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

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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 fulfil 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

1. Introduction

Energy security is defined by the International Energy Agency (IEA), “the uninterrupted availability of energy sources at an affordable price” [1]. Energy security concerns itself with guaranteeing that electricity, and fuel for transportation and other uses, remains accessible to all without any notable 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 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 the century in the Portuguese river basins, and thermoelectric plants, fuelled with either coal, oil or, more recently, natural gas [2].

From the standpoint of energy security, this is a very solid system, as both sources of energy are dispatchable, despite some limitations on hydropower. Hydropower can serve as a strong base for electricity production, while leaving the thermoelectric plants to make up for the rest as needed. The only major risks for energy security would be the threat of drought lowering the available levels of hydropower, which was not a common issue last century, and geopolitical issues leading to a lack of imported 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 become necessary to move away from this mode of energy production, in particular, its thermoelectric component, as it became ever clearer the impact that this sector has had in inducing anthropogenic climate change.

As human emissions of greenhouse gases (GHG) increase, leading to a rise in global average temperatures, combatting this trend has become one of the main policy goals of virtually all governments, pushed forwards by strong, international grassroots movements. This means transforming human activity to allow for carbon neutrality, for greenhouse gas emissions to be balanced out by the capture of those gases, retaining atmospheric balance. Portugal has, since the 2016 COP22, committed to achieving carbon neutrality by 2050 [3], a goal that was pushed forward to 2045 at COP27, in 2022 [4].

With Portuguese greenhouse gas emissions at around 60 MT [5], while carbon capture mechanisms being expected to capture 9 to 13 MT of greenhouse gas emissions yearly by 2050 [6], reaching carbon neutrality means necessarily decreasing GHG emissions substantially over the coming years. To this process is given the name “decarbonization”.

In Figure 1, a distribution of GHG emissions by sector in Portugal is displayed.

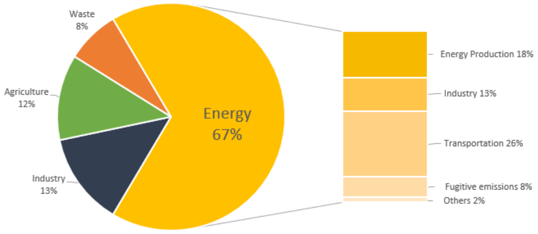


Figure 1 GHG Emissions by Sector, 2020.[7]

The energy sector takes up a large majority of the sources for greenhouse gas emissions, with electricity production, industrial combustion and transportation making up the majority of that. Therefore, it is only sensible that any decarbonization strategy tackles this sector with particular vigour.

The current decarbonization strategy can be summarized as a two-step process, tacking the energy sector in particular. The first step is the electrification of the energy sector, replacing fossil fuels as direct energy sources, electrifying industry and transportation. The second step is to decarbonize electricity production.

Decarbonizing electricity production is generally attempted through installing large capacities of renewable energy sources, mostly photovoltaic and wind power, while phasing out thermal power plants.

This creates an issue of energy security as, unlike the thermal power they are meant to replace, those renewable energy sources are non-dispatchable. They cannot be programmed to operate on demand for the needs of the grid, but rather produce energy on the basis of the availability of the natural resource from which they extract their energy.

In a system dominated by renewable energy sources, even if the capacity is built above demand, there will be moments when there won’t be enough production to cover demand, meaning there will be energy deficits, while at other points, there will actually be an excess of energy production, also capable of causing issues to the energy system.

This project attempts to answer two questions.

The first one is whether the current plan for the energy transition in Portugal will ensure energy security for the coming years.

And, if not, whether there is a solution that can be found to decarbonize the energy system while ensuring energy security in the country.

To answer these questions, a program was created capable of simulating the energy system expected to exist in Portugal in 2035 and 2040, and capable of adding alternative energy sources to the mixture, while outputting the energy balances at a hourly rate and other impacts the system would have, such as greenhouse gas emissions.

2. Methodology and Materials

To verify the energy security of the energy system being planned for Portugal, and to test the results of proposed solutions, a simulation of various scenarios is carried out.

