Nuclear power in Portugal’s energy transition

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Abstract - **This thesis investigates the feasibility of incorporating nuclear power into Portugal's energy mix to achieve carbon neutrality by 2050. Through the utilization of the EnergyPLAN modeling system, reference and predictive models are developed to assess various scenarios and their implications.**

The findings demonstrate that, with a lower installed capacity, nuclear power can play a significant role in decarbonizing Portugal's electricity generation sector by 2040. The inclusion of nuclear power offers reliable and uninterrupted electricity generation, reducing the reliance on external interconnections for power balancing and minimizing the need for extensive interconnection infrastructure. Notably, nuclear power presents cost advantages when compared to renewable energy-focused models.

Public opinion plays a crucial role in shaping policy decisions concerning nuclear power. Effective communication strategies that prioritize transparency, education, and engagement are essential to address concerns and foster positive public perception.

This research provides valuable insights and recommendations for policymakers, energy planners, and stakeholders involved in Portugal's energy transition. The findings support informed decision-making, highlighting the potential of nuclear power as a reliable, low-carbon energy source. Emphasizing the importance of a diversified energy mix, this study contributes to Portugal's pursuit of a sustainable and resilient energy system, aligning with its ambitious carbon neutrality goals by 2050.

Keywords: nuclear power, Portugal, energy transition, carbon neutrality, EnergyPLAN

1 Introduction

1.1 Motivation

The increased use of fossil fuels and global population growth have disrupted the earth's climate and weather patterns, leading to unpredictable and extreme weather events. Without corrective action, this instability will have far-reaching consequences, causing social, political, and economic chaos. The Paris Agreement, signed by Portugal and other countries in 2015, set the goal of limiting global warming to a maximum of 1.5°C above pre-industrial levels, requiring an 80% reduction in GHG emissions by 2050. However, recent reports from the Intergovernmental Panel on Climate Change (IPCC) highlight that current commitments fall short by approximately 20% of the necessary reductions needed by 2030. Portugal's GHG emissions, as displayed in Figure 1, have not shown a clear downward trend, posing a significant challenge for achieving the 2050 goal [1] [2].

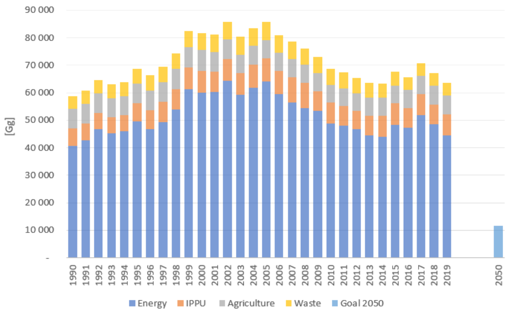

Figure 1 - GHG emissions by sector in Portugal from 1990 to 2019 and minimum goal for 2050 [1][2]

The potential role of nuclear energy in the transition to a low-carbon future is being evaluated globally.

1.2 Objectives and scope

The objectives of this thesis are:

- To analyze the Portuguese plan for achieving carbon neutrality by 2050, including the targets and strategies outlined in the plan.

- To assess the potential role of nuclear power in the Portuguese energy mix as a means of achieving decarbonization objectives.

To accomplish these goals, the thesis employed the EnergyPLAN modeling system to develop models, enabling the comparison of various scenarios and their implications.

2 Portuguese framework

2.1 Power Sector

To comprehensively assess Portugal's energy consumption, it is essential to consider both primary energy and FEC. Figure 2 provides an overview of Portugal's primary and FEC, along with domestic production. In 2021, primary energy consumption remained relatively stable at 20.817 ktoe, while FEC witnessed a significant increase of nearly 5% within a year, amounting to 16.148 ktoe. With domestic production at 6.882 ktoe, it becomes evident that Portugal heavily relies on fuel imports to meet its energy needs.

