Load Monotone Curve for Balance of Energy including non-renewable sources. Ambition Scenario, 2035

In the graphs of Figures 28 and 29, the straight line across the curve has been expanded significantly, as thermal power plants allow to do balance the electric grid for smaller deficits, or at least alleviate its imbalance for larger deficits, allowing for a flattening of the curve. Nevertheless, it is also noteworthy that, despite this, there are consistently at least one thousand hours where the deficit is too large to overcome, even with the support of all existing energy sources. It is a considerable improvement, but not, at the installed capacity that is planned for, not capable of solving all problems.

It is also important, when studying this system, to acknowledge the greenhouse gas emissions that are provoked through the use of these plants. For that, the emissions of GHG for each of the modeled years in each scenario are displayed in the graph on Figure 30.

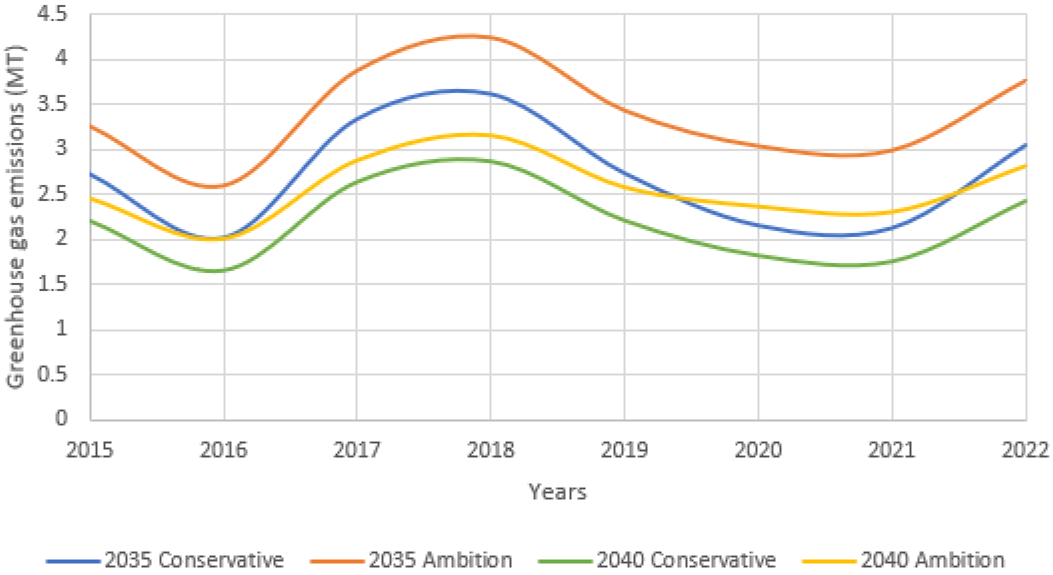


Figure 30 Greenhouse gas emissions by Model Year for various Scenarios

The information from the graph can be put into perspective with the emissions caused by the use of those sources in the actual years in the historical record.

	2015	2016	2017	2018	2019	2020	2021	2022
Emissions (MT)	18.604	15.773	20.169	17.168	14.852	12.292	10.837	11.789

Table 3 GHG Emissions by Historical Year

Comparing the graph of Figure 30 to Table 3, it is noticeable that, between the historical values of greenhouse gas emissions and those predicted by the model, there is quite an improvement, with both values diminishing considerably. This is to be expected, after all, the installed capacity is quite inferior in the predicted models. But it must be taken into account that the historical years functioned at power balance, while the current model clearly leaves out many ours in deficit which, to be easily resolved, would probably mean a significant increase in non-renewable energy production and corresponding greenhouse gas emissions.

Through this, we can better consider the important contribution that the thermal power plants give to the grid system, and what impact it has in the ambitions for a fuller decarbonization. Increasing, or rather, maintaining the installed capacity of these energy sources would certainly be the easiest way of solving the energy security problems presented by this model, even if that still means abdicating much of the security and decarbonization that is being accomplished.

3.6 FULL-SYSTEM ANALYSIS

Ultimately, the model is able to give an answer to the question for which it was created: will the Portuguese grid have energy security by 2035 or 2040? By all accounts, for every historical year used as a model and for every scenario tested, the answer is negative, and by quite a lot. For each year, thousands of hours would be left without a proper way of fulfilling the expected demand using only resources available at a national scale.

Moreso, the model is also capable of predicting that the decarbonization efforts and predictions that are currently in place are unable to be fulfilled under such regimen. Although there is quite an improvement in reducing greenhouse gas emissions and the dependence on fossil fuels, this improvement has more to do with not having the ability to provide electricity year-round than anything else, making it somewhat of an hollow accomplishment. And even then, the amount of greenhouse gas emissions that would be created under this still faulty system are still quite higher than those currently predicted, as can be clearly seen comparing the results of section 3.5. to those presented in the graphs of Figure 31.

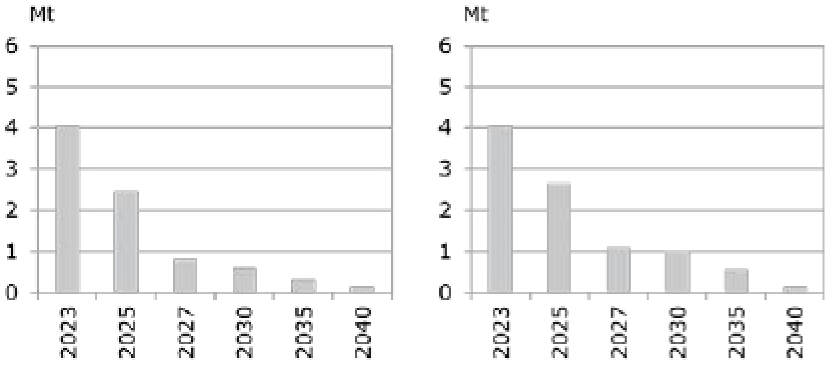


Figure 31 CO2 emissions, for an average hydrological regimen, on a conservative and ambitious scenario respectively [RMSA]

A good deal of this difference can be explained by our model lacking the connections to the Spanish grid. Even so, that only further illustrates how much of the decarbonization program in Portugal relies on the Spanish program working well enough not only to supply Spain, but also Portugal.

The end result of this model, therefore, serves to justify the goal of the following parts of this project, that of testing how adding other sources of energy input and energy carrying could improve this future problem, and make the Portuguese grid more secure and more self-reliable than it is currently planned to be.

CHAPTER 4. ADDING A NUCLEAR BASELOAD

On the next part of the project, the nuclear component is added. In the current plans for the energy system in Portugal for 2035 and 2040, no addition of nuclear power is being contemplated. The goal of this portion of the project is to study what sort of impact that component, should it be implemented, would have, using our model to predict those results.

As such, this simulation is achieved by adding to the already-built model a new module for nuclear power. This module is inserted between the non-dispatchable renewable energy balance and hydropower, as displayed in the flowchart in Figure 32.

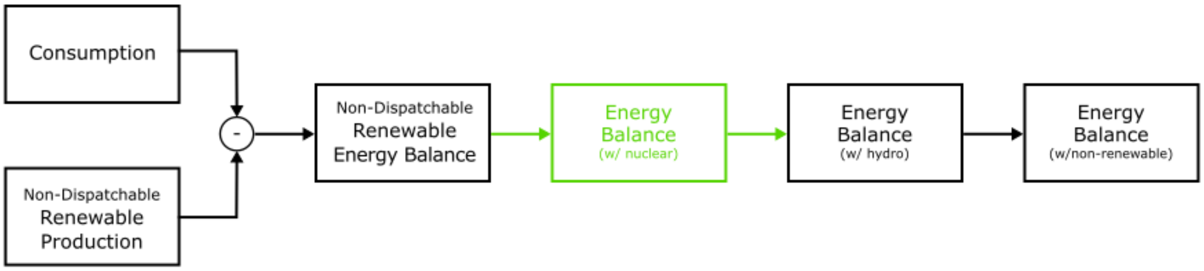


Figure 32 Flowchart of Energy System including Nuclear Component

This allows for the hydrological strategy to take into account the impact that adding nuclear power has to the balance of energy. This is because, ultimately, nuclear power is also a non-dispatchable energy source, although while the non-dispatchable renewable energy sources that have been used are intermittent, that is, their production is irregular throughout time, the opposite is true for nuclear power, whose production is constant in time, with the power plants producing a stable energy flow at all points in time. It is also non-dispatchable in that it is not easy or practical to turn off the plant when there is excess electricity in the grid or to reduce its power production when it would be useful for energy balance.

Nevertheless, it should be noted that this inflexibility of nuclear power is, nowadays, somewhat exaggerated. Nuclear power can reduce its power production if necessary to accommodate grid balance needs and, with an improvement on nuclear flexibility research and technology, this ability should be expected to improve with time.

Despite this consideration, for purposes of this model, nuclear power was considered to operate as an inflexible baseload provider. A reason for this is that, ultimately, nuclear flexibility operations function by diminishing energy production from a power plant without decreasing the costs of its production, thereby making nuclear power more expensive. This creates the risk of making flexibility operations, although technically possible, economically unsound. This is a constraint that must be taken into account and, similarly to other constraints for the model, can be expressed through assuming greater inflexibility.

This means that, ultimately, the model is remarkably simple. It merely takes the hourly values of the energy balance from the non-dispatchable renewable energy sources for each years, and adds to it the nuclear baseload being tested, indiscriminately. The results are also quite easy to understand, as seen in the graphs of Figures 33 and 34, comparing them side by side: it results in a vertical translation of the curve by precisely the same value as the nuclear baseload.

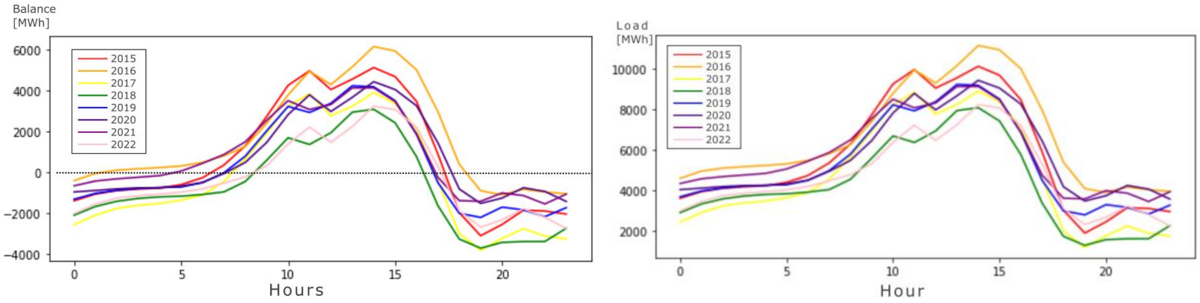


Figure 33 Hourly Balance of Energy including Non-Dispatchable Renewable Sources, and a Nuclear Baseload of 5 GW [Right]. Conservative Scenario, 2035

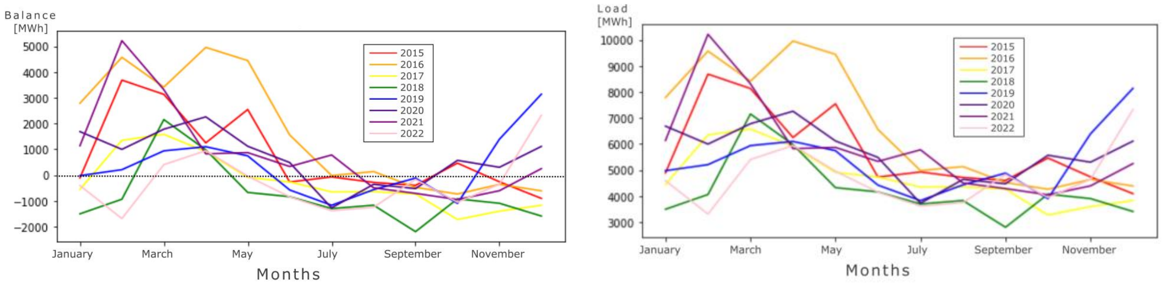


Figure 34 Monthly Balance of Energy including Non-Dispatchable Renewable Sources, and a Nuclear Baseload of 5 GW [Right]. Conservative Scenario, 2035

Comparing the monotones between the balance with only non-dispatchable renewable energy sources, and then with also nuclear power, is also useful to get an impression of the impact that a nuclear baseload could have for the energy strategy in Portugal, as displayed in the graphs of Figure 35.

