# Nuclear Energy in the context of decarbonization and Portuguese energy mix

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**Abstract**

Considering that the world is facing the greatest challenge in human history, and given the urgency of reducing $CO_2$ emissions, the main goal of this thesis was to present a feasible alternative to the government's plan (RNC2050). A modeling program was used to examine the Portuguese design and determine its practicality. Wind energy was determined to be the renewable energy source with the most promise, but solar energy was found to be less cost-effective. The battery requirement was greater than anticipated in the plan. Due to the lack of a stable energy basis, concerns about supply security have been raised (according to the plan, it will be the hydro and batteries). The viability of building a nuclear power station in Portugal as a low-carbon energy source and to achieve carbon neutrality by 2050 was investigated. Again, a modulation tool was used to model how the energy mix would change if nuclear power were included, as well as predicted electrical generation. The addition of a nuclear power plant to the energy mix proved to be economically viable. It would boost supply security and generate revenue. It would relieve pressure on renewable energy targets, allowing decarbonization to be achieved. However, changing public opinion and assessing the dangers will be required. A quick life cycle analysis was used to assess the benefits and drawbacks of solar, wind, and nuclear technologies.
**Keywords:** Climate Change; Decarbonization; Carbon Neutrality; Nuclear Power in Portugal

## 1. Introduction

Global warming has already proven to be the most difficult challenge civilization has ever faced. The Paris Agreement, adopted in 2015 at the 21st Conference of the Parties in Paris, said that it is critical to keep global average temperature increases below 2°C over pre-industrial levels in order to mitigate and control the effects of climate change. The international community also agreed to attempt to keep the temperature rise below 1.5 degrees Celsius [17]. It would be essential to reduce 45% of greenhouse gas emissions (GHG) during the 2020-2030 decade in order to keep world average temperature increases below 1.5 degrees Celsius. Global current policies are heading for an increase of 14%.

The European Commission introduced the European Green Deal towards the end of 2019 and pledged to achieve carbon neutrality by 2050, i.e. zero net GHG emissions [4]. To make this achievable, all member states were required to submit plans and objectives that might be met by 2050. The Portuguese government created the National Energy and Climate Plan 2021-2030 (PNEC2030) and the Roadmap for Carbon Neutrality 2050 (RNC2050), both of which outline the steps needed to reach carbon neutrality by 2050.

To achieve carbon neutrality, the European Commission categorized certain nuclear and gas activities as transactional in early 2022 - those that cannot yet be replaced by low-carbon alternatives and are commercially viable and contribute to climate change mitigation[7] [8].

The description of the problem above reveals the urgency of drastic climate action. Despite the fact that Portugal has already produced a Carbon Neutrality Roadmap and is one of the Member States with the highest percentage of renewable energy in its energy mix, it is critical to provide alternatives and challenge the plan's practicality. This thesis was written with the goal of examining the RNC2050's practicality and presenting an alternate option.

It is critical to ensure the safety and reliability of the Portuguese energy system, and we cannot compromise the electricity supply despite our primary goal of carbon neutrality. The main goals of this thesis are to analyze the Roadmap for Carbon Neutrality in 2050, to simulate energy needs according to the government plan, design a nuclear power plant that will serve as a basis for the Portuguese energy mix, simulate the energy mix with the insertion of a nuclear power plant in Portugal, and make an integrated assessment of solar, wind, and nuclear technologies.

## 2. Background

This section provides a quick overview of Portugal's current energy mix as well as an overview of nuclear energy's global status.

### 2.1. Energy mix and Consumption in Portugal

It is crucial to analyze consumption by sector in order to frame Portugal's energy needs. Since 2000, the transportation sector has accounted for the biggest share of consumption; oil and petroleum products constitute the industry's primary, and practically sole, energy source. In addition, the industrial sector accounts for a large portion of total consumption.

Despite a significant decrease in fossil fuel consumption, Portugal is one of the European Union countries with the highest energy dependence[1]. This metric indicates how dependant an economy is on imports to meet its needs. In 2018, energy dependence was 75.9%. Portugal was the 7th most energy-dependent country in the EU27, with a dependency rate of roughly 20% higher than the EU27 average.

Import balance has been declining over the years. This decline is mostly due to an increase in domestic energy output, which is mainly caused by the growing trend in renewable energy penetration and a strong focus on and support for self-consumption.

In 2018, the installed power for electricity production in non-renewable power plants was mostly in natural gas plants without cogeneration. All renewable power plants, to a greater or lesser extent, have seen their installed power increase. Production through photovoltaics had an increase of almost 1000% compared to 2008 values.

### 2.2. Nuclear Energy

The biggest investment in nuclear energy was made between 1970 and 1985, with the construction of about 63% of the total of operational reactors today. Although there was a strong desire for an atomic future, many governments judged that the risks outweighed the benefits due to various technical difficulties encountered , particularly the catastrophic disasters at Three Mile Island in 1979, Chernobyl in 1986, and Fukushima in 2011. The development of additional reactors has come to a halt over the years.