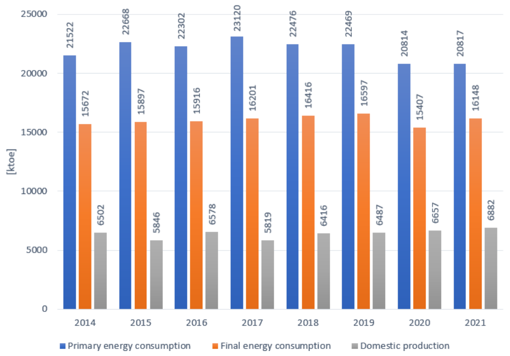

Figure 2 - Primary energy consumption, final energy consumption and domestic production from 2014 to 2021, adapted from [3], [4].

Portugal's energy dependence (ED), the level of reliance on imports to meet the country's energy needs, remains significant within the EU, despite a notable decrease in fossil fuel consumption. In 2021, the ED was 67,1%, a 1,3 percentage point increase from 2020. This rise can be attributed to the substantial growth in the electricity import balance, which saw a 226% increase compared to 2020, reaching 409 ktoe. The import balance for all energy sources increased by 369 ktoe (+2,5%) compared to the previous year. However, domestic energy production experienced a modest 3,4% increase [3], [4].

Figure 3 illustrates the total imports (IMP), exports (EXP), FEC, international maritime navigation (IMN) and international aviation (IA) values used to compute the Portuguese ED from 2015 to 2021.

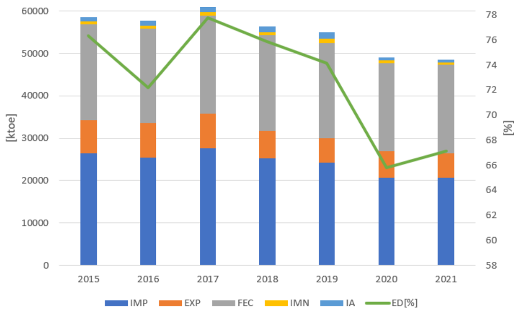

Figure 3 - Imports, Exports, FEC, IMN, IA and ED in Portugal from 2015 to 2021, adapted from [3].

Oil emerged as the primary energy source for Portugal, accounting for 44,4% of the country's FEC (40,6% of primary energy consumption). Conversely, coal consumption experienced a significant decline of 65,4% compared to 2020, primarily due to the cessation of coal-based electricity production in Portugal.

The industry and transportation sectors collectively account for over 60% of Portugal's FEC. The transportation sector held the largest share in 2021, representing 34,1% of the FEC, followed closely by the industry sector at 30,8%. The domestic sector accounted for 18,6% of the energy consumption, while the services sector constituted 13,3%. The remaining energy consumption was attributed to the agriculture and fishing sector, making up 3,2% of the total.

2.1.1 Electricity sector

Hydro power plants play a big role in Portugal and their production is dependent on the precipitation of each year. In 2016 hydro was responsible for almost 30% of the gross production, but in 2017 it had a share lower than 15%. Such variability is complemented with production from fossil fuels, notable in 2017 where nonrenewable thermal represented about 60% of gross electricity production and the import balance favored the export direction. With the gradual decrease of coal as primary energy from 2017 to 2021, the import balance reached a maximum favoring import. Figure 4 illustrates the gross electricity production from 2014 to 2021.

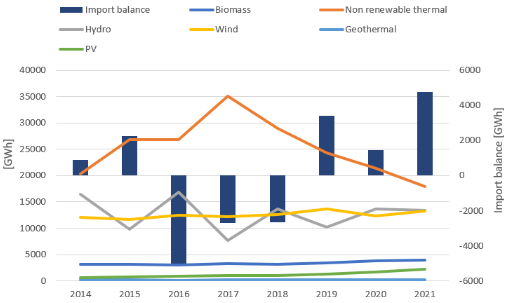

Figure 4 - Import balance and electricity generation by source from 2014 to 2021, adapted from [3], [4]

In 2021 renewable generation supplied 59% of the Portuguese demand. Wind power was the most important renewable source, accounting for 26% of total consumption, while hydro power accounted for 23%. Biomass provided around 7% of total consumption, while solar photovoltaic (PV) provided 3,5%. Natural gas contributed 29% of nonrenewable use, while coal, which was already somewhat residual, supplied 1,4%. The trade balance with other nations favored imports, which accounted for 10% of domestic consumption [3], [4].