This simulation is for the years 2035 and 2040, and it was created using Python script. As inputs, data from the years between 2015 and 2022 were used. This historical data includes electricity consumption and production, installed capacity and water inflow. The first two were obtained from the ENTSO-E Transparency Platform [8], while the latter two were obtained from REN Data Hub [9].

As for the scenarios used, they were based on the RMSA 2022 report. From this report, two distinct scenarios were used, the Conservative and Ambition ones, whose differences are based on macroeconomic indicators, regarding a more pessimistic or optimistic outlook on Portuguese economic growth.

The program simulates the energy system for each model scenario on an hourly basis, allowing for a comprehensive treatment of the system at each moment of time.

The program is organized through modules, each simulating a distinct energy system, organized as shown in the flowchart in Figure 2.

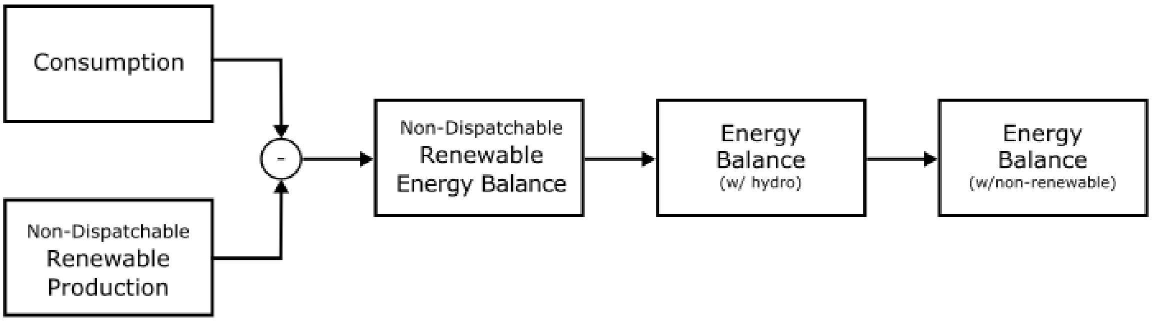


Figure 2 Flowchart of the System Model

The non-dispatchable renewable energy sources are simulated from the historical data, with the capacity factor of each source, for each hour, being calculated, and multiplied by the installed capacity in each scenario. This, combined with the variety of the various historical years, allows for the intermittency of these sources to be simulated.

Similarly, consumption mostly follows current patterns, only with the yearly value increased accordingly to the scenarios laid out in the RMSA. The one significant change to this, in this work, was considering the impact of the introduction of an electrical vehicle fleet, in the context of electrifying transportation energy consumption.

The hydropower system is quite more complex, as it has some dispatchability. Hydropower dams can retain water in the reservoirs and, through that, store potential energy to be later transformed to electricity. Furthermore, by using water pumping systems, excess electricity can be transformed into potential energy to be redeployed later as electricity.

From a control perspective, such a system could be very beneficial, and has led to hydropower dams being often called a “natural battery” [10]. This term is not particularly accurate, however, as sustainability concerns mean that hydropower cannot be used in such a fashion and should, at best, be described as a sort of energy stabilizer, with a regular flow that is changed according to the needs of the energy system in extraordinary situations.

It should also be taken into account that hydropower is already a very saturated system, with very little room to increase installed capacity. In fact, with the prospects of drought for the coming decades in the Iberian Peninsula [11], its role in the energy system should be considered to decrease, although those problems weren’t modelled in this work.

Finally, non-renewable energy sources are considered to be fully dispatchable, that is, they can be connected when it is necessary to fulfil deficits, fulfil a deficit as far as the installed capacity allows it, while not operating during hours with energy balances or excesses.

Through this model, a simulation, and later alternate solutions, can be tested in a thorough manner, that being the bulk of the work.

3. Simulation Results

By running the program through the scenarios laid out for 2035 and 2040 on the RMSA report, it is possible to reach solid conclusions regarding the energy security of the systems being proposed.