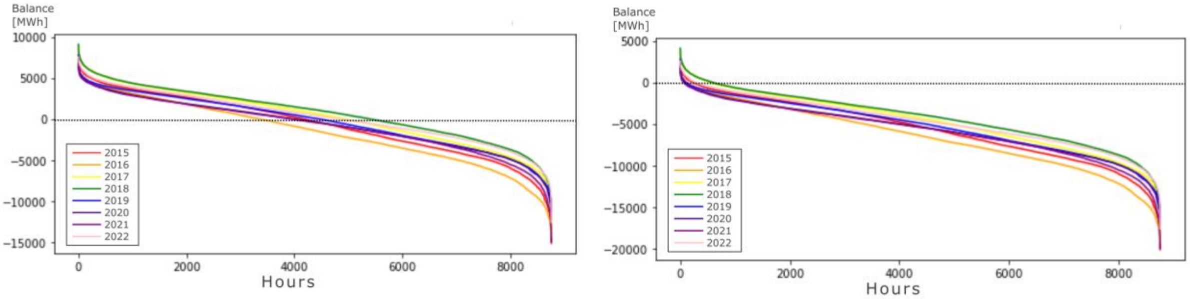


Figure 35 Load Monotone including Non-Dispatchable Renewable Sources, and a Nuclear Baseload of 5 GW [Right]. Conservative Scenario, 2035

From the monotones, it can be seen that the nuclear baseload is quite good at decreasing the number and severity of the deficits. But it also increases the number and severity of the excesses of energy, which can be counter-productive, especially to its economics, as excess electrical power can have, in the market, negative values. Excess energy is a matter of concern in these scenarios, one that must be taken into account when discussing feasibility.

When one includes the hydropower and non-renewable thermal components of the system, we are no longer dealing with a vertical translation, however, as the graphs of Figure 35 demonstrate.

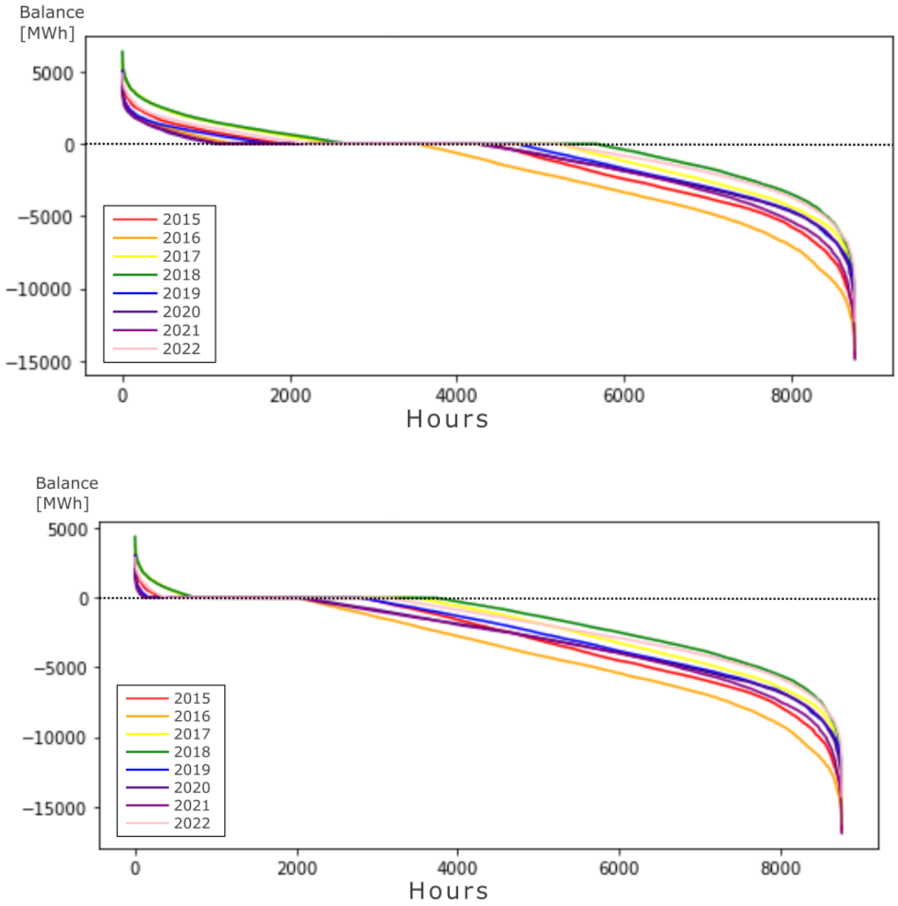


Figure 36 Load Monotones without Nuclear Baseload (Above) and with a 2 GW Nuclear Baseload (Below). Conservative Scenario, 2035

Some differences are notable. Firstly, the number of deficit hours has decreased dramatically, going from averaging almost 2000 a year to an average of little more than 300 deficit hours per year, with some years having as few as only 13 deficit hours. And, obviously, the break in the monotone curve, corresponding with the hours that are perfectly balance at zero, through the contributions of hydropower and thermal power, is pushed to the left. There are also many more hours with excess power, with the severity of many of those excesses having also increased.

A more thorough analysis of the impact that the nuclear baseload has on the load monotone curves, and on the system, in particular in solving the problems of energy security and helping towards decarbonization, is given on section 4.2. But before anything, it is important to consider the matter of costs for implementing such projects.

4.1 ON NUCLEAR POWER ECONOMICS

Nuclear power is often criticized as not being economically viable when compared to renewable energy sources, and this has a lot to do with a LCOE that often rises slightly above that of renewable sources [36]. LCOE is not the best marker to compare intermittent and dispatchable energy sources [37], however and, if the added costs of intermittency are considered, then the full costs of energy (FCOE) are much more promising for nuclear, as is the energy return on investment (EROI) [38].

Considering returns on investment is particularly important since, ultimately, it is the need for a great upfront investment that often makes countries reluctant to attempt an ambitious nuclear program. Therefore, it becomes necessary, when presenting plans for adding nuclear baseloads, to present an estimate of what sort of investment would be needed to build the power plant capable of accomplishing it.

Estimating the current building costs of a nuclear power plant is a complicated endeavor. According to the World Nuclear Association, there aren't enough data points to give a very confident answer, especially as most nuclear power plants in North America and Western Europe have been built decades ago [39]. Basing our estimates on the economics of decades-old projects is not particularly useful. A full generation of nuclear reactors has risen since then, and regulations and markets have changed significantly. Another difficulty towards finding out the actual costs of such a project is investor secrecy, that keeps much of the necessary information out of our reach.

Despite all this, from the nuclear power plants built recently, and from research being carried out by countries seeking to build or increase their nuclear fleets, some results can be reached. In particular, as Poland prepares to build a nuclear fleet, a good deal of useful research has been made, to advise and comment this policy and its costs, by both the government and members of civil society.

In an edition of the Pulaski Policy Papers, a series of publications focusing on Polish political issues, published by the Casimir Pulaski Foundation [40], several recent nuclear plant construction projects from around the world were aggregated and analyzed, to reach a conclusion on the breadth of costs and construction time for such projects by reactor type. Those results are expressed in Table 5.

Reactor type	Total installed power [$MW_{el,net}$]	Unit	Planned costs		Actual costs	
			Minimum	Maximum	Minimum	Maximum
AP1000	7020	[M USD/$MW_{el,net}$]	2.52	6.40	3.15	11.64*
		[B USD]	17.69	44.93	22.11	81.71
APR1400	8508	[M USD/$MW_{el,net}$]	1.73	4.54	2.28	4.54*
		[B USD]	14.72	38.63	19.40	38.63
EPR	9900	[M USD/$MW_{el,net}$]	2.21	9.39	2.74	9.60*
		[B USD]	21.88	92.96	27.13	95.04

Table 4 Installed Power and Costs for Different Nuclear Reactor Types [33]

As can be seen, there is a great deal of variation between minimum and maximum costs, and also between planned costs and actual costs of a project. In fact, the report states clearly that all projects run behind initial construction schedules and almost all go above the initial budget, as vendors underestimate the costs and timetables of their projects.

A more detailed look at the results from the project points to different regions suffering differently from those issues, with North America and Europe having particularly large increases in budgets, and generally paying more towards the upper end for construction of nuclear power, while China and South Korea in particular have their costs mostly towards the lower end. The reasoning for this, and how this deficiency in European and North American building costs could be alleviated, certainly merits further study.

For the sake of this project, however, let's choose the value of 5 million euros (5.28 million USD at the time of writing) by installed production of an electrical MW, as an estimate for the costs to be considered. This means that, for a nuclear baseload of 1 GW, the minimum being considered in the calculations, we are dealing with a 5 billion euros investment. For a nuclear baseload of 8 GW, it is a 40 billion euros investment.

This are certainly massive investments, but it must be considered that modern nuclear reactors, such as the ones being considered, have a lifetime of up to 60 years [41]. Although capital costs aren't the only expenses for nuclear power, this nevertheless represents a very long-term investment and must be considered that way.

With that in mind, we can now move on to study the impact of implementing nuclear power in the Portuguese grid with a greater awareness of its investment needs.

4.2 IMPACT OF NUCLEAR BASELOADS

To study the impact that adding a nuclear baseload of a certain size could have for the model, it was necessary to test for several possible baseload sizes, and to do so for the four distinct scenarios the model considers, the Conservative Scenario for 2035 and 2040, and the Ambition Scenario for those same years.

For each scenario, different baseloads were tested, starting at 1 GW and adding one gigawatt per test until reaching a model where they were either no deficit hours left, or they were very limited in number. Ultimately, this meant that, for the Conservative Scenario, baseloads of up to 7 GW were simulated, while in the Ambition Scenario, an extra 8 GW nuclear baseload was tested as well.

To start the analysis of the results from those tests, we can look at the monotone curves obtained for a few of the tests, and compare them to one another. These are displayed in Figure 37.