Figure 5 shows the development of the, commercially used, interconnection capacity in the import and export directions between the year MIBEL began operating (2007), and 2021.

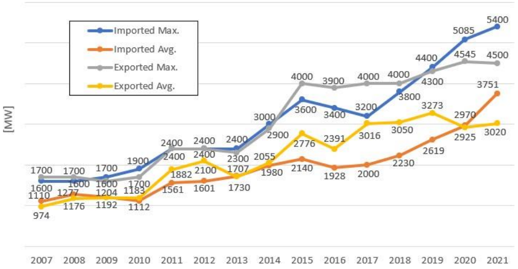

Figure 5 - Evolution of interconnection capacity available for commercial purposes, adapted from [5]

The order of magnitude, of the export capacity, was maintained from 2020 to 2021. For the import direction, the pattern of rise shown from 2017 to 2020 was confirmed in 2021, reaching a maximum value of 5.400 MW. Average values showed a significant rise from 2.970 MW to 3.751 MW in comparison to 2020 [5].

2.1.2 Transportation, Heating and Cooling sectors

From 2015 to 2021, Portugal's final energy consumption (FEC) experienced slight growth, but the COVID-19 pandemic caused a decrease in 2020 and 2021. In 2021, FEC was around 16.15 million tonnes of oil equivalent (Mtoe), with the transportation sector accounting for 34% of total energy consumption. Road transport dominated the sector, while domestic aviation, navigation, and rail transportation had smaller shares. Oil and its derivatives constituted 98.8% of the transport sector's FEC in 2021, while electricity had a minimal share due to partial electrification of rail transport. Portugal historically had low heating and cooling demand, resulting in low energy efficiency in the housing sector. Cooking accounted for the largest portion of home energy consumption, followed by ambient heating, electrical equipment, and water heating. Cooling and lighting had negligible energy consumption. The majority of domestic heating relied on individual electric heaters, although central heating has increased. Ambient cooling equipment was used by a small percentage of households, while the majority had ambient heating equipment [6].

2.2 Nuclear Energy

Nuclear power has drawbacks such as the risk of radioactive pollution and the challenges of nuclear waste management. Accidents like Chernobyl and Fukushima have had a significant impact on public perception of nuclear power. Despite safety measures, catastrophic events shape opinions. However, nuclear power has a low death rate per unit of electricity generated. Effective management of nuclear waste remains a challenge, although reprocessing can reduce waste volume. Long-term waste disposal involves storing it in specially designed containers in stable, underground locations. Nuclear power is considered secure, stable, and reliable, with a low carbon footprint compared to fossil fuels. It can complement intermittent renewables and provide a baseload option. With ample uranium reserves, Portugal could enhance energy system resilience. Incorporating nuclear energy alongside renewables offers a promising path towards decarbonization [7].

3 Modeling energy systems with EnergyPLAN

3.1 EnergyPLAN - Advanced Analysis of Smart Energy Systems

EnergyPLAN offers several advantages as an energy system modeling tool. It features a user-friendly interface that allows non-experts to utilize it without extensive training. The software is highly flexible and customizable, enabling users to tailor it to their specific needs. It integrates environmental impacts, heat, and transportation sectors, allowing for optimization of the entire energy system, including sector interactions. EnergyPLAN is also open-source and transparent, enabling users to understand and modify its underlying assumptions and calculations. However, the software's bottom-up approach necessitates a substantial amount of input data, which can be time-consuming and challenging to gather. Additionally, the quality and accuracy of the input data greatly influence the simulation results, highlighting the software's dependency on data reliability [8].