In Figure 3, a monotone curve for the balance between energy consumption and the various renewable energy sources is displayed, for the Conservative Scenario for 2035. In the figure, the impact of the various renewable sources can be observed. Namely, it can be observed that, even with all renewable sources, around half of the hours of the year still have deficits, while the other half face excesses instead, which can also be problematic. Non-dispatchable sources do not allow for hourly balances to be established.

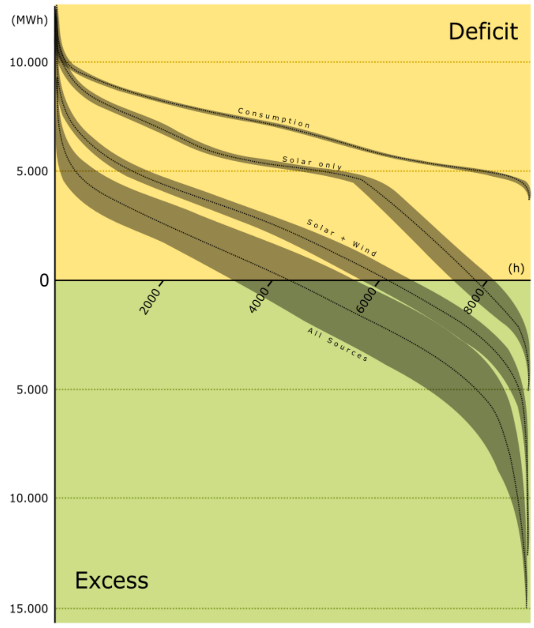


Figure 3 Load Monotone Curves for Consumption and Various Renewable Energy Balances. Conservative Scenario, 2035

Adding the hydropower system allows for a more balanced result to be achieved, due to the greater dispatchability of the hydropower system and the possibility to use pumping. Figure 4 displays the load monotone curve for the Conservative Scenario of 2035 when the hydropower system is added.

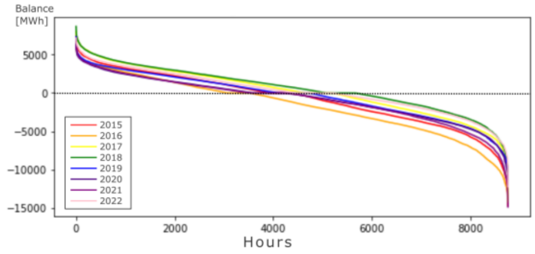


Figure 4 Load Monotone Curve for Balance of Energy including Hydropower. Conservative Scenario, 2035

The limited impact that hydropower can have on the system, due to its limitations in an already saturated system that relies on natural water inflow, is very noticeable.

Finally, adding the non-renewable thermal power sources, meaning the gas-powered thermoelectric plants still available in the scenario, a curve is obtained that further decreases the energy deficits, by providing dispatchable power when needed. That curve is displayed in Figure 5.

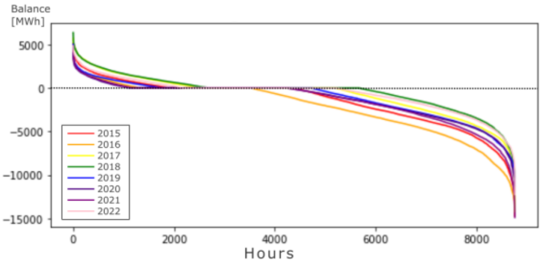


Figure 5 Load Monotone Curve for Balance of Energy including non-renewable sources. Conservative Scenario, 2035

From this graph, a final appraisal of the energy system, as is being considered for 2035 and 2040, in the RMSA reports, can be given, and it is a generally negative one, from the standpoint of energy security. For each year, at least 1000 hours should be expected to run on energy deficits, without enough supply to fit energy demand for the same period.

Also preoccupying is the still great dependence on non-renewable sources in this system, despite those being scaled-back significantly from their current capacity. Calculating, for each simulated year across the various scenarios, the GHG emissions associated with electricity production, one arrives at the graph displayed on Figure 6.