Worldwide, in 2020, 442 reactors were operational, of which 358 have at least 25 years of operation. Nuclear energy produced roughly 10% of total electricity in 2019, and production has been increasing in recent years. There are around 50 reactors under construction around the world.

The future, as we all know, will have to be carbon-free. Nuclear energy is currently the world's second largest source of clean energy, and it cannot be ruled out as a viable option for achieving decarbonization. The International Energy Agency's annual report proposes a 55 percent increase in nuclear electricity output by 2040 as one of the paths to a carbon-free environment. Since 2012, the production of energy from nuclear power has been increasing globally, with nuclear generation in Asia increasing by nearly 17% in 2019. The generation in Africa, South America, and Eastern Europe grew as well, but with less vigor. Nuclear power generation has decreased slightly in North America and Central Europe.

Opinions differ within the European Union: Germany, Spain, and the Netherlands want to phase out all nuclear-powered production. Belgium aims to gradually phase out its nuclear power plants. Reactors are under construction or planned in Bulgaria, Slovakia, Finland, Hungary, the Czech Republic, Romania, and Sweden [18].

## 3. Evaluation of the Portuguese plan

In this section, we explain the criteria used to create a model that is similar to the one developed by the RNC2050, as well as the projection based on the government's efforts and plans for reducing GHG emissions.

### 3.1. Criteria taken into account for the creation of the model

Portugal aims to achieve carbon neutrality in 2050. For this to be possible, it was defined that in 2030 the reduction must be from -45% to -55%, in 2040 from -65% to -75% and, finally, from -80% to -90% in 2050.

The OSeMOSYS modeling system was utilized to create the model, which enables not only an integrated long-term assessment but also energy mix planning. Given capacity and technological limits, OSeMOSYS utilizes linear programming to minimize discounted power system costs. In order for the model to be reliable, it was needed to forecast energy consumption until 2050, taking into account possible population growth and the economy's growth trajectory. The final consumption of electricity is expected to follow a similar path as in figure 1.

The model created in OSeMOSYS is represented by technologies that produce and use different energy sources (fuels). For each modeling year, all technologies defined in the model have associated operational and investment expenses. The goal

[1]Energy dependence is given by the amount of energy that must be imported in relation to its consumption

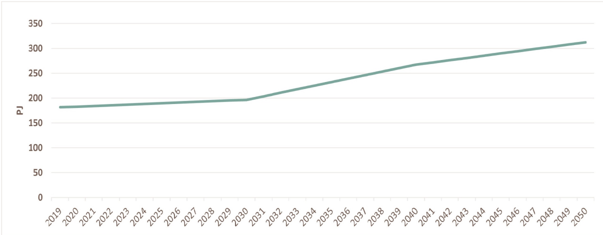


Figure 1: Forecast of final electricity consumption in Portugal. Fonte: RNC2050

of OSeMOSYS is to allocate the best feasible use of these technologies, given their costs, technical qualities, and user-defined criteria, in order to fulfill the above-mentioned power consumptions. Because it is critical to incorporate consistent data into these models, values for costs, particular efficiencies, capacity factors, construction and life durations, and emissions were defined using IEA-ETSAP E-TechDS data sheets [1].

The model's goal is to minimize the overall discounted cost of the technologies utilized $(t)$ over a time horizon expressed in years $(y)$, while ensuring that the defined consumption is met. The total discounted cost is calculated using the sum of all technologies' capital, fixed and variable costs, as well as the cost of emissions $(e)$ per technology (Equation 1). The technologies are determined by the capacity factor $(c)$, the efficiency of fuel conversion $(\varepsilon)$, the operational lifetime $(yy)$ , and emissions $(e)$. To ensure that consumption is met, the model must comply to the constraint in the equation 2: both the final and intermediate fuel consumptions of the technologies in each time frame $(l)$ must be less than the fuel supply produced by the total installed capacity of the technologies (which is multiplied by a $k$ factor that converts the capacity in GW to PJ). This capacity may have existed previous to the modeling period, or it may be installed as needed each year. Refer to the OSeMOSYS documentation for more information on all of the equations used [13] [12].

