# Nuclear power in Portugal's energy transition

**Bernardo Miguel Grilo Marçal**

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## Energy Engineering and Management

Supervisor: Prof. Duarte de Mesquita e Sousa

### Examination Committee

Chairperson: Prof. Francisco Manuel Da Silva Lemos

Supervisor: Prof. Duarte de Mesquita e Sousa

Member of the Comittee: Dr. António Eusébio Velho Roque

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

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# Resumo

Esta dissertação investiga a viabilidade da introdução da energia nuclear no mix energético português para atingir a neutralidade carbónica até 2050. Através da utilização do sistema de modelação EnergyPLAN, são desenvolvidos modelos para avaliar vários cenários e as suas implicações.

Os resultados demonstram que, com uma capacidade instalada inferior, a energia nuclear pode desempenhar um papel na descarbonização do parque electroprodutor em Portugal até 2040. A inclusão da energia nuclear oferece uma produção fiável e ininterrupta, reduzindo a dependência de interconexões externas para o equilíbrio de energia. Vantajoso, em termos de custos quando comparado com modelos centrados nas energias renováveis.

A opinião pública desempenha um papel crucial na definição das decisões políticas relativas à energia nuclear. Estratégias de comunicação que privilegiem transparência, educação e o envolvimento são essenciais para promover uma perceção positiva por parte do público. Embora as centrais nucleares estejam equipadas com múltiplas barreiras físicas para evitar a libertação de isótopos radioativos para o ambiente, os acontecimentos catastróficos em grandeescala têm um impacto duradouro na perceção do público. A gestão dos resíduos a longo prazo é a questão mais premente.

Esta investigação fornece informações para os decisores políticos, planeadores de energia e partes interessadas envolvidas na transição energética de Portugal. Os resultados destacam o potencial da energia nuclear como uma fonte de energia fiável e com baixo teor de carbono. Este estudo contribui para o desenvolvimento de um sistema energético sustentável e resiliente em Portugal, alinhado com os seus ambiciosos objetivos de neutralidade carbónica até 2050.

**Palavras-chave:** energia nuclear, Portugal, transição energética, neutro em carbono, EnergyPLAN

# 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. While nuclear power plants are equipped with multiple physical barriers to prevent the release of radioactive isotopes into the environment, large-scale catastrophic events have alasting impact on public perception. Long term waste disposal is the most pressing matter.

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 andresilient energy system, aligning with its ambitious carbon neutrality goals by 2050.

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

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# Nomenclature

| | |
|---|---|
| **BWR** | Boiling water reactors |
| **CEEP** | Critical Excess Electricity Production |
| **COVID-19** | Corona virus disease of 2019 |
| **DGEG** | Directorate-general for energy and geology |
| **ED** | Energy dependence |
| **ERSE** | Regulatory entity for energy services |
| **EU** | European union |
| **EXP** | Exports |
| **FEC** | Final energy consumption |
| **FR** | Fast reactors |
| **GCR** | Gas-cooled reactors |
| **GHG** | Greenhouse gas |
| **HTGR** | High-temperature gas-cooled reactors |
| **IA** | International aviation |
| **IAEA** | International atomic energy agency |
| **IMN** | International maritime navigation |
| **IMP** | Imports |
| **INE** | Statistics Portugal |
| **IPCC** | Intergovernmental panel on climate change |
| **IPPU** | Industrial processes and product uses |
| **LWGR** | Light water graphite reactors |
| **MIBEL** | Iberian electricity market |
| **PHWR** | Pressurized heavy water reactors |
| **PV** | Photovoltaic |
| **PWR** | Pressurized water reactor |
| **RE** | Renewable energy |
| **RES** | Renewable energy sources |
| **RNC2050** | Roadmap for carbon neutrality 2050 |
| **TCF** | Technology capacity factors |

# Chapter 1

# Introduction

This chapter establishes the relevance of the topic and clarifies the objective of the thesis, allowing the reader to know what to expect. It concludes by explaining in brief the structure of the document.

## 1.1 Motivation

Throughout history, the earth's climate and weather patterns were relatively predictable, maintaining an equilibrium state. However, the significant increase in greenhouse gas (GHG) emissions, primarily caused by the use of fossil fuels and global population growth, has disrupted this balance. As a result, our ability to predict weather patterns and climate with certainty has become increasingly challenging. Without taking corrective action, we face the prospect of an increasingly unstable climate, characterized by unpredictable hurricanes, tornadoes, heatwaves, wildfires, floods, droughts, food shortages, and record-breaking global temperatures. This instability will inevitably lead to social, political, and economic chaos. It is crucial that we recognize the long-lasting impact of GHGs, such as carbon dioxide ($CO_2$) which can persist in the upper atmosphere for hundreds of years. Even if we were to cease using fossil fuels, the best outcome we can hope for is the stabilization of a warmer climate to which we must adapt. It is imperative that we address the root causes of climate change and take proactive measures to mitigate its effects, fostering resilience and sustainability for future generations [1].