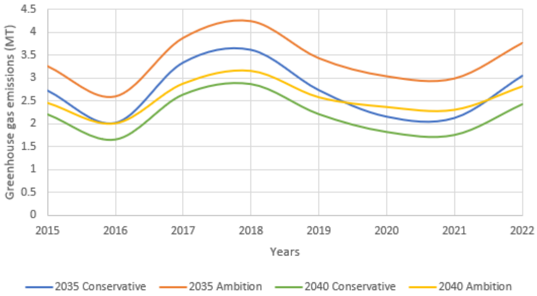


Figure 6 Greenhouse gas emissions by model year for various scenarios of the RMSA-22

Although for each year, a significant improvement on GHG emissions is noted, compared to the actual objectives for those years, that are meant to be consistently below 1 MT of GHG emissions, there is a clear inability to achieve those targets. And adding the consideration that these lower values come with being unable to provide electricity year-round, then it becomes a rather hollow accomplishment.

This end result serves to justify the following parts of the work, as testing other energy sources and energy carrying technologies could improve this problem and make the Portuguese grid more secure and more self-reliable that it is currently planned to be.

4. Adding a Nuclear Baseload

The first part of the project that deals with finding alternative solutions for the energy security crisis adds a nuclear component to the current plans for the energy system in Portugal for 2035 and 2040.

This component is added to the model in the way depicted in the flowchart of Figure 7, between the non-dispatchable renewable energy balance and the hydropower system.

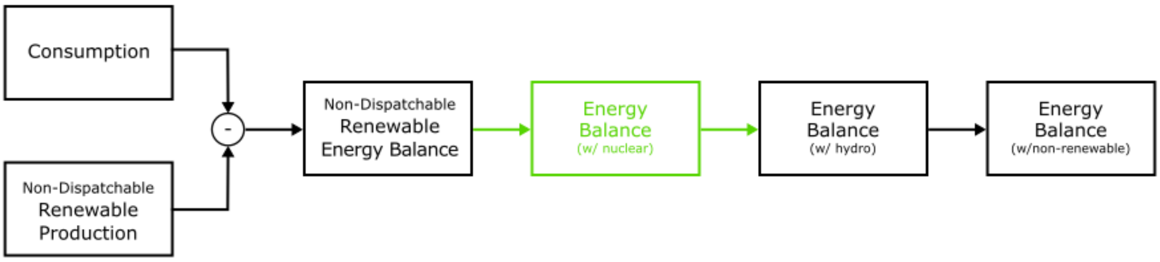


Figure 7 Flowchart for the Energy System including Nuclear Power

This allows for the hydrological strategy to account for the impact that adding nuclear power has to the balance of energy. Ultimately, nuclear power also functions as a non-dispatchable energy source, even if one that, rather than working intermittently, it works as a baseload, producing a constant flux of energy.

This is not, in fact, a correct assessment of nuclear power, has flexibility to its energy production is indeed possible [12], but for the purposes of this model, it was considered to work approximately as such.

The direct impact of the nuclear baseload on the system, therefore, is to shift the balance of energy, across the year, the exact amount of its baseload. Upon allowing for the hydropower system and for the non-renewable energy sources to impact the model as well, however, a different balance is reached, that can be observed by comparing the various graphs in Figure 8, corresponding to the overall balance after implementation of different nuclear baseloads.

For each scenario, the straight line of energy balance goes further to the left, as the number of deficit hours decreases and that of excess hours increases as more of a baseload is added. This straight line also tends to