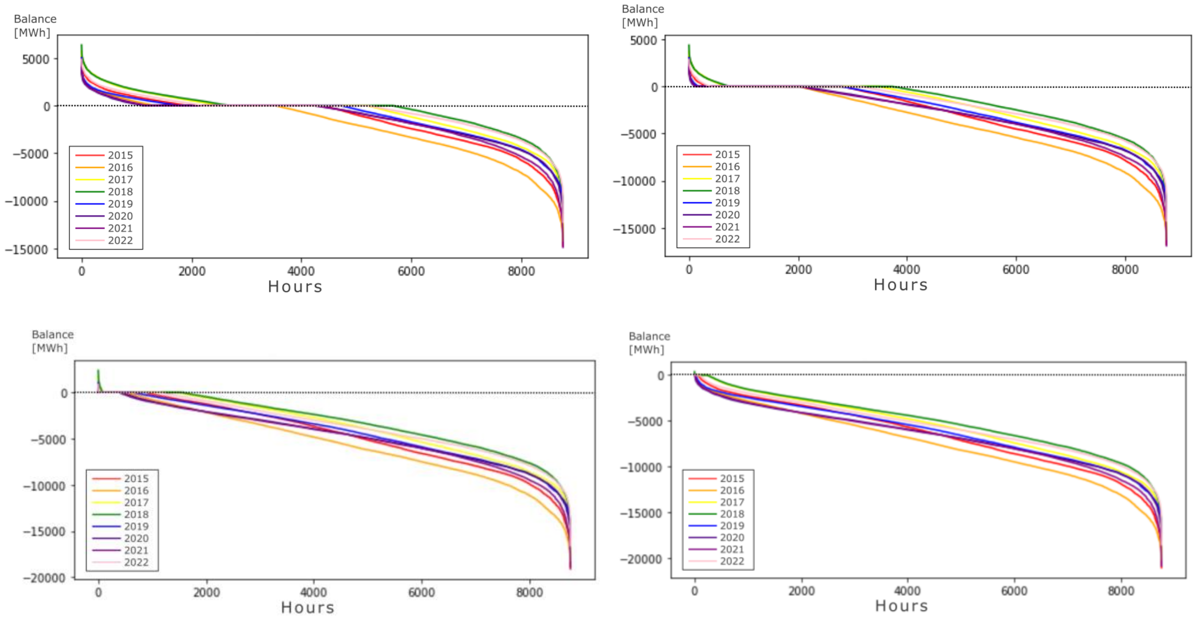


Figure 37 Load Monotones for no nuclear baseload and baseloads of 2, 4 and 6 GW. Conservative Scenario, 2035

Ultimately, the same behavior is seen, and could be expected, for each scenario. As a nuclear baseload is added, the straight line of energy balance goes ever further to the left, as the number of deficits decreases and that of excesses increases and, as more of a baseload is added, this straight line of balance also begins to disappear, as the overwhelming majority of hours retain an excess of power. It should be noted, however, that even at the 6 GW baseload mark, there are still a few hours in some of the years tested that still face energy deficits, even if not very big ones.

Besides the load monotones, however, other data was acquired to get a fuller perspective of the impact of the nuclear baseloads. Namely, for each scenario, for each year and for every test of a nuclear baseload, the number of hours remaining with an energy deficit, the total value of those yearly deficits and the non-renewable energy needed to be consumed each year were also acquired. With the value of non-renewable energy consumed, an estimate was also calculated for the GHG emissions necessary to maintain the energy system.

From that data, the graphs of Figure 38 were composed.

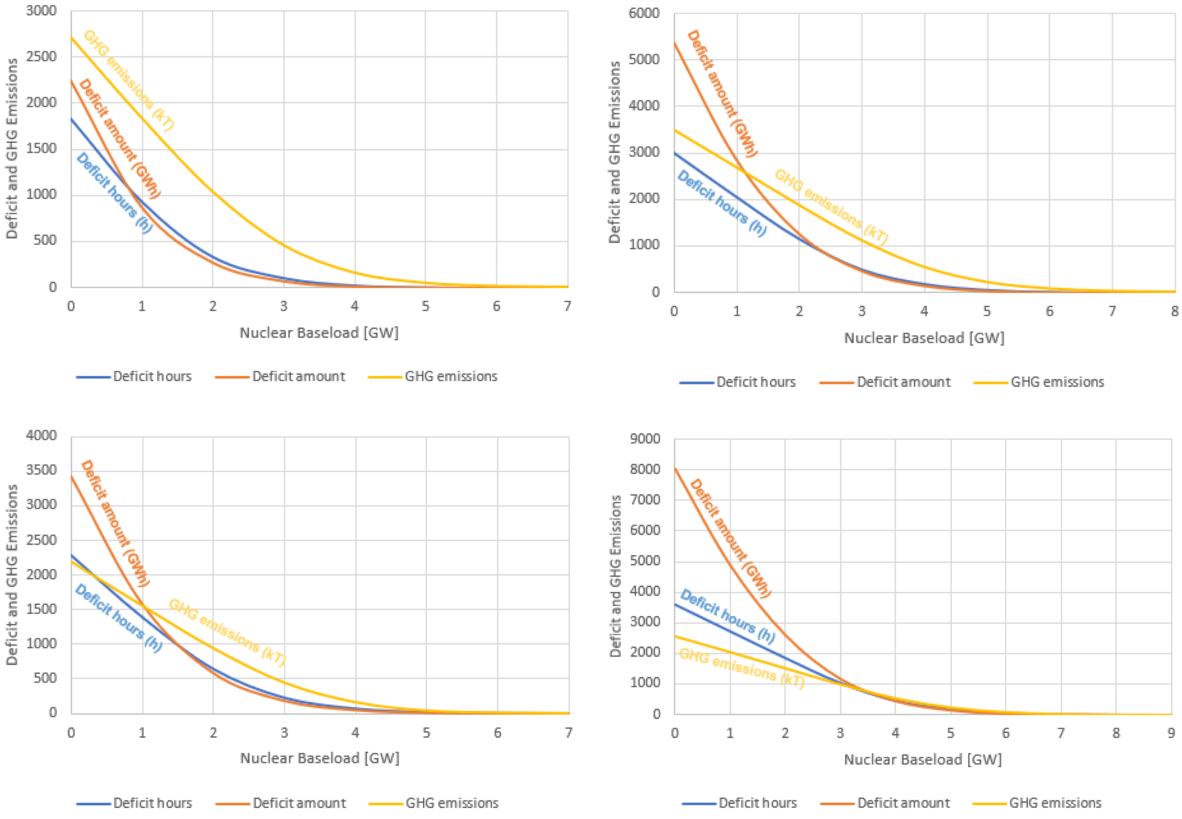


Figure 38 Graphs on Deficits and GHG Emissions in relation to Nuclear Baseload. Conservative Scenario (Left Column). Ambition Scenario (Right Column). 2035 (Upper Row). 2040 (Lower Row).

Comparing the four graphs, in particular when comparing those from the same scenario (same column) or for the same year (same row), some observations can be made. Namely, that comparing 2035 with 2040, for both scenarios, while the energy deficits increase for the latter year, the GHG emissions decrease for each scenario. This is because it is expected for the installed capacity of non-renewable thermoelectrical plants to decrease during those five years. It is also clear that are greater energy deficits in the Ambition Scenario than in the Conservative one, which is also to be expected, as the energy demand increases due to greater economic growth.

For all scenarios, the general behavior of the studied values as the nuclear baseload increases is the same. Not only do they decrease, with less deficits, with less intensity as well, and less GHG emissions, but they decrease in a logarithmic fashion, meaning that for ever increase in the baseload, its impact on the system is lesser than before. This is only sensible, as there are less deficit hours to cover, meaning that more of the energy of the baseload goes instead to making the excesses even larger. This is not quite ideal, especially as the price for producing that energy, and the investment necessary for building the power plant, would remain mostly the same while scaling the size, meaning that, as the nuclear baseload increases, the same cost produces a lesser result for the system. Not to mention increasing the issue of excess power.

With that taken into account, a recommendation could be made for the system.

4.3 RECOMMENDATION ON ADDING NUCLEAR BASELOAD

The first conclusion to take from the study performed in this chapter is that nuclear power alone is not able to fully cover the deficits encountered in some hours throughout the historical years. At least, it is not able to do so in a sensible manner, without creating a very unsound investment. It should also be mentioned that, in the tests where non-renewable power is used in very specific hours, this is also economically unsound, as a power plant would have to be maintained for very little use. Having very frequent energy excesses would also most likely make energy prices uncompetitive for producers. Essentially, it is an unworkable system.

Even so, adding a nuclear baseload of a more appropriate size could be very helpful, if not to solve the problem altogether, at least to alleviate it considerably, and leave room for an improvement to the system. Perhaps a sensible solution could be to have a nuclear baseload of 3 to 4 GW in 2035, depending on the scenario that is aimed for, with a larger baseload being needed for the Ambition Scenario, and one more GW being added by 2040. Considering the economic discussion in section 4.1, installing such a system would mean an investment between 15 and 20 billion euros, with an added 5 billion for 2040.

Such a system would have the characteristics outlined in Table 6.

	Recommended Baseload (GW)	**Number of Deficit Hours**	**Deficit amount (GWh)**	**GHG emissions (kT)**
2035 Conservative	3	106.5	72.25	455.3
2040 Conservative	4	67.5	45.851	164.700
2035 Ambition	4	186.5	149.750	536.600
2040 Ambition	5	181.5	153.343	242.600

Table 5 Characteristics of Recommended System by Scenario

Each system leaves out some amount of deficit, across a range of hours, and also a number of greenhouse gas emissions. Still, its impact on alleviating the problem is quite significant, especially when compared to the same scenarios without any nuclear baseload, as displayed in Table 7.

	% of Deficit Hours (no baseload = 100%)	**% Deficit Amount** (no baseload = 100%)	**% GHG emissions** (no baseload = 100%)
2035 Conservative	5.8%	3.2%	16.8%
2040 Conservative	3.0%	1.3%	7.5%
2035 Ambition	6.2%	2.8%	15.4%
2040 Ambition	5.1%	1.9%	9.5%

Table 6 GHG emissions by Scenario, as percentage of emissions without a baseload

As can be seen, it is a great improvement on all fronts, reducing the stress on the grid substantially. It should also be pointed out that, in terms of the GHG emissions, a few hundred kilotons of greenhouse gases are quite a small amount, compared to the natural carbon natural capture that is expected for Portugal, at around 13 megatons.

Nevertheless, there are still some issues with this solution. The number of remaining deficit hours certainly is unfortunate, especially as those numbers could increase in a less favorable hydrological scenario, but more worrisome still would be the great amount of electricity excesses that would exist throughout the year, excesses that could very well make the electricity market in Portugal inoperable. However, removing these excess hours without disturbing the overall balance of the system, and probably even improving it, would be best performed through curtailing renewable energy sources, diverting investment into them into nuclear power and, in particular, doing so in a deliberate manner, looking at the hours with the greatest excesses and understanding what energy resources could be withdrawn that would help decrease those while not harming the more balanced hours.

Finding solutions to those issues demands looking beyond nuclear power.

CHAPTER 5. ADDING HYDROGEN PRODUCTION

A final part of the proposed solution that is studied in this project is adding a hydrogen economy component to the plans for decarbonization in Portugal. This means using hydrogen to serve as an energy carrier, using electricity to produce it, using it as a form of storing it for later use and then releasing that energy back into electricity when necessary.

This production of hydrogen will be accomplished through water electrolysis. There are other methods to produce hydrogen from renewable sources, some of which are interesting from a scientific perspective, such as thermochemical cycles, whose energy efficiencies might be better than electrolysis, but those are still at an earlier stage of research and development, and their commercialization is even farther behind [42].

Water electrolysis of hydrogen works through a water splitting reaction, as described in Equation 1.

$$2\,H_2O\ (l) \rightarrow 2H_2\ (g) + O_2\ (g)$$

Equation 1 Water Splitting Reaction

This is an endothermic reaction, and so an energy input is required. Water electrolysis is simply the accomplishment of a water splitting reaction using an electrical energy input. This energy input is, at least, 286 kJ per mol [43]. This means that the theoretical maximum limit for the efficiency of this process is 39.4 kWh per kg of hydrogen.