$$
\begin{aligned}
Min \sum_y TotalDiscCost_y(t,(c,\varepsilon,yy,e)) \\
= \sum_y [CapitalDiscCost_y(t,(c,\varepsilon,yy,e)) \\
+ FixedDiscCost_y(t,(c,\varepsilon,yy,e)) \\
+ VariableDiscCost_y(t,(c,\varepsilon,yy,e)) \\
+ EmissionsDiscCost_y(t,(c,\varepsilon,yy,e))]
\end{aligned} \quad (1)
$$

subject to:

$$
FuelDemand_{y,t,l} \leq FuelSupply_{y,t,l} \leq TotalCap_{y,t,l}(t,(c,\varepsilon,yy,e))k, \quad \forall \quad y,t,l \quad (2)
$$

| | RNC2050 | | | |
|---|---|---|---|---|
| **[MW]** | **2020** | **2030** | **2040** | **2050** |
| Coal | 1,80 | 0,00 | 0,00 | 0,00 |
| Natural Gas | 4,90 | 3,75 | 2,40 | 0,20 |
| Fuel Oil | 0,70 | 0,20 | 0,10 | 0,00 |
| Hydro | 7,10 | 8,50 | 8,50 | 8,50 |
| Wind | 5,20 | 7,90 | 10,00 | 13,25 |
| Solar PV | 1,90 | 7,10 | 16,95 | 26,20 |
| Geothermal | 0,10 | 0,10 | 0,10 | 0,00 |
| Biomass | 0,90 | 1,50 | 1,40 | 1,60 |
| Batteries | 0,00 | 0,90 | 2,00 | 4,00 |
| **Total** | **22,6** | **30,0** | **41,5** | **53,8** |

Table 1: Evolution of installed capacity proposed in RNC2050

A reference energy system was created that characterizes the Portuguese electricity system. OSeMOSYS models the energy system as a depiction of reality, from primary energy to its transformation into energy carriers via various technologies, and finally to its final use.

### 3.2. Modelling according to the National Plan

Following the definition of the model's base values, some constraints and requirements were imposed to get the model closer to the one proposed by the government in the RNC2050. The last coal-fired power plants in Portugal were shut down at the end of 2021. According to the government's plan, total decarbonization of the power generation sector would be achieved by 2050, with solar photovoltaic and wind technologies able to generate 50 percent of electricity in 2030 and 70 percent in 2050. Due to the intermittent nature of these resource, it is vital to ensure a base technology that provides dispatch capacity and supply security.

To align the model built in OSeMOSYS with the government's proposal, a scenario was created in which it was anticipated that:

- The capacity factor of photovoltaic solar technology will increase by 30% in the 2030s and by 55% in the 2040s, reaching 0.23 in summer days (compared to 0.15 presently);
- Coal-fired plants will shut down in 2021, and natural gas units in 2040;
- Due to forecasted reduced water availability, hydroelectric plants will not be able to exceed their current capacity of 7.1 GW;
- The model was forced to guarantee a maximum installed capacity of photovoltaic and wind so-

| | Modelation | | | |
|---|---|---|---|---|
| **[MW]** | **2020** | **2030** | **2040** | **2050** |
| Coal | 1,76 | 0,00 | 0,00 | 0,00 |
| Natural Gas | 4,73 | 3,38 | 2,65 | 0,00 |
| Fuel Oil | 0,91 | 0,19 | 0,11 | 0,00 |
| Hydro | 6,99 | 7,10 | 7,10 | 7,10 |
| Wind | 2,28 | 9,60 | 16,91 | 17,42 |
| Solar PV | 1,90 | 7,10 | 16,95 | 26,20 |
| Geothermal | 0,03 | 0,02 | 0,02 | 0,02 |
| Biomass | 0,81 | 0,52 | 0,44 | 0,52 |
| Batteries | 0,00 | 1,67 | 5,79 | 11,54 |
| **Total** | **23,7** | **32,2** | **44,8** | **52,2** |

Table 2: Evolution of installed capacity obtained with simulation

lar technologies in order to ensure that they do not exceed more than 1.2x the proposed weight.

Tables 1 and 2 show the evolution of installed capacity in the power production industry as planned by the government and as determined through modeling, respectively.

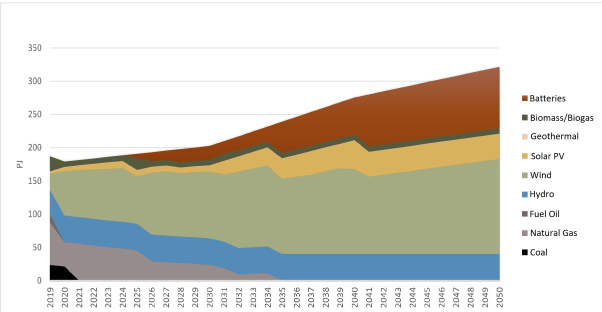


Figure 2: Forecast of Electricity Production in Portugal

It was also possible to obtain a forecast of electric energy production in the national territory, as shown in Figure 2.

## 4. Incorporation of a Nuclear Power Station in Portugal

The viability of incorporating nuclear energy into the energy mix is investigated in this section. The potential nuclear power facility is dimensioned, and the simulation results are displayed.