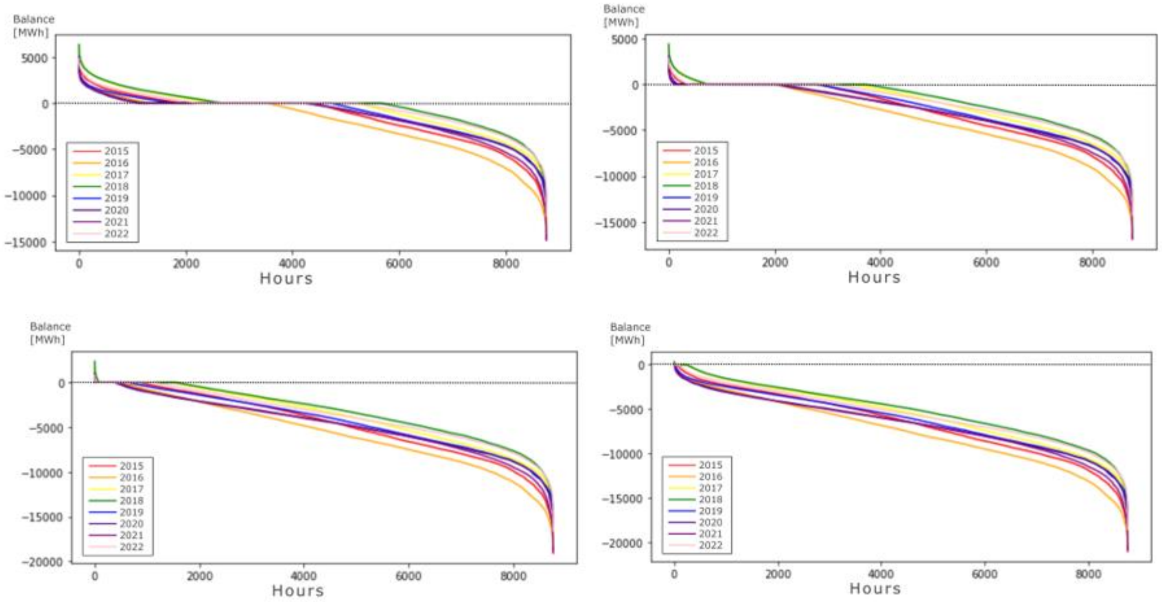


Figure 8 Load Monotone Curves for the system without a nuclear baseload and baseloads of 2, 4 and 6 GW. Conservative Scenario, 2035

disappear, as more and more hours find themselves facing energy excess.

A fuller perspective of the impact that nuclear power can have on the system is understood through observing the graph on Figure 9, where the evolution of the number of hours with energy deficits, the yearly amount of deficit energy, and the yearly required GHG emissions are compared.

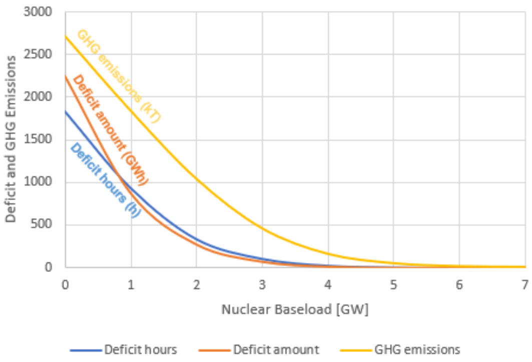


Figure 9 Graphs on Deficit and GHG Emissions in relation to Nuclear Baseload. Conservative Scenario, 2035

A general trend can be observed that, as a nuclear baseload is added, the number of hours facing energy deficit, the total deficit across the year, and the GHG emissions, not only decrease, but that they do so in a logarithmic fashion. This means that, for each increase in the baseload, its impact on the system is lessened that the one before.

	Recommended Baseload (GW)	**% of Deficit Hours** (no baseload = 100%)	**% Deficit Amount** (no baseload = 100%)	**% GHG emissions** (no baseload = 100%)
2035 Conservative	3	5.8%	3.2%	16.8%
2040 Conservative	4	3.0%	1.3%	7.5%
2035 Ambition	4	6.2%	2.8%	15.4%
2040 Ambition	5	5.1%	1.9%	9.5%

Table 1 Recommended Nuclear Baseloads by Scenario, with their respective impact on the system

This is quite sensible, as there are less hours to cover, but it does mean that, while the cost of adding a greater baseload remains mostly constant [13], the returns on that system are increasingly smaller, making the required investment less appealing. The problem of excess energy is also important to account for.

With that considered, some conclusions on this study can be made. While nuclear power alone is not able to fully cover the deficits encountered in the energy system, at least in an economically sound manner, adding a nuclear baseload of a modest size could be helpful at alleviating the issues caused by the energy transition. A sensible solution could be considered for a nuclear baseload of 3 to 4 GW for 2035, depending on the macroeconomic scenario, with a further GW being added by 2040. In Table 1, the impact that such baseloads would have on the system, compared to its performance in their absence, is displayed.