The hydrogen that is produced is then stored, either in its current form or as part of another substance, namely ammonia, until it is needed. At that point, it usually undergoes the reverse reaction in a fuel cell to create water and release energy in the process in the form of electricity. This is a process generally acknowledged to have no firm maximum efficiency below 100% [44], with current technological limitations being its most relevant challenge.

The goal of adding hydrogen production to this system is to use these two transformations, carried out by electrolyzers and fuel cells, to store energy chemically in the hydrogen. This has the dual benefit of providing a way to increase the fulfillment of energy production in the hours with greater deficits to the energy balance, and to consume some of the surplus electricity produced by the system. Beyond this, hydrogen production has the added benefit of hydrogen having value beyond the electricity grid, being consumed for industrial purposes and there being plans to expand transportation based on hydrogen fuels.

This means that, rather than having to be produced for the benefit of the grid alone, hydrogen could make use of the surplus electricity of the grid to create a valuable resource, that helps decarbonize other parts of society and create added value for electricity production.

As to where could this hydrogen component be introduced into the model, there are two plausible logics to be used. The first one would be to introduce it before nonrenewable energy sources. In that way, hydrogen production would help minimize the need to use nonrenewable energy and help further decarbonize the system. The other option would be to introduce it after nonrenewable energy sources. This minimizes the amount of hydrogen necessary to be employed to balance the grid, leaving more to be explored for industry and transportation. Ultimately, this is more of a question of preferences than anything else. For this project, for the sake of promoting a fuller decarbonization, the first option is followed, leaving the model as follows.

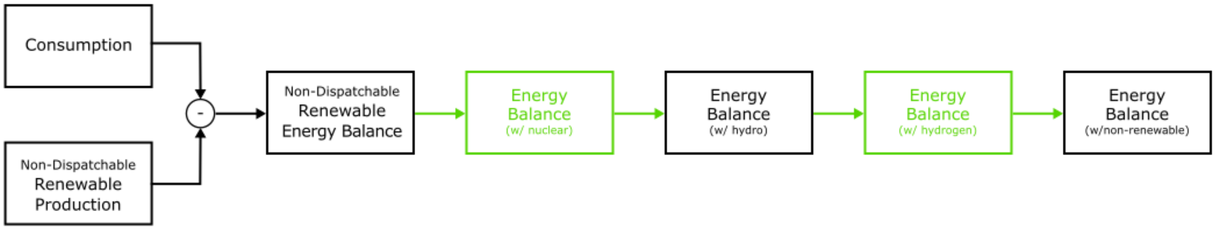


Figure 39 Flowchart for Model with Hydrogen System

Before advancing on how that model is implemented, it is important to discuss the economics and state-of-the-art for hydrogen production, at the moment of writing and as is expected to be in the near future. As both electrolyzers and fuel cells are up-and-coming technologies with a great deal of research, development and investment being put into them, this evolution is important to consider.

Then, the model can be implemented more solidly, with the various technological and economical aspects being contextualized. For the various scenarios, various tests will be carried out, including different installed capacities, to see their impact on the system.

Finally, a solution can be proposed and weighed in, taking into account its impact on the system and the cost that would be necessary to accomplish it.

5.1 HYDROGEN PRODUCTION ECONOMICS

The economic viability of green hydrogen is a question of great current debate. Although there is a great deal of interest in decarbonizing hydrogen production through the use of electrolysis, as it stands, the costs for producing hydrogen that way are still not competitive with the more common, steam methane reforming (SMR). A reason for this is that, while electrolysis demands the aforementioned 286 kJ per mol of hydrogen produced, the SMR process uses only 41 kJ for the same amount of hydrogen produced.

This also means that, for hydrogen produced through electricity from the grid, its carbon footprint is only an improvement over hydrogen produced through SMR if the fossil fuel penetration in the grid is below 14.3%, which is currently still quite challenging for most countries.

SMR is also quite a more established technology, helping to decrease costs. However, as electrolysis becomes more established, it also becomes more commercially viable, and its commercialization is expected to be much more viable by 2030.

To assess the commercial viability of hydrogen, the Levelized Cost of Hydrogen (LCOH) is a useful variable to estimate. It is estimated that, for green hydrogen to be cost competitive with blue hydrogen, produced through SMR, its LCOH needs to beat a target around 2.5 euros per kilogram of hydrogen [45]. This value currently seems unreachable. To understand why, we must understand how it is calculated.

The simplest possible formula for LCOH is displayed in Equation 2.

$$LCOH = \frac{Total\ Lifetime\ Production\ Cost}{Total\ Lifetime\ Hydrogen\ Production}$$

Equation 2 LCOH Formula

This formula can be made more complex and precise in a myriad of manners, including concerns such as depreciation of the investment, matters of financing and taxing, and another range of matters that are not very easily calculated, especially when dealing with a rising industry and modeling future years. To avoid those pitfalls, a simpler formula can be used to give an approximation for this project, as displayed in Equation 3.

$$LCOH = \frac{CAPEX + OPEX + Electricity\ Costs}{Total\ Lifetime\ Hydrogen\ Production}$$

Equation 3 LCOH Formula

The various parts of the formula can themselves be further reduced for a more thorough study.

Starting with CAPEX, this corresponds to the capital costs necessary to build the electrolysis infrastructure, meaning the electrolyzers. How this cost can be estimated is elaborated in the formula of Equation 4.

$$CAPEX\ (€) = CAPEX\ (€/kW)\ \times Installed\ Capacity\ (kW)\ \div\ Average\ degradation\ (h)$$

Equation 4 CAPEX Formula

Currently, the capital costs for electrolyzers are still considered to be a challenge for their implementation. However, as is normal for an emergent technology, it is expected that, in the near future, as the technology leaves the research and development stage of its lifetime, and becomes commercialized, that prices will decrease and become accessible. According to an article on the prospects of this technology for 2030, the expected values for these variables, for different sorts of electrolyzers, as well as the CAPEX necessary for an electrolysis plant with an installed capacity of 1 MW, and that same cost divided by each hour that the plant could be operating throughout its lifetime, are displayed in Table 8 [46].

		Alkaline	PEM	SOEC	AEM
System CAPEX	€/kW	200	400	400	400
Average Degradation	h	100.000	80.000	80.000	20.000
CAPEX (1 MW)	€	200.000	400.000	400.000	400.000
CAPEX per hour	€	2	5	5	20

Table 7 Information for Different Electrolyzer Technologies

It should be noted that Alkaline and Proton-exchange Membrane (PEM) electrolyzers are the ones with the greatest technological maturity at the moment. Solid Oxide Electrolyzer Cells (SOEC) and Anion Exchange Membrane (AEM) might become commercially available by 2030, but more focus should be put on the former two options.

Operating the electrolysis plant also requires OPEX, operational costs. In these, we are not considering the costs of electricity needed for the electrolysis process, as that was set apart in the formula. This value is usually considered to be rather low, with most studies putting it between 1 to 3% of CAPEX costs. Nevertheless, with lowering CAPEX costs, this relation might change, and so it is suggested that instead, a lifetime cost of around 50 euros per kW installed could be a better value. Whichever the case, OPEX is considered much smaller than CAPEX.

Looking next to the total lifetime hydrogen production, this value can be characterized by the amount of energy used to produce hydrogen and the efficiency of the electrolysis process, as follows in Equation 5.

$$Hydrogen\ Production\ (kg) = \frac{Energy\ Used\ (kWh)}{System\ Efficiency\ (kWh/kg)}$$

Equation 5 Relation between Hydrogen Production and Energy Used

The system efficiency for the various electrolyzers, as it is expected to be commercially available by 2030, is given in Table 9.

		Alkaline	PEM	SOEC	AEM
System Efficiency	kWh/kg	50	50	38	55

Table 8 System Efficiencies for Different Electrolyzer Technologies

It should be noted that, while the theoretical maximum efficiency for electrolysis is 39.4 kWh/kg, the SOEC system seems to go below that. The reasoning for this is that a solid oxide electrolyzer cell operates at temperatures between 500 and 850 ºC, allowing for high-temperature electrolysis, and using some thermal energy for the purposes of water splitting. This is certainly interesting, but it should be noted that such temperature ranges are only accomplished by fast nuclear reactors, so even the models discussed in the previous part of the project wouldn't allow for those temperatures to be obtained easily [47]. Using waste heat to help in water splitting operations could be interesting, however, but, in this study, that will not be fully considered.

What should be noted is that, with the given efficiencies, it would be possible, using 1 MW of electricity, to produce 20 kg of hydrogen.

If only leaves aside, for the moment, the costs of the electricity needed to supply for the electrolysis, the capital and operation costs of producing a kilogram of hydrogen could then be calculated as displayed in Table 10.

		Alkaline	PEM	SOEC	AEM
CAPEX and OPEX per kg of Hydrogen	€/kg	0.125	0.281	0.214	1.238

Table 9 CAPEX and OPEX per kg of Hydrogen for Different Electrolyzer Technologies

The differences between the costs ultimately reflect the maturity of the technology. It should also be mentioned that, although PEM electrolysis is slightly more expensive, this technology is considered to be more resilient when dealing with intermittent power sources, and so it could be more advantageous. Further study on that would be required, however.

But for each of these electrolyzers, but especially the first three, what becomes noticeable is that the price per kilogram of hydrogen produced is quite below the 2.5 euros per kilogram that are necessary for hydrogen to be competitive in the European market.

It is in the remaining variable, the electricity costs, that problems start to arise. According to REN, the average price for electricity in Portugal stands at 93.56 €/MWh [48]. It we consider that 50 kWh are necessary to produce 1 kilogram of hydrogen, then that gives us a cost of 4.68 €/kg, quite above market viability. Electricity costs are, ultimately, the most important factor in defining LCOH in the near future.

Of course, there are already ways around this. The electricity market is intermittent and, for several hours, lower prices can be found. To maintain a hydrogen price of 2.5 €/kg, the electricity price must be at 50 €/MWh, which is quite accomplishable for many hours and even as a daily average. Even accounting for the remaining costs, it is possible to find hours and days where it is possible to produce hydrogen at a competitive price.

The capacity factor of the system should also be taken into account. Some intermittent renewable sources can have problems providing a decently priced hydrogen supply due to operating at too low of a capacity factor, making the impact of the CAPEX and OPEX costs, that remain stable regardless of how much hydrogen is actually being produced, pushing the cost upwards for too low of a production.

Considering the scenarios laid out in our model, while prices are difficult to gage for 2035 and 2040, there are many hours where the energy balance is in excess. When energy is in excess, its price can very well be negative. Taking this into account, it is quite sensible to assume that, should the electrolyzers work during the excess hours, and refrain from consuming electricity during hours at balance or with an energy deficit, an affordable price for the hydrogen could be achieved.

5.2 FUEL CELLS ECONOMICS

Some of the hydrogen that is produced from electrolysis could then be retransformed to electricity through the use of fuel cells. Whether this would be more interesting, in terms of profit, than using it for industry or transportation, is a complex question to answer, but perhaps it should be considered that, should such a system be built for the purposes of helping to balance the grid, that there be obligations to use hydrogen for this purpose.

Regarding this operation and its viability, it is important to assert two things about fuel cells. The first being their efficiency at transforming energy stored chemically in hydrogen to electric energy. And the second being their cost, the investment needed to build and maintain such a system.