3.2 Energy Demand

According to the RNC2050 [9], there will be a reduction between 22% and 25% of the FEC, compared to 2015 and a growing electrification of the economy. Considering the 22% reduction, linear, until 2050 and that electricity will represent 50% and 65% of the total FEC by 2040 and 2050, respectively, Table 1 summarizes the demands considered for this work.

Table 1 - Total and electricity FEC for 2015, 2040 and 2050

FEC [TWh]	2015	2040	2050
Total	185	156	144
Electricity	48	78	95

Climate change will have a significant impact on Portugal's heating and cooling needs in the future. While winters are expected to become milder, summers will become hotter, leading to a decrease in heating demands and an increase in cooling demands. The focus of future heating system improvements will initially be on reducing the heating gap, while the overall heat demand is assumed to remain the same as in 2020. The main change will be in how heat is produced. Cooling demand is projected to increase by 40%. In the transport sector, significant changes are expected due to the introduction of new technologies and mobility concepts. The thesis assumes total electrification of the transport sector, while keeping the total kilometers traveled by each technology the same as in 2021. Any improvements in efficiency are offset by an increased desire to travel. The industry sector in Portugal contributes 13% of greenhouse gas emissions, mainly due to the use of fossil fuels for high-temperature industrial processes. Although energy consumption is assumed to remain the same as in 2021, coal and oil are replaced by hydrogen, while any efficiency improvements are balanced out by sector growth.

3.3 Energy Supply

This study examines the reference models (R-2040 and R-2050) aligned with the RNC2050 guidelines for Portugal's energy transition. The government aims to achieve complete decarbonization of the electricity generation sector by 2050, with solar PV and wind accounting for 50% by 2030 and 70% by 2050. Natural gas will be retained until 2040 for grid stability, and batteries are expected to become cost-effective by 2025. The predictive models (P-2040, P-2050, and P-2050R) analyze the integration of nuclear power. The minimum nuclear installed capacity required to meet the electricity demand for the entire year is 4,000 MW, and P-2050 expands nuclear capacity by 50% to meet the demand in 2050. P-2050R focuses on increasing wind and solar capacities while maintaining the 4 GW nuclear capacity. Hydro capacity remains at 7.1 GW due to anticipated availability decline, and dammed hydro water supply is constrained to achieve a consistent 6.36 TWh electricity production across all models. The study takes an optimistic view on renewable energy sources and a more pessimistic view on nuclear power.

3.4 Costs

There are several sources for cost forecasts. Lund et al. [63] demonstrated the difficulty of predicting future prices and concluded from a historical review of earlier projections that all of them were incorrect. As a result, cost forecasts are less essential than they appear at first because no prediction will be able to attain accurate figures. This thesis makes use of the EnergyPLAN's cost database for 2050 [64]. It comprises values that have been scientifically examined and are thus appropriate for the goals of this thesis. The referred database served as the foundation for both the reference and predictive models, allowing a more accurate comparison of the expenses of each model.

4 Results

The installed capacities of the energy models provide insights into the composition and scale of the energy generation infrastructure. Figure 6 illustrates the installed capacities of the different models. It is possible to observe a major discrepancy in total installed capacity which reaches 53,75 GW in the reference models and 36,20 GW (33,70 GW when an expansion in nuclear capacity is considered) for the predictive model by 2050.

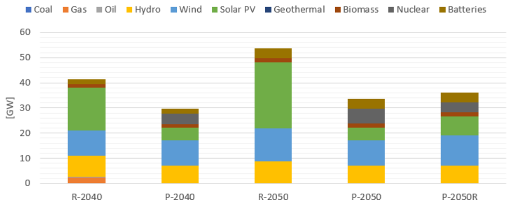

Figure 6 - Installed capacities [GW] for the different models

An overview of electricity production by source, for the different models, is illustrated by Figure 7.