### 4.1. Nuclear power plant sizing

Wind and solar, as previously said, are intermittent sources of energy, meaning that their production is dependent on weather conditions. It is vital to have a backup energy supply that can ensure consumption at critical periods. Plants with dispatch capacity in Portugal are fossil fuel and hydroelectric plants. With the construction of batteries and an increase in the installed capacity of pumped water, the government plan RNC2050 aims to close this gap. The government plan RNC2050 aims to close this gap by building batteries and increasing the installed capacity of pumped water. Its goal is to investigate the use of nuclear energy in order to present another option to the national plan, so that it, along with hydro, forms the foundation of the electricity generation system.

To dimension the nuclear power plant, a load duration curve [2] was constructed and a linear approximation to the equation was obtained.

$$P = -0,4046h + 7524[MW] \quad (3)$$

A base technology's installed power must be sufficient to deliver the minimum at all hours of the year (8760), i.e.,$P_{min} = 4000MW$.

To ensure the continued consistency of the data entered in the previous section, the IEA-ETSAP E-TechDS data sheet for nuclear energy was used and a capital cost of 2 700€/kW was assumed. Multiplying the installed power by this value gives an investment cost of 10 800M€. To make a forecast of the number of years of plant activity needed to amortize the investment, it is necessary to calculate the energy produced by the plant per year. The utilization factor[3] is given by the equation 4, where $a$ is the capacity factor of the nuclear plant, considered to be 0.88. The energy produced annually by the plant is given by the equation 5, $P$ represents the installed power.

$$h_a = 8760a = 7708,8h \quad (4)$$

$$W = P \times h_a \simeq 30835,2GWh \simeq 111PJ \quad (5)$$

In 2019, the average final price of energy contracted by merchants and direct consumers in the free, regulated market was 53.25€/MWh. To calculate the profit of the plant per unit of energy produced, it is necessary to discount the operation and maintenance costs (approximately €14/MWh) and fuel costs (approximately€10/MWh) [5]. It is possible to make a profit of roughly 29.25€/MWh. We get a net revenue of 902M€/year by multiplying this amount by the energy provided by the plant. Finally, dividing the investment cost by the annual revenue yields the conclusion that the investment will be repaid in around 12 years.

It should also be noted that, according to the International Energy Agency's 2020 report, *Projected Costs of Generating Electricity*, investment costs in that year ranged from 2 157$/kWe in South Korea

[2]The load duration curve consists of the annual consumption aggregated in decreasing order, relating the load to the number of hours in which this load is exceeded.

[3]The utilization factor is the number of hours the plant would have to operate at rated power to produce the amount of energy it does in a year.

to 6 920$/kWe in Slovakia [9]. In the worst-case scenario, with capital costs of around 6 500€/kW, the total cost of the plant would be 26 000M€, with a 29-year payback period.

Nuclear power plants have a 40-year base operating life, but with modern technology and proper maintenance, they can last up to 60 years. As a result, even with higher capital costs and construction delays, building a nuclear power plant in Portugal would still be profitable.

### 4.2. Modelling with nuclear in the power mix

The model's base parameters were defined similarly to those used in nuclear-free modeling. For the base year of 2019, data on consumption and installed power were included. The investment costs are estimated to be 2 700€/kW, the operation and maintenance costs (fixed and variable) to be 14€/MW, and the fuel costs to be 10€/MWh. The capacity factor is 0.88 because nuclear power plants operate continuously, with only maintenance and supply interruptions.

The nuclear power plant must have at least 4 GW of installed capacity, as described in the previous section. Because a nuclear power plant takes between 5 and 7 years to build, it was determined that the plant would not be ready to operate until 2030. (not considering construction delays). It was also assumed that, if profitable, the plant would be able to increase its capacity to 6 GW in 2040, after a ten-year period. Because nuclear power plants are inflexible technologies, their output will always be stable and predictable, so the plant was designed to operate at maximum capacity.

The results of the nuclear power plant's integration into the Portuguese electricity system are presented in the table 3. The major discrepancy in the roadmap for carbon neutrality can be seen in the total installed capacity. Because the nuclear power plant produces a consistent amount of electricity, the expected increase in electricity consumption does not necessitate a significant increase in installed capacity. With nuclear in the mix, solar energy no longer makes sense, but wind energy retains a significant role in the energy mix. The batteries are similar to the RNC2050, but with a lower priority and the sole purpose of storing solar and wind surplus.

The estimated electricity production in national territory with a nuclear power plant is shown in Figure 3.

| | Modelation | | | |
|---|---|---|---|---|
| **[MW]** | **2020** | **2030** | **2040** | **2050** |
| Coal | 1,76 | 0,00 | 0,00 | 0,00 |
| Natural Gas | 4,73 | 3,38 | 0,00 | 0,00 |
| Fuel Oil | 0,91 | 0,19 | 0,10 | 0,00 |
| Hydro | 6,99 | 6,26 | 6,76 | 7,10 |
| Wind | 6,24 | 9,19 | 9,32 | 11,80 |
| Solar PV | 2,28 | 3,23 | 3,06 | 0,18 |
| Geothermal | 0,03 | 0,02 | 0,01 | 0,01 |
| Biomass | 0,81 | 0,52 | 0,36 | 0,28 |
| Batteries | 0,00 | 0,63 | 1,24 | 3,25 |
| Nuclear | 0,00 | 4,00 | 6,00 | 6,00 |
| **Total** | **23,7** | **23,4** | **20,8** | **22,6** |