Regarding fuel cell efficiency, although there is no theoretical limit below 100% for their functioning, it is necessary to understand what the limitations in existing or predicted technology will be. Similarly to electrolyzers, fuel cells are an upcoming technology that is expected to become cheaper, more resilient and more efficient in the coming decade. In fact, electrolyzers and fuel cells are very similar technologies, using the same components to ultimately create reverse reactions. As such, it could be expected that the developments being forecast for electrolyzers will also apply to fuel cells. However, based on the literature focused on large-scale stationary fuel cells, the evolution displayed in Table 11 is expected on commercially-available systems up to 2030 [49].

		2021	**2024**	**2030**
CAPEX	€/kW	2800	2000	1500
OPEX	€/kW	4	3	2
Electrical Efficiency	(%)	50	52	58

Table 10 Data on Fuel Cells by Year

There are drastic improvements, which can only be expected to continue from 2030 to 2035 and 2040. Nevertheless, let's take these values as they are. This means that a fuel cell plant capable of transforming hydrogen into 1 MW of electricity would cost 1.5 million euros to build and would need, to produce 1 MWh of electricity, around 51.8 kg of hydrogen.

With this considered, we can then establish the system for hydrogen production and power generation, using electrolyzers and fuel cells.

5.3 IMPLEMENTATION OF THE HYDROGEN SYSTEM

The hydrogen system for the grid therefore functions using electrolyzers during hours with surplus electricity, transforming that electricity into hydrogen, and using fuel cells during hours with an electricity deficit, transforming hydrogen back into electricity. In this sense, it is not particularly dissimilar to the functioning of hydropower with water reservoirs, although the issue of exceeding a maximum storage capacity is less pressing, as excess hydrogen can and should be sold for other uses. Therefore, there is no practical need to keep a sustainable flow, as there is in hydropower.

The way this system is implemented is expressed in the flowchart of Figure 40.

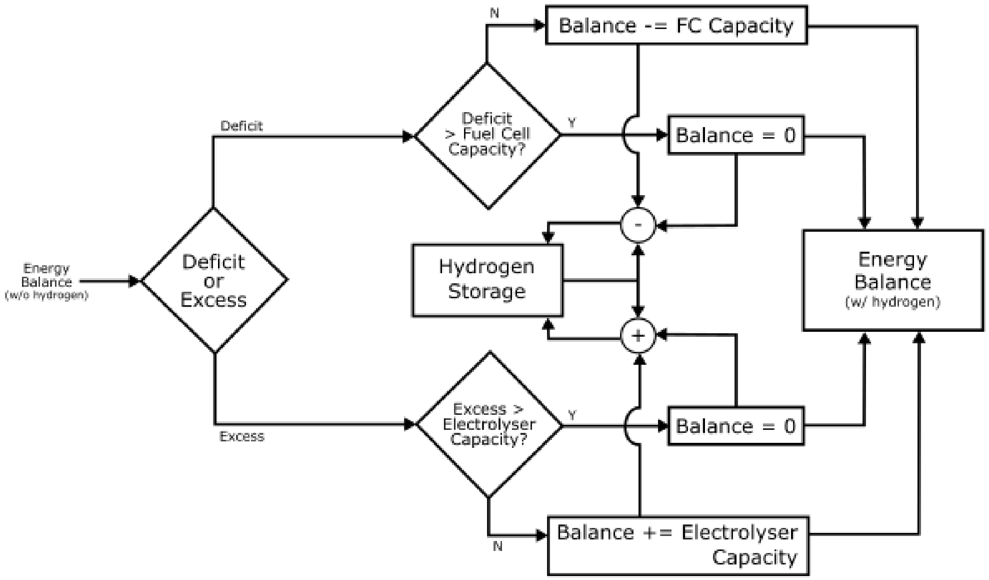


Figure 40 Flowchart for Hydrogen System Model

For the purposes of testing the impact that such a hydrogen system would have on the energy balance, a series of tests were conducted, in which a fixed value was chosen for the electrolyzer and fuel cell capacity, while changing the nuclear baseload installed. This fixed value was set at 2.5 GW, as it is the value planned to be achieved in Portugal by 2030, and although there are plans for up to 5.5 GW of electrolyzer capacity [50], this exercise is already helpful for studying the impact of adding a nuclear baseload and a hydrogen system to the Portuguese energy production system. This 2.5 GW hydrogen system would have a CAPEX of around 500 million euros.

The tests performed go from no nuclear baseload to a baseload of 4 GW to the Conservative Scenario, and 5 and 6 GW for the Ambition Scenario, for 2035 and 2040 respectively.

The analysis of the results from the various tests can start with observing the load monotone curves for the model and comparing them to those without the hydrogen system, for different baseload sizes, as displayed in Figure 41.

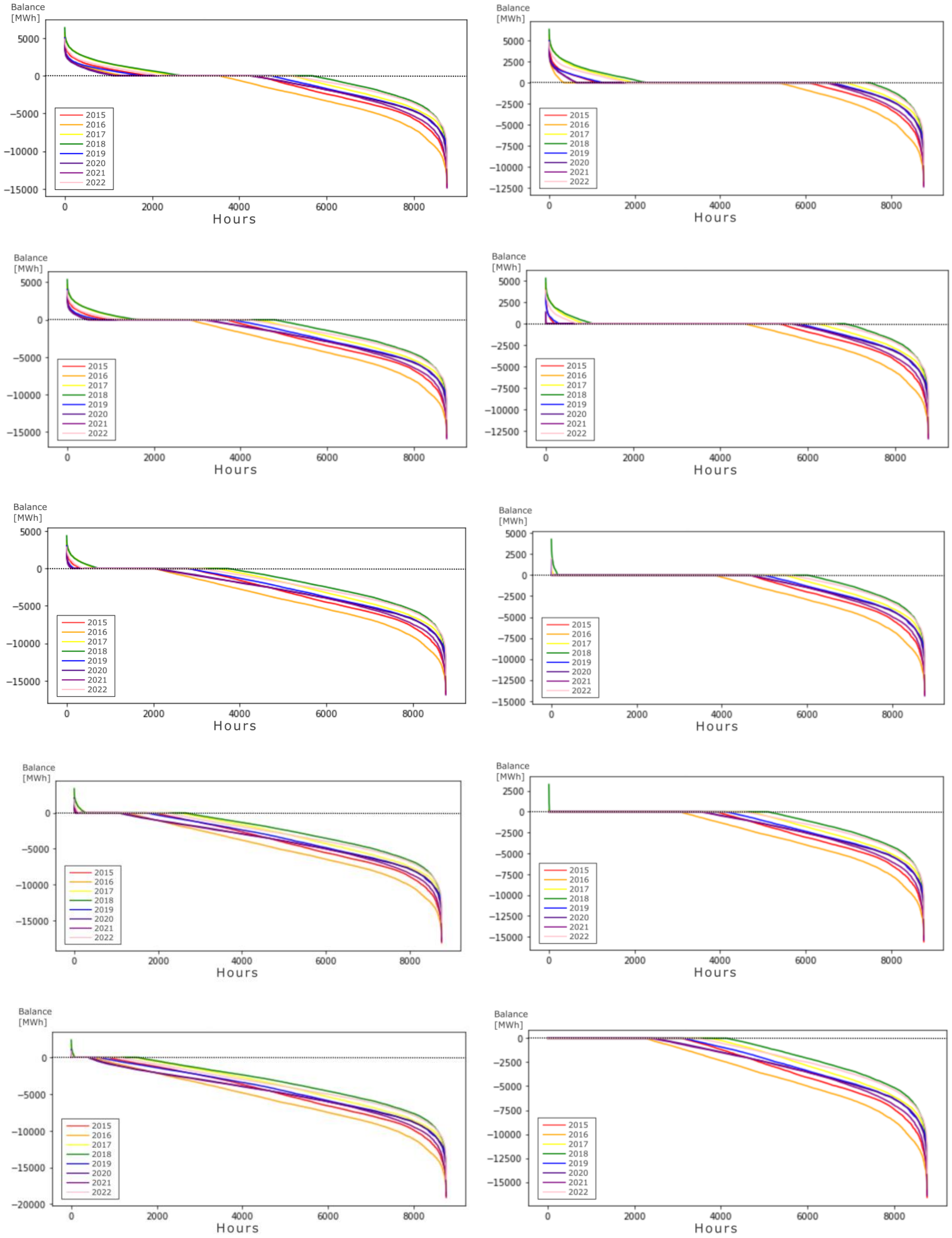
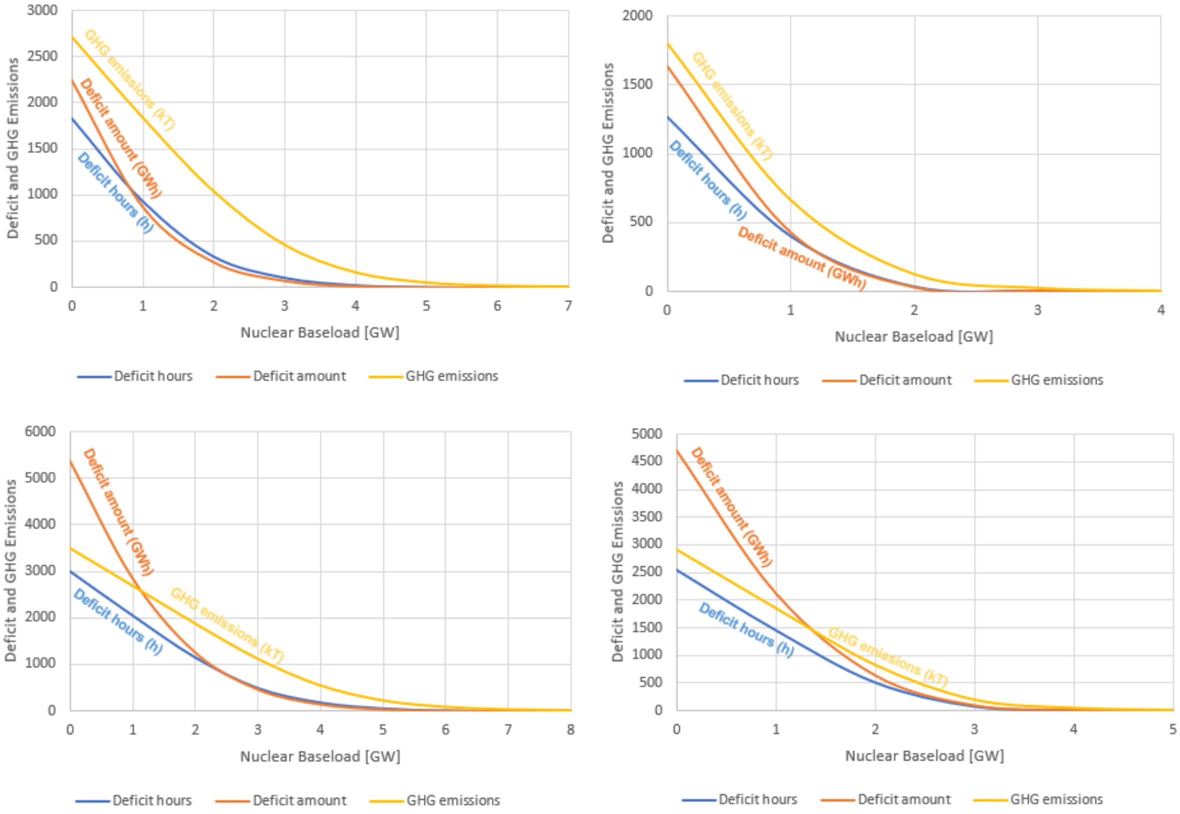


Figure 41 Monotone Loads without (Left) and with (Right) a 2.5 GW Hydrogen System implemented, for no Baseloads (upper row) and Baseloads of 1, 2, 3 and 4 GW for each successive row. Conservative Scenario, 2035

The impact of the hydrogen system is quite visible from those graphs, helping to decrease the number of hours with deficit, but also bringing greater balance to the system as a whole by balancing many hours with excess energy and alleviating the excesses felt in others. In fact, with the hydrogen system installed alongside a 4 GW nuclear baseload, there are no hours with deficit whatsoever for this scenario. In fact, already with a 2 GW nuclear baseload, in the Conservative Scenario for 2035, most years have no deficit hours or a very small number of them already.