In summary, nuclear power, despite its lower installed capacity, provides a significant portion of electricity due to its high load factor and operational continuity. The data underscores the potential of nuclear power as a reliable energy source, even with a lower efficiency of 33% compared to other sources.

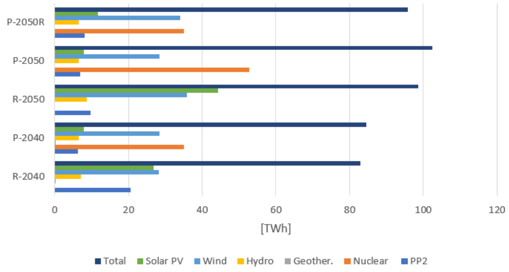

Figure 7 - Electricity production [TWh] for the different models

Analyzing Figure 8, which shows the interconnection capacities required by the different models, in order to avoid CEEP and to allow the electricity demand to be supplied, it is clear the reference models require higher interconnection capacities.

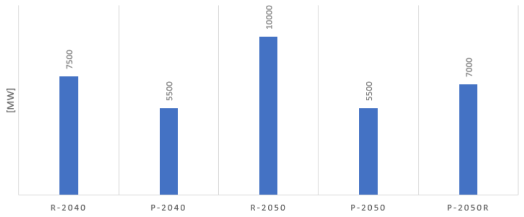

Figure 8 - Interconnection capacities [MW] for the different models

Figure 9 illustrates the results for annual CO2 emissions for the reference and predictive models in 2040 and 2050.

The predictive models achieved lower levels of CO2 emissions, with both 2040 and 2050 recording 2,94 Mt annually. In fact, this represents a decarbonized energy supply system. Such emissions are due to the industry sector demand. The inclusion of nuclear power in these models contributed to emission reductions compared to the reference models.

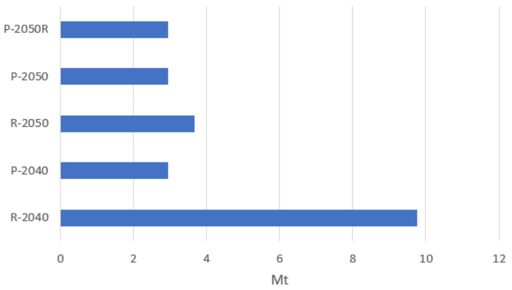

Figure 9 - CO_2 emissions [Mt] for the different models

Figure 10 presents an interesting comparison of the various costs associated with different energy models, showing that nuclear power can offer substantial benefits in certain contexts.

Examining the total investment cost, it is clear the predictive models incorporating nuclear power represent more economical options compared to the reference models that predominantly rely on RES.

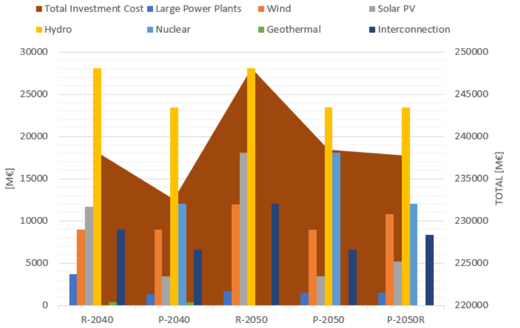

Figure 10 - Total and individual investment costs [M€] for the considered installed capacities, by each model

As the data illustrates, the annual investment costs adhere to the same trend as the total investment costs. The fixed operations expenses follow suit, rendering the reference models - which emphasize RES - as the more substantial investment. However, the major advantage of RES lies in its lack of fuel consumption, which results in lower variable costs, especially in the case of the 2050 reference model. Contrastingly, the 2040 reference model continues to depend heavily on natural gas, thus incurring significant costs associated with natural gas exchange as well as exchanges of other fuels. It's noteworthy that model P-2050R, despite its higher share of RES and, consequently, reduced fuel consumption, does not exhibit lower variable costs than model P-2050.