Table 3: Evolution of installed capacity obtained by modeling, with nuclear in the mix

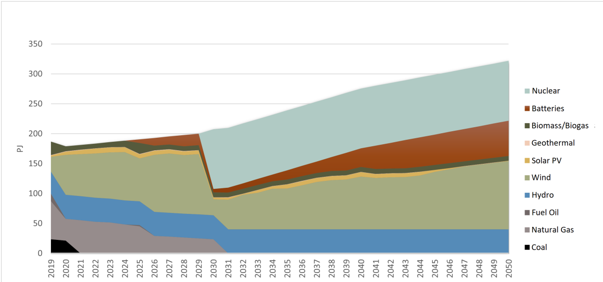


Figure 3: Forecast of Electricity Production in Portugal with Nuclear in the energy mix

## 5. Results Analysis

### 5.1. Comparison to RNC2050 without Nuclear

The total capacity obtained by modulation is similar to the total capacity proposed in the RNC2050 in a first analysis. In terms of electricity generated from the burning of fossil fuels, the model was forced to shut down coal plants in 2021 and natural gas plants in 2040, in accordance with government policy. As previously stated, it was decided to limit the installed capacity of hydro technology to the current level of 7.1 GW, as the availability of water is expected to dwindle. Pumped hydropower, according to the RNC2050, could be used to increase this capacity. The installed capacity of wind farms reached the maximum level (according to the defined restrictions). In terms of the installed capacity in solar parks, it is observed that by 2040, the model is slightly higher than that proposed in the national plan; however, solar technology becomes no longer cost-effective and stabilizes in the 2040-2050 decade.

The main point of contention between the model and the RNC2050 is the batteries. The model predicts that 5.8 GW more power will be required in 2040 than was proposed in the roadmap, and another 6.2 GW will be required in 2050.

Regarding wind technology, the simulation found that 8 GW will be installed between 2020 and 2050, compared to the 5 GW planned in RNC2050. Wind turbines must be installed in accordance with certain regulations, and only certain locations are suitable for their installation. Given that wind turbines have a 20-year lifetime and that the current limit of new locations is nearing, it is plausible to assume that the installed capacity will increase by 8 GW in 30 years, assuming that old turbines are replaced by new turbines with new technology and more power. Portugal wants to invest in offshore wind turbines as well, but in a more limited way because the Portuguese coast faces some challenges in terms of proper turbine placement. OSeMOSYS, the program used, aims to allocate technology use in the most efficient way possible, and the wind farms have a good cost-effectiveness ratio. If no restrictions were imposed, the program would allocate 23 GW of installed capacity to this technology. Given that the onshore grid is nearing capacity, it would be very interesting to expand the opportunities for offshore wind.

Portugal's solar energy goal is ambitious: by 2050, it plans to increase from 1 GW to 26 GW. According to the modeling results, the wind-solar system may be able to supply 50% of final consumption in 2030, but not 70% in 2050. This would necessitate a higher installed photovoltaic capacity than the one obtained. Even assuming a capacity factor improvement of up to 55 percent, the modeling results suggest that solar parks are not the most cost-effective technologies. It's worth noting that when this improvement is inserted, the modeling assumes that the entire installed capacity will show this increase in efficiency, which will not be the case. Obtaining the installed capacity proposed in the RNC2050 is feasible, but it comes at a cost that could be better spent on a more profitable technology.

As previously stated, the most difficult aspect of the energy transition is ensuring supply security, dispatch capacity, and flexibility. Wind and photovoltaic parks are intermittent technologies, which means they aren't completely reliable. As a result, it's critical to ensure that no grid outages occur if they fail. The RNC2050 intends to store electricity using pumped dams and batteries, and thus serve as a base technology for ensuring supply security in extreme situations. The government plan estimates that 4 GW of batteries will be required by 2050, but modeling results suggest that 11.5 GW will be required. The installation of this capacity on the horizon in question may be possible, but this technology is still undergoing extensive research and development, and many questions remain unanswered. As a result, it may be impossible to meet the governmental plan's readiness requirements for the installation. With the predictions made about future water availability, it is critical to ensure that the Portuguese will not be without electricity in years of extreme drought, when water energy cannot be relied upon. Energy dependence decreases significantly without fossil fuels; however, in years with less water, we cannot expect to rely on electricity imports, so it is critical to ensure the existence of a base technology capable of delivering electricity when intermittent technologies fail.