It is also useful, to study the impact of the hydrogen system in the model, to compare the graphs that were used in section 4.2, when studying nuclear baseloads, comparing the number of hours with deficit, the total yearly value for the deficit and the GHG emissions for each year. Those graphs for each scenario, side-by-side with their counterparts without a hydrogen system, are displayed in Figure 42.



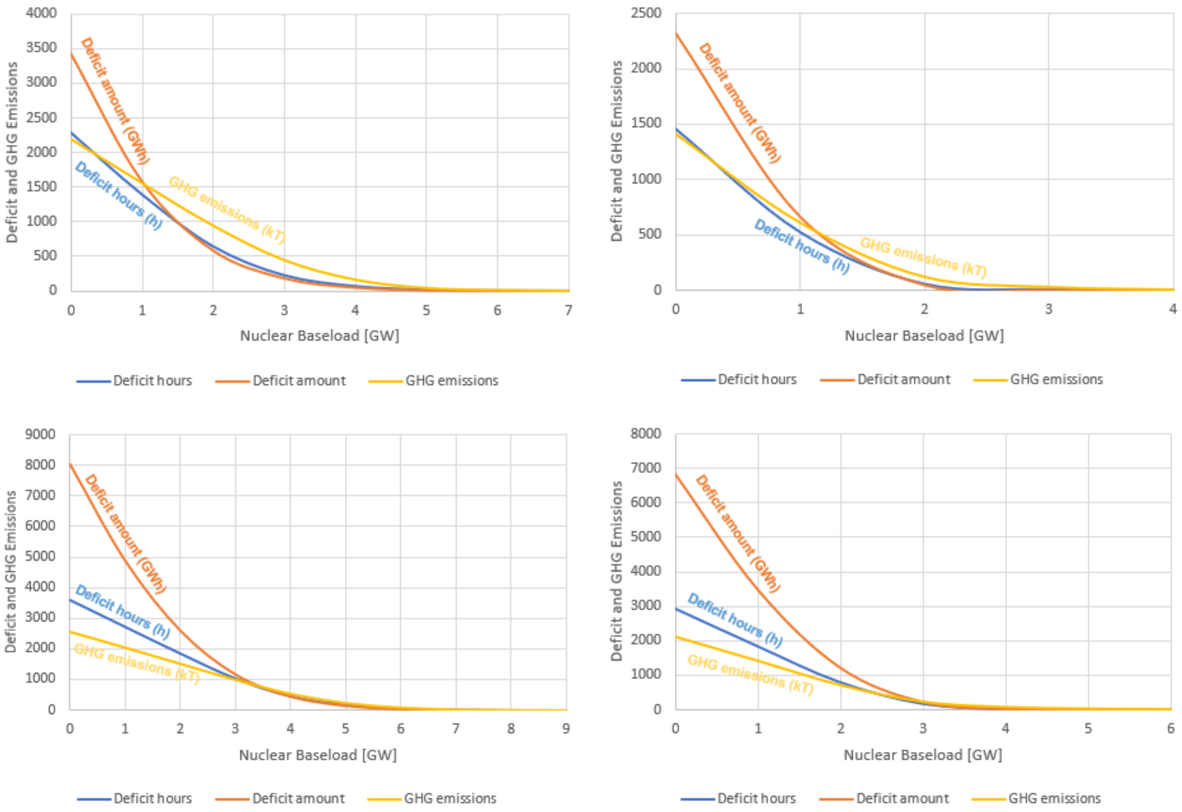


Figure 42 Graphs on Deficits and GHG Emissions in relation to Nuclear Baseload, Without (Left) and With (Right) a 2.5 GW Hydrogen System. Conservative Scenario, 2035 (First Row). Ambition Scenario, 2035 (Second Row). Conservative Scenario, 2040 (Third Row). Ambition Scenario, 2040 (Fourth Row)

It is noticeable that, for all scenarios, the inclusion of the hydrogen system allows for the deficit values and GHG emissions to fall to near zero with a smaller nuclear baseload. This can be explained through the hydrogen being used, through the fuel cells, to cover more hours with deficits, at once decreasing their numbers at the end and reducing the use of non-renewable thermal energy, and therefore GHG emissions.

Another important aspect to consider, before making a recommendation for an energy system, is the amount of hydrogen that is produced through the electrolyzers, the amount that is later consumed through the fuel cells to balance deficit hours, and the amount that is not used for that and could become commercially available through this system. In the graphs of Figure 43, the total amount of hydrogen produced, and the amount that is stored at the end of the year, and that could be used for commercialization, is compared, for each scenario, for the different nuclear baseloads.

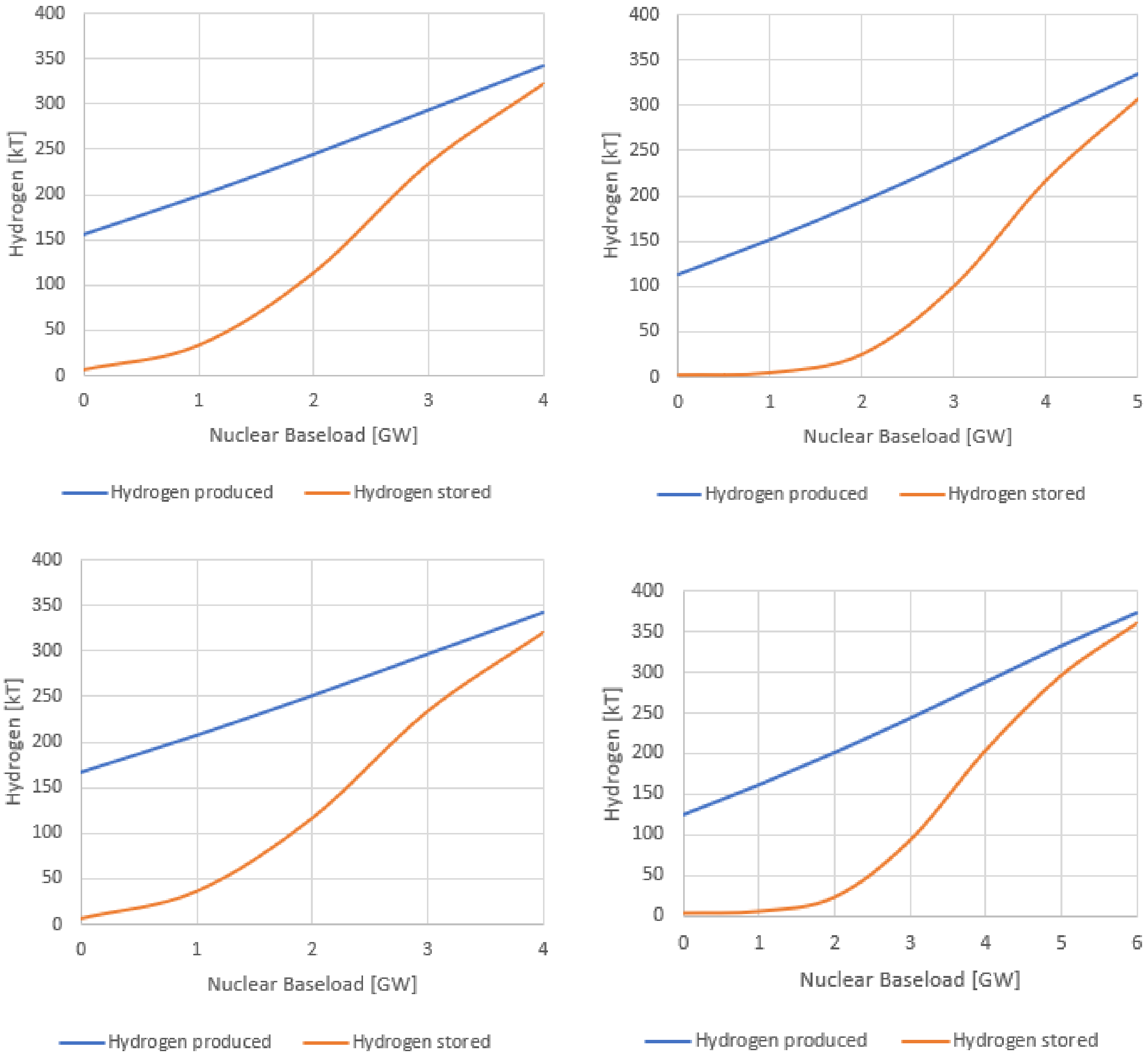


Figure 43 Graphics for Hydrogen Produced and Stored throughout the Year for different Baseloads. 2035 (Upper Row), 2040 (Lower Row). Conservative Scenario (Left Column). Ambition Scenario (Right Column)

The two curves have very interesting behaviors. The curve for hydrogen produced is almost perfectly linear, rising around 40 kT of hydrogen produced for each added GW of nuclear baseload. This corresponds, for each GW of baseload added, an increase in 228.31 MW of the average power dedicated to producing hydrogen, an increase of more than 9% to the capacity factor of the electrolyzer.

The curve for the hydrogen stored at the end of the year behaves rather differently. At first rather small, its values increase quite faster than those of the total produced hydrogen, nearing this value while decreasing the growth speed of the curve and approaching linear behavior at a certain point. This makes sense. As the baseload increases, there are less deficits to be fulfilled through hydrogen, allowing for more to be stored to become available for commercial use. This means that adding a greater baseload can, at a certain point in the system's evolution, allow for an extra 120 kT of hydrogen to be commercially available for an added GW of nuclear baseload.

This has a significant impact in assessing the best solution for the problem. Adding nuclear baseload, even if it has diminishing returns on the impact it has on the energy balance of the system, can have a considerable impact in its hydrogen production and commercialization. With this in mind, the final recommendation for the energy system can be given.

5.4 RECOMMENDATION ON AN HYDROGEN AND NUCLEAR SYSTEM

The presence of a hydrogen system, as detailed in this chapter, alters significantly the impact that a nuclear baseload could have on the electric system for 2035 and 2040 and, therefore, changes the recommendations that could be made for the various scenarios. In particular, the hydrogen system makes it so that it is no longer merely a question of adding a greater nuclear baseload for ever-decreasing returns but making it rather productive to add a baseload if it allows for the hydrogen system to increase its commercial output outside the electric grid, to industry and transportation.

The first thing that should be noted is that adding a nuclear baseload is very important for this system to work. Hydrogen alone cannot fix the energy security concerns in Portugal, and it is especially poor in doing so in a financially constructive manner. Not only do generally large energy deficits remain, in the tests run without a nuclear baseload for each scenario, but the hydrogen that is produced is almost entirely consumed to try and balance out those deficits. Adding a nuclear baseload not only helps decrease the number of hours in deficit and the severity of those deficits, but also allows more hydrogen to be left out for commercial use.