There is a massive improvement on all fronts, considerably reducing the stress on the grid. In particular, GHG emissions do reach a level much closer to that which is hoped for those years, in the decarbonisation process.

However, this solution still has its issues, namely that it does not completely solve the problem of energy security, especially with a less favourable hydrological scenario, as is expected to happen, and it still leads to worrisome amounts of electricity excesses throughout the years, that could render the electricity market in Portugal inoperable.

Finding solutions to those particular issues demands looking beyond nuclear power.

5. Adding Hydrogen Production

A final part of the proposed solution is adding a hydrogen economy component, in the form of a power-to-power system.

The production of hydrogen is accomplished through water electrolysis, as the most developed method of sustainable energy production [14], and which is accomplished through the water splitting reaction. The reverse reaction is also used to transform hydrogen back into electricity.

Through these two transformations, carried out by electrolyzers and fuel cells respectively, energy can be stored chemically in the hydrogen. This allows excess electricity to be consumed productively and stored for later use during hours facing electricity deficit, helping to further balance the system. Beyond this, hydrogen has a value beyond electricity, being consumed for industrial purposes and having interesting prospects in terms of transportation based on hydrogen fuels.

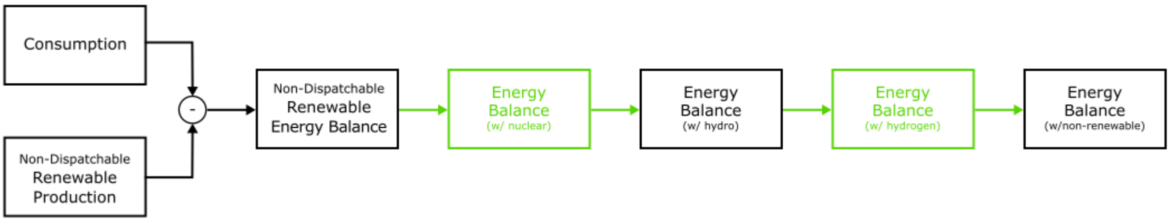


Figure 10 Flowchart of the Energy System with a Nuclear Baseload and Hydrogen System

Hydrogen can therefore be produced with a surplus, creating a valuable resource that helps decarbonize other parts of society and create added value to the electricity system to help fund its decarbonizing transition.

This hydrogen system is inserted into the overall model between the hydropower system and the non-renewable energy sources. This helps promote a fuller decarbonization, even if sacrificing some hydrogen output in the process. The model then appears as displayed in the flowchart of Figure 10.

In the simulations that were run in this work, a hydrogen system with an installed capacity of 2.5 GW, both for electrolysers and fuel cells, was used, following the investments that were expected at the time in Portugal in regard to hydrogen production [15].

Considering the expected system efficiencies for electrolysers [16] and fuel cells [17] for the coming years, the overall system efficiency for the power-to-power hydrogen system that is being proposed here would be around 40%. Because of this, for the hydrogen system to function properly, an energy surplus would be necessary, that is, for excess electricity to considerably surpass deficit electricity.

Because of this, the hydrogen system's impact is rather limited when there is no nuclear baseload, but it improves substantially once a baseload is implemented. A comparison of the