In terms of the estimation of electrical prodution (figure 2), due to the uncertainty associated with water availability, a maximum of 40 PJ per year was established (in 2019 there were about 39 PJ). This value will be higher in years when there is an abundance of water and lower in years when there is a drought. The model also predicted that the electricity stored in the batteries would have a significant weight, and that when combined with hydro technology, it would provide a strong foundation for the Portuguese electrical system. When part of the production from solar and wind farms is not needed, the batteries will charge and feed the grid.

### 5.2. Comparison to RNC2050 with Nuclear

The addition of a nuclear power plant in Portugal has a significant impact on the energy needs forecasted by the carbon neutrality roadmap.

With the abandonment of natural gas plants, the use of fossil fuels can be eliminated in 2040, as planned. Hydropower dependence would be reduced, and modeling suggests that installed capacity could be reduced in comparison to current capacity.

The addition of a nuclear power plant in Portugal has a significant impact on the energy needs forecasted by the carbon neutrality roadmap.

With the abandonment of natural gas plants, the use of fossil fuels can be eliminated in 2040, as planned. Hydropower dependence would be reduced, and modeling suggests that installed capacity could be reduced in comparison to current capacity. Dam construction will continue to make sense for storage and irrigation, and dams will play an important role in the energy mix in years when there is plenty of water.

The value of electricity generated in the future will be determined by the plant's ability to supply energy during critical periods. Nuclear power plants can generate electricity at any time of day, on a consistent basis, regardless of the weather conditions. The construction of a nuclear power plant in Portugal may result in lower electricity costs.

Nuclear energy is capable of producing both electricity and hydrogen. Nuclear reactors of Generation IV can provide hydrogen all over the world by combining nuclear energy with thermo-chemical water separation and electrolysis [19].

The compatibility of nuclear reactors with the majority of renewable energy sources is still unknown. Nuclear power plants are rigid, in the sense that they always produce maximum power and, as a result, the same amount of electricity. Wind and solar power plants, on the other hand, produce more or less depending on the weather. Solar technology has another unique feature: it can only generate electricity when the sun is shining. This means that during the night, another source of energy is required to compensate for the lack of sunlight. Natural gas is currently the only source capable of meeting this requirement.

The path to carbon neutrality is not yet clear, and natural gas may be used in the meantime; however, we will have to abandon this source in the future. In order for Portugal to achieve its goal of 70% wind-solar by 2050, it will need a low-carbon source that can compensate for these technologies' fluctuations. Batteries aren't yet viable, and there are a slew of unanswered questions about long-term storage. By 2050, however, it may be a viable option.

Another option is nuclear technology; small reactors or microreactors are being developed to meet renewable energy needs [3].

## 6. Integrated Analysis of the wind, solar and nuclear technologies - Life Cycle Assessment

This section aims to provide a comprehensive analysis of the technologies that will have the greatest impact on the future energy mix of the country. The analysis will only be conducted for photovoltaic solar, onshore wind, and nuclear technologies because thermal plants will no longer produce energy and hydro technology will not see significant increases in installed capacity. Battery storage was also left out of the analysis because it is still a developing technology with no clear plan for implementation in Portugal.

### 6.1. Levelized Cost of Energy - LCOE

The cost evaluation is critical in the integrated analysis of an electricity production technology. The LCOE, which represents the cost per unit of electricity produced over a set period of time, is one of the most commonly used calculations. The LCOE evaluates fixed and variable investment costs and serves as a guide for determining the minimum electricity price at which revenues equal costs, including a rate of return on capital equal to the discount rate.

The LCOE of onshore wind technology ranged from 41-89€/MWh in 2018 and in applications within the EU27, while the LCOE of solar PV technology with installed capacity above 1MW ranged from 43-168€/MWh.

There was no nuclear power plant commissioning between 2008 and 2019, despite the fact that several are under construction. Nuclear technology's LCOE in the United States ranged from 72€ to 82€ per MWh. The high investment costs are offset by the technology's high capacity factor (about 88 percent) [6].

The higher the investment costs, the higher the LCOE, but the capacity factor is the same. This is the main reason why some solar parks have such high LCOE values; investment and operating and maintenance costs have dropped dramatically in recent years, but increasing capacity factor has proven difficult. This indicates that if there is an increase in nuclear technology demand and development, as well as a reduction in costs, the value of the LCOE of nuclear plants could become highly competitive. However, due to delays in project approvals and construction, the LCOE of nuclear power has been rising in recent decades. As a result of previous nuclear disasters, safety precautions have been increased and are becoming increasingly restricted.

### 6.2. Greenhouse Gas Emissions

The analysis of each technology's GHG emissions cannot be limited to the production of electricity. Thermal power plants are the primary source of greenhouse gas emissions in the atmosphere due to combustion, but in order to assess each technology's impact, it is necessary to examine emissions over the course of the technology's useful life. Only the following emissions are relevant to the technologies under consideration [15]:

- *One time upstream emissions*: emissions related to the extraction of raw materials, manufacture of materials and components and transport (from manufacture to installation site). They only happen once;
- *One time downstream emissions*: emissions related to the end of a plant's life, caused by decommissioning, transport for all waste disposal, recycling, etc.