From an energy system perspective alone, the presence of the hydrogen system allows for decreasing the nuclear baseload and retain, in comparison to the system modelled without the hydrogen presence, results that are actually better than those proposed in the following chapter. Such a recommendation might be as is displayed in Table 12.

	Recommended Baseload (GW)	**Number of Deficit Hours**	**Deficit amount (GWh)**	**GHG emissions (kT)**
2035 Conservative	2	31.25	26.510	124.575
2040 Conservative	2	58.38	50.669	120.894
2035 Ambition	3	79.13	86.085	193.696
2040 Ambition	3	191.375	232.311	214.426

Table 11 Characteristics of Systems by Scenario

In this case, there is a decrease in 1 GW for the proposed baseloads for 2035, for both scenarios, and a decrease in 2 GW for the proposed baseloads for 2040, for both scenarios as well. And, in comparison with the results obtained for the previous chapter, they are almost all improvements, in terms of number of deficits, the severity of those deficits and the GHG emissions.

This recommendation, however, is not sound when it comes to the commercial possibilities of the hydrogen system. In the Conservative Scenario for 2035, for example, only 46.2% of the hydrogen produced would be available for commercial use at the end of the year, compared to 79.7% that is available if another GW of nuclear baseload is added. This represents an increase of more than 120 kT of hydrogen commercially available, which would represent an added value of around 300 million euros.

The question then becomes, how much value in hydrogen is needed to be commercially available for it to be commercially sound to add an extra GW of nuclear baseload. Finding that value, then the proper recommendation for an energy system would be having a nuclear baseload going up to the point where the curve of added hydrogen availability crosses that of economic viability and maximize the profits.

Acknowledging the limitations, with the existing data for this project, of finding an exact value for that point, the recommendation of Table 13 is given, that attempts to maximize hydrogen commercial availability with a minimization of the investment needs for such a system.

	Recommended Baseload (GW)	**Number of Deficit Hours**	**Deficit amount (GWh)**	**GHG emissions (kT)**	**Commercial Hydrogen (kT)**
2035 Conservative	4	0	0	3.969	233.291
2040 Conservative	4	0.625	0.230	5.699	319.783
2035 Ambition	5	0.5	0.175	9.199	306.839
2040 Ambition	5	7.375	2.898	16.370	294.875

Table 12 Characteristics of Recommended Systems by Scenario

Under these conditions, both the yearly hours facing energy deficits and those needing to resort to non-renewable energy are almost negligible, as are GHG emissions, while around 90% of the hydrogen produced each year is commercially available at the end. This requires, at least for the year 2035 in each scenario, a larger baseload than the recommendation for last chapter, but this added investment comes with the benefit of significantly increasing the hydrogen output of the system for commercial use. This means an investment of 20 billion euros for 2035, with an added 5 billion by 2040.

Although such a system is still faced with the threats of added hydrological pressures and other concerns of energy security, it presents a much more stable and secure basis than most, allowing for a first step towards a more fully decarbonized society that nevertheless stands firmly on its feet.

CHAPTER 6. CONCLUSIONS

This project could be said to be answering two questions. The first of which is, is the current plan for the energy transition in Portugal ensuring energy security in the coming years? And the second one being, if it's not, is there a solution that can be found to decarbonize the energy system while ensuring energy security in Portugal? In these concluding remarks, a reexamination of those questions, and the answers that were provided to them, will be given.

6.1 ON THE ENERGY SECURITY CRISIS

Throughout the first part of the project, by simulating the energy system in 2035 and 2040, an answer was obtained to the first question, and it is very decidedly negative. It is not a matter of a few hours each year that are on the line, or of small, occasional deficits. It is a consistent pattern of a sizeable percentage of hours across the year not having nearly enough the capacity to fulfill demand.

Concurrently to these times of scarcity, each year suffers as well of several of hours where the energy system produces an overabundance of electricity, overloading the grid and, most likely, creating unprofitable, or even negative prices during many hours. This is also quite an issue, as it might make energy production systems commercial unviable.

If we are to assume that interconnections with the Spanish grid are what will sustain this system, then at the very least an analysis of the energy security over the Spanish energy transition should be performed and compared to the Portuguese result, to ensure that this doesn't cause an issue. And of course, the economic problems that this might cause need to be accounted for.

It is also very concerning how, comparing the Conservative and Ambition Scenarios, and their results in the simulation, it becomes clear that, although both situations are dire, that of the Ambition Scenario is consistently an aggravated one, either having greater deficits or requiring a greater effort and investment to be corrected. The two graphs on Figure 36 display this issue clearly.

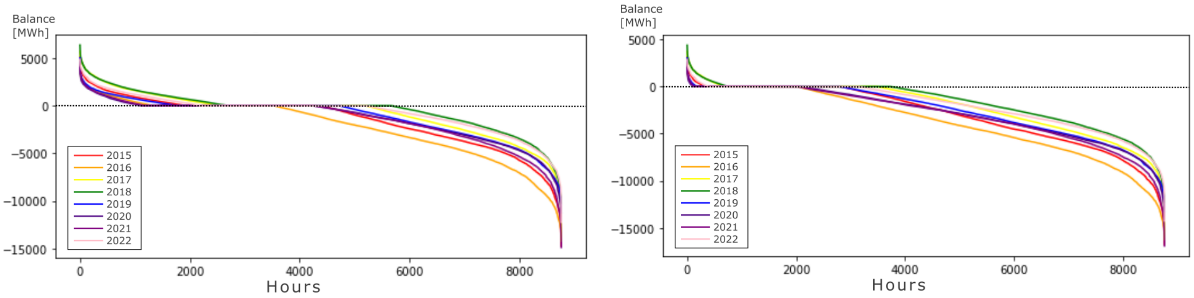


Figure 36 Load Monotone Curves for Balance of Energy, 2035. Conservative Scenario (left), Ambition Scenario (right)

This is quite a preoccupying trend. The Ambition Scenario differs from the Conservative one in that it presupposes a larger economic growth in Portugal. If, for that economic growth, which reflects itself in a growth of energy demand, there is not an accompanying increase in energy production, then this aggravated crisis ultimately serves to stifle whatever economic growth there might come to be. In essence, the Portuguese economy will not be able to withstand its own growth if there isn’t enough investment in the energy system in the coming years.

In no uncertain terms, this report concludes that there is a coming energy crisis to Portugal, if the current path of energy transition is followed. This is an important issue for which awareness must be raised, among policy makers, the scientific community and the wider public, so that solutions can be found. Considering the situation by 2035, building such solutions should start as soon as possible.

6.2 ON THE PROPOSED SOLUTION

In the second and third part of the project, after it was demonstrated that the energy security of Portugal is not ensured by the system currently being planned for its transition, a solution was proposed using nuclear power and a hydrogen power-to-power system to create an economically viable energy system that does not suffer from the same problems of energy security.

The models involving only the nuclear power system found themselves lacking, mostly due to a tendency for decreasing returns for ever greater nuclear baseloads, while the costs for installing that baseload remain constant. Ultimately, although any nuclear baseload that is added can contribute significantly to improving energy security in the system, it is unlikely that it is economically viable to provide a large enough nuclear baseload to fulfill all the necessities of energy security. However, it is possible that, with a decently-sized nuclear baseload and the connections to Spain, this could prove enough to build a viable system. Ensuring that would demand further study of the transition in that country.

Adding to the model a hydrogen system, and it is possible to find a system for energy security that not only can achieve better results with a smaller nuclear baseload but that, more importantly, provides a good economic reasoning to increase that investment, by creating an added value in the hydrogen to be commercialized. From the values that have been encountered for the economics of these systems, it seems possible that such a system could be economically viable. More study into the implementation of such a system is required to clarify whether the economic viability of such a project, but the results that were obtained point in a promising direction.

In fact, answering the question of whether this system is economically viable is made further complicated by the way that the energy system functions. The policies that are implemented, and the choices that are made, are not driven by a single-minded agent whose goals correspond to those of national interest, but rather, they are made by the individual decisions of self-interested agents trying to maximize their own gains and pursue their own interests. In other words, it is a free market, rather than a nationalized sector. The merits of that aside, it makes both determining the viability of such a project, and making it viable to begin with, more challenging. The hydrogen system that is proposed could, using electricity at negative or very low prices, achieve economic viability by providing hydrogen that is quite below the market value. However, it is hard to imagine that private vendors would find that acceptable, even if their product does indeed have a negative value. Self-interest could easily trump over both rationality and common interest.

Whether the energy system is run towards national interest or towards a multitude of differing and even competing interests will affect its implementation and viability. Which means that more than answering questions of engineering and logistics, it becomes necessary to answer questions of policy and economics.

6.3 FUTURE WORK

There are a number of questions and areas of research that this project should be seen as, more than finding solutions, simply begging the question. That could mean perfecting the simulation, including matters such as changes in consumption patterns that weren't pursued here, such an increase in residential heating and cooling, or increased working-from-home situations, or the myriad of other complex societal details that could an impact in our energy consumption patterns. A simulation is always an exercise in imperfectly modeling a real-life system. There is also room for improvement and for making things more complex and more life-like than they currently are.

The most relevant change to make would be running such a system not only simulating the Portuguese energy system, but also the Spanish and perhaps even the European one. Answering the question of whether the energy crisis in Portugal will also reflect in Spain and, more important yet, whether the periods of deficit and excess in each system complement each other, which would be very fortunate, or if they coincide, which would be very problematic. What cannot be perpetuated is the waving away of this question, and assuming that the Spanish energy system will always be there to save Portugal.

Testing these models in more sophisticated software, like EnergyPLAN, and comparing the conclusions obtained there, would also be very interesting, especially as it could provide some optimization that is difficult to accomplish in the program that was developed for this project.

Changing some of the ideas for the solution could also be helpful. Perhaps combining nuclear heat with high-temperate electrolysis methods could be interesting. Perhaps combined electrolyzer-fuel cell systems change the economic calculations significantly. A number of factors could make this system different, and from those differences, a great deal of research could be extracted.

An interesting and unorthodox path to study would be to, to help soften the blow of the investment needs for the systems that have been discussed, assess the impact of reducing the installed capacities for the non-dispatchable renewable energy sources. Throughout this work, the scenarios set out in RMSA were followed, but generally, their results have been affected by the large numbers of hours in excess.

Instead of assuming that this means nuclear power has no place in the Portuguese energy system, it would be fair to ask whether, if a nuclear solution were pursued, the investment in renewable energy sources should be reduced. This would help alleviate the problem of excess energy while having very little impact during deficit hours and would reduce the overall investment needed for the energy transition. From studies in the Netherlands [51] and Switzerland [52], it is quite possible that such a system would also have lower overall costs, which would be quite a boon.

Finally, a deeper and more complex economic study of the project would also be very important, including the investment that would be necessary and the energy return that would be accomplished, so that economic feasibility could be ensured. Currently, the answer that can be provided to the question of whether this alternative works is that it looks promising and warrants further study. More thorough work is needed to turn what are tentative prospects into any sort of certainties.

This is all to say, there is a lot of work that could be continued from this point. Finding a solution to the energy crisis will be complicated, and require more work than what was conceivable to be done, given the scope of this project. However, one can hope that, through the work carried out here, the pursuit for a solution might be encouraged.

REFERENCES

[1] “Basic energy access lags amid renewable opportunities, new report shows”. International Energy Agency (IEA), 6 June 2023, https://www.iea.org/news/basic-energy-access-lags-amid-renewable-opportunities-new-report-shows. Accessed 28 October 2023.