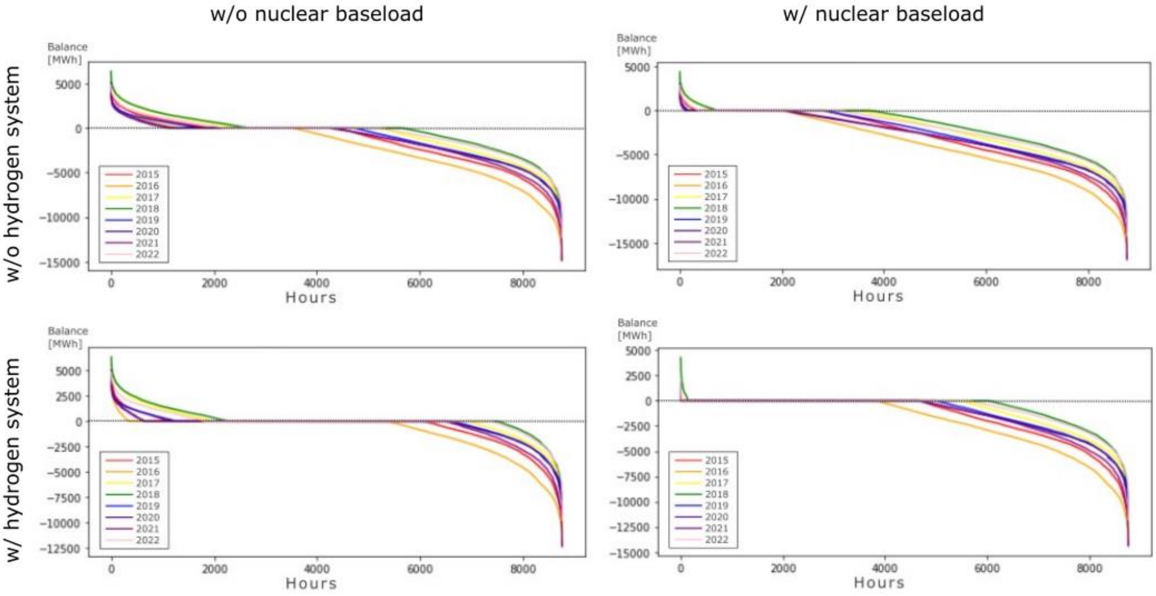
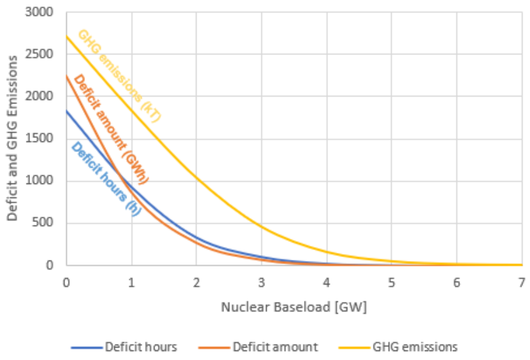
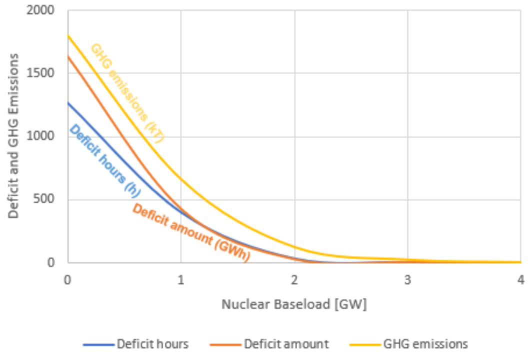


Figure 11 Load Monotone Curves for Systems in different configurations. Conservative Scenario, 2035

various systems' impact is provided in Figure 11, comparing the load monotone curves of the originally modelled system, with systems where a nuclear baseload of 2 GW is added, a hydrogen system of 2.5 GW is added or both systems are added.

The impact of the hydrogen system is quite visible in the graphs of Figure 11, helping to decrease the number of hours with deficit and bringing greater balance to the system as a whole. The necessity of, to this system, adding a nuclear baseload is also quite intuitive, but the graph displayed in Figure 12 helps further demonstrate the impact that these two systems can have working in tandem.





Including the hydrogen system allows for the deficit values and GHG emissions to fall to near zero with a smaller nuclear baseload.

Another important aspect to consider when making a decision is the commercial availability of hydrogen through this system. The graph on Figure 13 displays the total amount of hydrogen produced and the amount stored at the end of the year, available for commercialization, for each nuclear baseload.