As it can be seen in Table 4, solar PV emits the most GHGs of the three technologies studied, primarily due to manufacturing and raw material consumption. In the upstream phase, all technologies produce more emissions, but nuclear technology produces the most emissions at the end of its life cycle.

The construction of a solar park, as mentioned in the section 6.5, necessitates a large amount of materials per unit of electricity produced. The high value of GHG emissions referred to in the table 4 is the result of the entire process of extracting, manufacturing, and installing these materials.

### 6.3. Water Consumption

Water is one of the most valuable natural resources, and it is required at every stage of the electricity

|  | *One time upstream (g CO2e/kW)* | *One time downstream (g CO2e/kW)* |
|---|---|---|
| **Solar PV** | 1 630 000 | 37 800 |
| **Wind** | 619 000 | 22 400 |
| **Nuclear** | 350 000 | 175 000 |

Table 4: Emissions resulting from the life cycle of solar PV, wind and nuclear technologies [15]

|  | **Water Consumption (l/MWh)** |
|---|---|
| **Solar PV** | 329 |
| **Wind** | 8 |
| **Nuclear** | 7 090 |

Table 5: Water consumption in the life cycle of solar PV, wind and nuclear technologies [10]

production technology's life cycle, from resource extraction to production and decommissioning. Water consumption is shown in the table 5 according to each technology's life cycle stage [10].

Water usage analysis in each technology presents some challenges. Water use is not linear, and unlike greenhouse gas emissions, water impacts are local. Water consumption analysis must be done regionally and take other factors into account, such as water availability and local fauna and flora.

Because water requirements are so high in nuclear power plants, they must be located near an abundant source of water, such as a river or the sea. The availability of water, as well as the seismicity of the area and proximity to the consumer market, are all factors that influence the location of a nuclear power plant. As a result, despite Portugal's extensive coastline, the ideal location could be next to a river. To generate electricity, nuclear power plants use water in the form of steam. The water in the most common plants (PWR) is separated from the reactor and thus is radioactive-free. To minimize radioactivity leaks, the cooling systems are designed so that, in the event of a leak, the water is directed to the plant rather than to the outside. Before being reintroduced into a river or the sea, contaminated water is also treated. Fuel cooling also necessitates the use of water [14].

### 6.4. **Land Use**

Another important consideration when evaluating electricity generation technologies is the requirements each technology has in terms of land use. The territory of a technology's use is not easily defined. Table 6 shows the land requirements per MW of installed capacity [16]. Land use analysis always yields binary results: either the land is used or not. It's crucial to distinguish between land that will be

|  | **Land Use (m^2/MW)** |
|---|---|
| **Solar PV** | 10 000 - 60 000 |
| **Wind** | 2 600 - 1 000 000 |
| **Nuclear** | 6 700 - 13 800 |

Table 6: Land use for solar PV, wind and nuclear [16]

used solely for electricity production and land that can be used for multiple purposes.

The area around nuclear power plants will be exclusive and cannot be used for any other purpose, but the safety zone around the plant will continue to have fauna and flora, subject to security constraints.

Wind turbines and solar parks have been shown to have a significant environmental impact, both on local fauna and flora as well as on the urban life that surrounds them. Turbines have been linked to noise pollution, reduced wildlife, and lower land values in the vicinity of these parks. For the production of electricity, solar plants require a large and exclusive area; the land used has little permeability, and the temperature in the area can rise by 2-3 degrees Celsius near the solar cells, which can easily reach temperatures of 65 degrees Celsius on hot summer days.

Any of these technologies must be installed after a thorough examination of their environmental impact on the land, as well as on animal and plant life. It's worth noting that Portugal's Roadmap for Carbon Neutrality calls for the installation of 26 GW of photovoltaic solar and 13 GW of wind power, compared to the current 1.1 GW and 5.5 GW, respectively.

The equation 6 is used to make a rough estimate of the area required to satisfy the power proposed in the RNC2050, where $P_p$ is the peak power of the panels, $G^r$ is the irradiance in STC conditions (*Standard Test Conditions*: $Gr = 1000W/m2$), and $\eta^r$ is the efficiency under these conditions. A 15 percent average efficiency was considered.

$$A = \frac{P_p}{G^r \eta^r} \qquad (6)$$

Assuming that the efficiency of the panels does not improve, it was discovered that a total area of about $173km^2$ will be required to meet the 26 GW capacity proposed in the government plan. This finding highlights the urgent need for a study to determine the true impact of using this area solely for the generation of electricity using solar energy.