[2] “Energy Security”. IEA. https://www.iea.org/topics/energy-security. Accessed 28 October 2023.

[3] “Uma história de dois séculos: Portugal acende a primeira lâmpada”. EDP, 14 August 2019, https://www.edp.com/pt-pt/historias-edp/uma-historia-de-dois-seculos-portugal-acende-a-primeira-lampada. Accessed 28 October 2023.

[4] RNC 2050. Roadmap for Carbon Neutrality 2050, p. 3

[5] “Portugal está em condições de antecipar neutralidade carbónica para 2045”. Portugal.gov.pt, 7 November 2022, https://www.portugal.gov.pt/pt/gc23/comunicacao/noticia?i=portugal-esta-em-condicoes-de-antecipar-neutralidade-carbonica-para-2045. Accessed 27 October 2023.

[6] Inventário Nacional de Emissões 2022. Agência Portuguesa do Ambiente, p. 1

[7] RNC 2050. Roadmap for Carbon Neutrality 2050, p. 16

[8] Inventário Nacional de Emissões 2022. Agência Portuguesa do Ambiente, p. 5

[9] “Economic.” Merriam-Webster.com Dictionary, Merriam-Webster, https://www.merriamwebster.com/dictionary/economic. Accessed 24 Oct. 2023.

[10] Potência instalada nas centrais produtoras de eletricidade (2008-2022). Direção Geral de Energia e Geologia (DGEG), https://www.dgeg.gov.pt/pt/estatistica/energia/eletricidade/producao-anual-e-potencia-instalada/. Accessed 24 October 2023.

[11] Potência instalada nas centrais produtoras de eletricidade (2008-2022). Direção Geral de Energia e Geologia (DGEG), https://www.dgeg.gov.pt/pt/estatistica/energia/eletricidade/producao-anual-e-potencia-instalada/. Accessed 24 October 2023.

[12] Disponibilidade de Energia Elétrica para Consumo (2000-2022). Direção Geral de Energia e Geologia (DGEG), https://www.dgeg.gov.pt/pt/estatistica/energia/eletricidade/producao-anual-e-potencia-instalada/. Accessed 24 October 2023.

[13] Electricity Generation by Source – Portugal. International Energy Agency (IEA), https://www.iea.org/countries/Portugal. Accessed 24 October 2023.

[14] Spier, Fred. “Big History: The Emergence of an Interdisciplinary Science?”. World History Connected, https://worldhistoryconnected.press.uillinois.edu/6.3/spier.html#_ednref16. Accessed 28 October 2023.

[15] “Energy Sovereignty”. NEU newsletter, https://www.newslettereuropean.eu/energy-sovereignty/. Accessed 24 October 2023.

[16] Flexibility Solutions for High-Renewable Energy Systems – Spain. BloombergNEF, ACCCIONA. December 2019. https://assets.bbhub.io/professional/sites/24/Flexibility-Solutions-for-High-Renewable-Energy-Systems-Spain-Outlook.pdf. Accessed 24 October 2023, p. 7

[17] Silva, Bárbara. “Governo garante que fim do carvão não aumentou importação de eletricidade de Espanha”. Sapo Eco, https://eco.sapo.pt/2022/02/07/governo-garante-que-fim-do-carvao-nao-aumentou-importacao-de-eletricidade-de-espanha/. Accessed 24 October 2023.

[18] RMSA 2022. Relatório de Monitorização de Segurança de Abastecimento do Sistema Elétrico Nacional 2023-2040. Direção Geral de Energia e Geologia (DGEG), p. 38

[19] Henze, Veronika. “Energy Storage Investments Boom As Battery Costs Halve in the Next Decade”. 31 July 2019. BloombergNEF. https://about.bnef.com/blog/energy-storage-investments-boom-battery-costs-halve-next-decade/. Accessed 24 October 2023.

[20] Brook, Barry & Alonso, Agustin & Meneley, Daniel & Misak, Jozef & Blees, Tom & Erp. Why nuclear energy is sustainable and has to be part of the energy mix. January 2014. Sustainable Materials and Technologies. 1-2. 8-16. 10.1016/j.susmat.2014.11.001.

[21] Watson, Nicholas & Ashton, Lucy. “Towards a Just Energy Transition: Nuclear Power Boasts Best Paid Jobs in Clean Energy Sector”. 14 April 2012. International Atomic Energy Agency (IAEA). https://www.iaea.org/newscenter/news/towards-a-just-energy-transition-nuclear-power-boasts-best-paid-jobs-in-clean-energy-sector. Accessed 24 October 2023.

[22] Non-baseload Operation in Nuclear Power Plants: Load Following and Frequency Control Modes of Flexible Operation. 2018. International Atomic Energy Agency (IAEA).

[23] “The nuclear phase-out in Germany”. Federal Office for the Safety of Nuclear Waste Management. 19 April 2023. https://www.base.bund.de/EN/ns/nuclear-phase-out/nuclear-phase-out_node.html. Accessed 28 October 2023.

[24] Ritchie, Hannah. “Data on the German retreat from nuclear energy tell a cautionary tale”. 10 May 2023. The Washington Post. https://www.washingtonpost.com/opinions/2023/05/10/germany-end-nuclear-cost-climate-health/. Accessed 28 October 2023.

[25] Chazan, Guy & White, Sarah & Abboud, Leila & Hancock, Alice. “Germany seeks ‘grand bargain’ with France over energy”. 4 October 2023. Financial Times. https://www.ft.com/content/8a57f1be-20cb-4632-aecd-1a68f5211057. Accessed 28 October 2023.

[26] “Polish government approves first nuclear power plant”. World Nuclear News. 12 July 2023. https://world-nuclear-news.org/Articles/Polish-government-approves-first-nuclear-power-pla. Accessed 28 October 2023.

[27] “Nuclear Power in Russia”. December 2021. World Nuclear Association. https://world-nuclear.org/information-library/country-profiles/countries-o-s/russia-nuclear-power.aspx. Accessed 28 October 2023.

[28] Hayley, Andrew. “China expects to OK 6-8 nuclear power units per year in green energy drive”. 27 September 2023. Reuters. https://www.reuters.com/business/energy/china-expects-ok-6-8-nuclear-power-units-per-year-green-energy-drive-2023-09-27/. Accessed 28 October 2023.

[29] “South Korea considering new nuclear plants”. 12 July 2023. World Nuclear News. https://world-nuclear-news.org/Articles/South-Korea-set-to-back-new-nuclear-plants. Accessed 28 October 2023.

[30] “BARC Activities for Indian Nuclear Power Program”. Bhabha Atomic Research Centre (BARC). https://www.barc.gov.in/randd/artnp.html. Accessed 28 October 2023.

[31] Vlasov, Artem. “Preparing 60 Years in Advance: The UAE’s First Nuclear Power Plant and Plans for Future Decommissioning”. April, 2023. International Atomic Energy Agency (IAEA). https://www.iaea.org/bulletin/preparing-60-years-in-advance-the-uaes-first-nuclear-power-plant-and-plans-for-future-decommissioning. Accessed 28 October 2023.

[32] RMSA 2022. Relatório de Monitorização da Segurança de Abastecimento do Sistema Elétrico Nacional para o período de 2023-2040. 25 October 2022. https://www.dgeg.gov.pt/media/ck2pa4s2/rmsa-e-2022.pdf

[33] Serrenho, A., Warr, B., Sousa, T., Ayres, R., Domingos, T. Structure and dynamics of useful work along the agriculture-industry-services transition: Portugal from 1856 to 2009, Structural Change and Economic Dynamics, Volume 36, 2016, Pages 1-21, ISSN 0954-349X, https://doi.org/10.1016/j.strueco.2015.10.004.

[34] Carvalho, P. S. “Apesar do preço, consumo de gasolina e gasóleo bate recorde em Portugal” 12 May 2022. Sapo ECO. Accessed 4 July 2023.

[35] Soares, P.M.M., Careto, J.A.M., Russo, A. et al. The future of Iberian droughts: a deeper analysis based on multi-scenario and a multi-model ensemble approach. Nat Hazards 117, 2001–2028 (2023). https://doi.org/10.1007/s11069-023-05938-7

[36] Projected Costs of Generating Electricity 2020. International Energy Agency (IEA). 2020. https://www.iea.org/reports/projected-costs-of-generating-electricity-2020. Accessed 29 October 2023.

[37] Schemikau, L., Smith, W. H. & Falcon, R. Full Cost of Electricity ‘FCOE’ and Energy Return on Investment ‘EROI’. August 2022. SRRN.

[38] The RIC Report – Nuclear Necessity. BofA Global Research. 9 May 2023.

[39] Economics of Nuclear Power. August 2022. World Nuclear Association. https://world-nuclear.org/information-library/economic-aspects/economics-of-nuclear-power.aspx. Accessed 29 October 2023.

[40] Oettingen, Mikołaj. Costs and timeframes of construction of nuclear power plants carried out by potential nuclear technology suppliers for Poland. 23 June 2021. Pulaski Policy Papers. ISSN 2080-8852

[41] APR1400. KEPCO E&C. https://www.kepco-enc.com/eng/contents.do?key=1533. Accessed 29 October 2023.

[42] Acar, Canan & Dincer, Ibrahim. Selection criteria and ranking for sustainable hydrogen production options. 8 December 2022. International Journal of Hydrogen Energy. Volume 47, Issue 95.

[43] T. Shinagawa, K. Takanabe. Towards Versatile and Sustainable Hydrogen Production through Electrocatalytic Water Splitting: Electrolyte Engineering. ChemSusChem. Volume 10, Issue 7. 16 December 2016.

[44] Haseli, Y. Maximum conversion efficiency of hydrogen fuel cells. International Journal of Hydrogen Energy. Volume 43, Issue 18. 3 May 2018.

[45] Barillas, Ana. The path to 2.5 GW of green hydrogen in Portugal. November 2021. Aurora Energy Research. https://www.apren.pt/contents/documents/ana-barillas-aurora.pdf. Accessed 24 October 2023.

[46] Bernuy-Lopez, C. Electrolysis technologies and LCOH: current state and prospects for 2030. 13 April 2023. Hydrogen Tech World. https://hydrogentechworld.com/electrolysis-technologies-and-lcoh-current-state-and-prospects-for-2030. Accessed 24 October 2023.

[47] El-Emam, R. S., Ozcan, H., & Zamfirescu, C. (2020). Updates on promising thermochemical cycles for clean hydrogen production using nuclear energy. Journal of Cleaner Production, 262, 121424.

[48] REN Data Hub – Mercado. https://datahub.ren.pt/pt/eletricidade/mercado/. Accessed 24 October 2023.

[49] Cigolotti, V., Genovese, M. & Fragiacomo, P. Comprehensive Review on Fuel Cell Technology for Stationary Applications as Sustainable and Efficient Poly-Generation Energy Systems. 13 August 2021. Energies 2021, 14, 4963.

[50] “Um país mais verde, mais cedo: o Plano Nacional de Energia e Clima 2030 está a ser revisto pela primeira vez”. Portugal.gov.pt, 30 June 2023, https://www.portugal.gov.pt/pt/gc23/comunicacao/noticia?i=-um-pais-mais-verde-mais-cedo-o-plano-nacional-de-energia-e-clima-2030-esta-a-ser-revisto-pela-primeira-vez. Accessed 24 October 2023.

[51] Possible role of Nuclear in the Dutch energy mix in the future. 1 September 2020. ENCO.

[52] Achieving Net Zero Carbon Emissions in Switzerland in 2050. 2022. Nuclear Energy Agency.