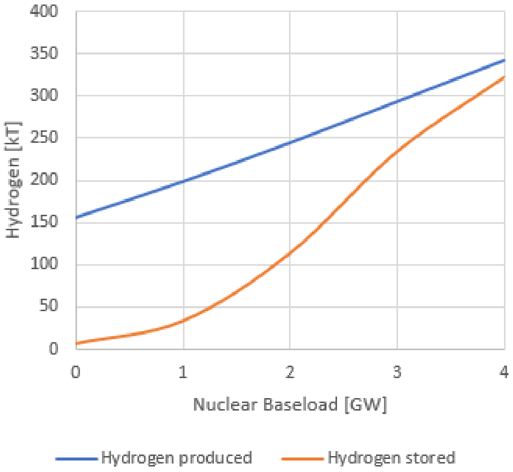


Figure 12 Hydrogen Produced and Sotred throughout the Year for different Baseloads. Conservative Scenario, 2035

While the curve for hydrogen production is almost perfectly linear, rising around 40 kT of hydrogen produced for each added GW of nuclear power, the curve for hydrogen stored at the end of the year behaves rather differently, at first being rather small, but increasing faster and nearing the value of hydrogen produced and approaching linear behaviour, allowing for the storage of an extra 120 kT of hydrogen by having a baseload of 3, rather than 2 GW.

This has a significant impact in assessing the best solution for the problem, especially if commercializing hydrogen is seen as lucrative.

	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 2 Recommended Nuclear Baseloads by Scenario, with their respective impact on the system

A full system recommendation, as depicted in Table 2, must account for this.

The recommendation operates with the assumption that the commercialization of the hydrogen is, at least, somewhat viable, and hence finds a balance between increasing hydrogen for commercial use and maintaining investment costs.

Under these conditions, yearly hours facing energy deficits and GHG emissions are practically negligible, while around 90% of the hydrogen produced each year is commercially available. Although this might require, at least for the year 2035, a larger baseload than the previous recommendation, this added investment comes with the benefit of significantly increasing the hydrogen output of the system for commercial use.

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.

6. Conclusions

Returning to the two questions that were presented in the introduction as defining the scope of this project, answers can now be provided to them.

Does the current plan for the energy transition in Portugal will ensure energy security for the coming years? The answer is decidedly negative. There is a consistent pattern of a sizeable percentage of hours across the year not having nearly enough capacity to fulfil demand. Concurrently to these times of scarcity, there are also plenty of hours with an overabundance of electricity, overloading the grid and creating unprofitable, even negative prices for it. This is also a problem that might make energy production systems commercially unviable.

Relying on the interconnections with Spain is probably not enough, especially as that country is expected to undergo its own transition process very similar to the Portuguese one [18], that could lead to similar issues.

There is a energy crisis coming to Portugal, if the current path of energy transition is followed. New solutions must be found.

As for the second question, is there a solution that can be found to decarbonize the energy system while ensuring energy security in the country? The answer is positive. The solution proposed in this project, using nuclear power and a hydrogen power-to-power system, creates an economically viable energy system that does not suffer from the same problems of energy security and decarbonizes the economy profoundly.

There is no denying that there are political and economic constraints to this solution, but that there is a functional way to accomplish this transition is, in itself, already good news. Work must be done to either build such a solution, or find a new one, and it must be done as quickly as possible, as 2035 is not very far ahead.

7. Future Work

There are a number of questions and areas of research that this project, more than finding solutions, simply begs the question.

The simulation can be perfected in many ways, changing consumption patterns in ways that weren't explored here, such as increasing residential heating and cooling, or increased working-from-home situations, or the myriad of other complex societal details that could impact energy consumption patterns. A simulation is always an exercise in imperfectly modelling real life, and there is room for improvement and for making things more complex and life-like.

An important improvement, for example, would be allowing the system to simulate the Iberian market as a whole, to answer more firmly the question of the energy crisis within the actually existing conditions of the grid.

There are also many more scenarios that could be tested, beyond the ones from the RMSA report, that should be tested in this program. And more than test these scenarios, the program could be made to find its own optimal solutions, given parameters to work with.

A deeper and more complex economic study of the entailed projects would also be very important, detailing the investments that would be necessary and the energy return that would be accomplished, so that economic feasibility could be ensured.

There is still much that can be continued from this point. Finding a solution to the energy crisis will be a complex process. Our hope is to have done a good contribution in that direction.

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