### 6.5. **Materials**

Finally, the materials used in each technology are examined. The decomposition of materials for so-

| Materials (ton/TWh) | Solar PV | Wind | Nuclear |
|---|---|---|---|
| **Aluminium** | 680 | 35 | 0 |
| **Cement** | 3 700 | 0 | 0 |
| **Concrete** | 350 | 8 000 | 760 |
| **Copper** | 850 | 23 | 0 |
| **Glass** | 2 700 | 92 | 0 |
| **Iron** | 0 | 120 | 4 |
| **Lead** | 0 | 0 | 0 |
| **Plastic** | 210 | 190 | 0 |
| **Silicon** | 57 | 0 | 0 |
| **Steel** | 7 900 | 1 800 | 310 |
| **Total** | **16 447** | **10 260** | **930** |

Table 7: Range of materials requirements for various solar, wind and nuclear technologies [16]

lar, wind, and nuclear technologies is shown in the table 7.

In 2015, the industrial sector accounted for roughly 13% of total national emissions. This sector is one of the most difficult to decarbonize because the technological options for reducing emissions are still limited. Given the importance of finding alternative solutions, a significant amount of research has been done, primarily to reduce the carbon footprint of cement and concrete. Carbon capture and storage could play a significant role in decarbonizing the cement industry in Portugal. However, much more research and development is required in this area before it becomes cost-effective [2].

Solar technology not only has one of the highest requirements per TWh produced, but it also necessitates a wide range of materials. Because some of the materials used in the production of solar panels are critical and do not occur in abundance in nature, optimization and research into new materials is important. The importance of panel recycling cannot be overstated.

## 7. Conclusions

### 7.1. Final Conclusions

The goal of this study was to assess the feasibility of Portugal's plan to achieve carbon neutrality by 2050 and to investigate the possibility of building a nuclear power plant in the 2030-40 decade.

Following the completion of the analysis, some doubts about the feasibility of the proposal in the RNC2050 have arisen, particularly with regard to solar photovoltaic. In section 6.4, the area required to install the proposed 26 GW is estimated. It appears that about $173km^2$ of installed area will be required in total. It will be critical to comprehend the implications of this area for Portugal, not only in terms of the occupation of land that could be used for other purposes, but also in terms of the necessary adjustments to the Portuguese electricity grid. However, the most pressing question in relation to the government plan is the percentage of wind and solar power. Given the intermittency of these technologies, having 70% of total installed capacity in this group is only possible if there is another source of energy that ensures supply security. This foundation will be built in the RNC2050 using hydroelectric plants and batteries. Portugal turned off the last coal plants at the end of 2021, believing that the country would be able to compensate for the loss, primarily through hydropower. The year 2022 has been a year of drought, and as a result, dam-generated electricity is limited. The recession brought on by the Covid19 pandemic, as well as the subsequent conflict between Russia and Ukraine, has resulted in a significant increase in inflation and a significant increase in natural gas supply tensions. Closing coal-fired power plants was hasty, resulting in an increase in Portugal's energy dependence and a decrease in supply security.

It is also possible to conclude that, despite increased energy dependence due to uranium imports, the construction of a nuclear power plant is not only economically viable, but can also be an important factor in the decarbonization process. Many changes, however, would be required, including a shift in public opinion as well as a reduction in investment costs and delays. Finding a safe solution for radioactive waste would also be necessary. Construction times in North America and Europe have exceeded 13-15 years, with final costs exceeding 3-4 times initial budgets. In contrast, most East Asian projects (which began construction in 2012) were completed in 5-6 years with no major cost overruns [3].

When people are concerned about energy security, such as energy availability and high electricity prices, public support for nuclear power is strongest. When people have more faith in government, they are more likely to support it. Transparent and participatory decision-making processes also improve public support and perceptions of procedural justice [11].

Finally, achieving carbon neutrality by 2050 will require ensuring safety and reliability, and cannot be with high electricity costs. The proposed national plan lays out a possible path to decarbonization, in which the majority of electricity generated comes from solar and wind power, and national energy dependence is reduced to a minimum compared to the current situation. The installation of a nuclear power plant would increase the country's energy dependence as well as the use of its uranium resources. It would entail betting on a technology that is unpopular with the public, accepting the risks of a nuclear disaster in exchange for a possible decrease in the country's security. On the other hand, constructing a nuclear power plant in Portugal would not only increase the country's wealth but also increase its security of supply.

### 7.2. Future Work

Following the completion of this work, it is necessary to discuss future work that may be required. An economic study of the investments required to complete the proposed Roadmap for Carbon Neutrality in Portugal, as well as the proposed solution with nuclear in the energy mix, would be beneficial; Finding a low-carbon, cost-effective solution that adapts to solar energy and generates electricity when the sun isn't shining, whether it's flexible nuclear reactors or batteries; Conduct a study to determine the impact of installing the proposed solar and wind capacity in the RNC2050 (all of the points discussed in section 6 must be considered, as well as the effects on public health, fauna and flora, and supply security); Conduct a similar investigation into the possibility of constructing a nuclear power plant in Portugal; Develop nuclear technology, whether it's for microreactors, electrolysis, or thermochemical water separation.


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