Despite the initial investment cost associated with nuclear energy appearing quite substantial, the reliable generation reduces the dependency on external interconnections for balancing power supply, thereby curbing the additional costs associated with expansive interconnection infrastructure. An investment in 26,20 GW of solar PV equates to an expenditure of 18.078 M€, which is marginally lower, by 42 M€, than the cost for 6 GW of nuclear power. The impact of enhanced interconnection capacity is particularly evident in the reference models, where the cost of 7.500 MW of interconnection capacity matches that of 10 GW of wind power capacity, both standing at 9.000 M€. Interestingly, in the model P-2050R, augmenting the solar PV and wind capacity by 2GW and 2,5GW respectively proves to be more cost-effective than extending the nuclear installed capacity by 2GW, even when accounting for the increased requirements for interconnection.

The additional cost of 1,4 GW in hydro power capacity in the reference models is indeed notable, standing at 4.620 M€. It represented an increase of 0,5 TWh for 2040 and 2 TWh for 2050. When analyzing the annual costs, it's essential to take into account not only the fixed operation expenses, but also the variable costs as clearly delineated in Figure 11. As the data illustrates, the annual investment costs adhere to the same trend as the total investment costs. The fixed operations expenses follow suit, rendering the reference models - which emphasize RES - as the more substantial investment. However, the major advantage of RES lies in its lack of fuel consumption, which results in lower variable costs, especially in the case of the 2050 reference model. Contrastingly, the 2040 reference model continues to depend heavily on natural gas, thus incurring significant costs associated with natural gas exchange as well as exchanges of other fuels. It's noteworthy that model P-2050R, despite its higher share of RES and, consequently, reduced fuel consumption, does not exhibit lower variable costs than model P-2050.

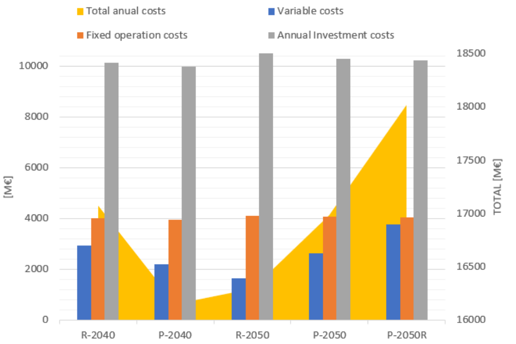

Figure 11 – Annual investment, fixed operations, variable and total annual costs [M€] for the different models

Figure 12 provides a dissection of total annual costs. the significant variation here is that the variable costs presented, deliberately omit the costs tied to electricity exchange. The influence of electricity imports on annual costs becomes evident from this data. As expected, in the absence of electricity exchange costs, model P-2050 now exhibits higher variable costs than model P-2050R.

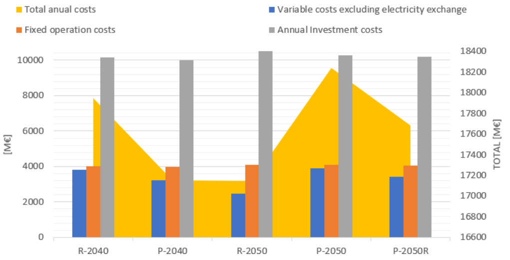

Figure 12 - Annual investment, fixed operations, total annual and variable costs excluding electricity exchange costs [M€] for the different models

5 Conclusion

The study highlights a difference in installed capacity between reference and predictive models by 2050. Nuclear power plays a significant role in electricity generation despite lower capacity. It can lead to decarbonization by 2040, while insufficient battery capacity emphasizes the need for dispatchable sources like nuclear power. Nuclear energy reduces interconnection costs, and though renewable energy has lower variable costs, intermittency can increase costs.

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