In 2015, recognizing the urgency of the issue, numerous countries worldwide, including Portugal, took a significant step forward by signing the Paris Agreement. This agreement was established with the aim of effectively combating climate change and limiting global warming to a maximum of 1.5 °C (with 2 °C as the upper limit). The European Union (EU), basing its calculations on the reference year of 1990, determined that achieving this goal necessitates a substantial reduction of at least 80 % in GHG emissions by the year 2050 [2].

Leading up to the 26th Conference of the Parties of the United Nations Framework Convention on Climate Change in 2021, the Intergovernmental Panel on Climate Change (IPCC) delivered a sobering conclusion. While acknowledging the ambition of current commitments, the IPCC determined that the collective pledges to limit GHG emissions are insufficient, falling short by approximately 20 % of the necessary reductions required by 2030. These reductions are crucial for maintaining a viable trajectory towards stabilizing global warming at 1.5 °C above pre-industrial levels [3].

Figure 1 displays the GHG emissions ($CO_2$ equivalent) in gigagrams by sector in Portugal from 1990 to 2019 [4] and the goal for 2050.

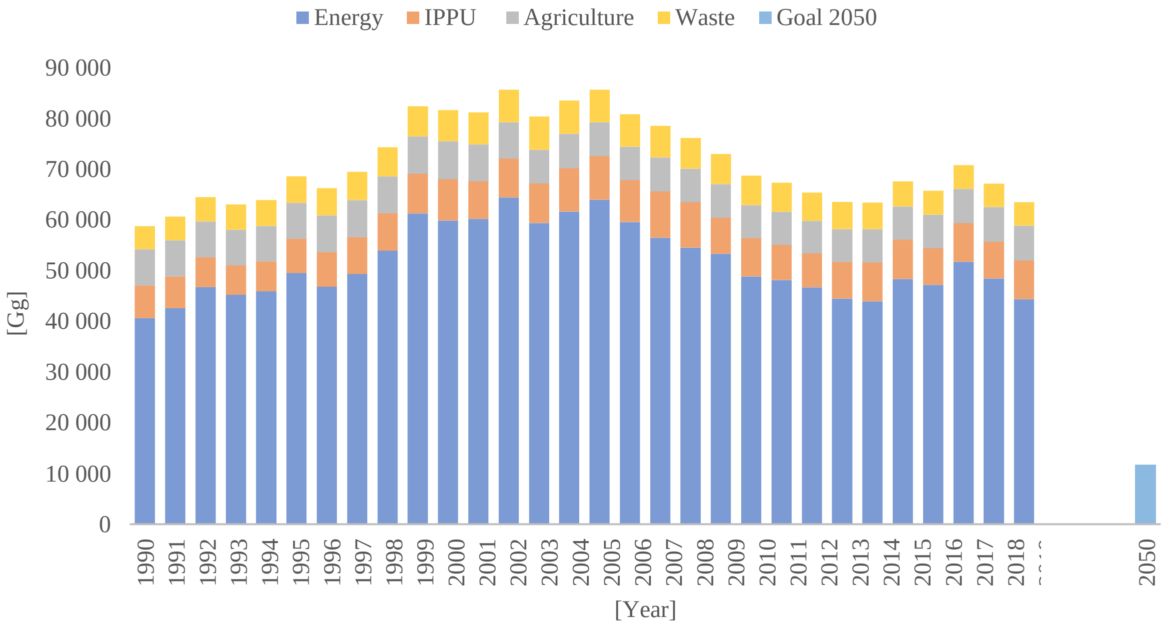

*Figure 1 - GHG emissions by sector in Portugal from 1990 to 2019 and minimum goal for 2050 [2][4]*

The minimum goal set for 2050 underscores the magnitude of the challenge that lies ahead. It is evident that total emissions have increased since the reference year, reaching their peak in 2005. Although emissions in 2019 were lower than the levels recorded in 2015 (the year of the Paris Agreement), there is no clear downward trend in sight. The International Energy Agency reports that 2020 witnessed significant declines in both global energy demand (4 %) and global $CO_2$ emissions (5.8 %) due to the corona virus disease of 2019 (COVID-19), with the latter experiencing a further decrease as coal and oil demand were particularly affected while renewable energy sources (RES) saw growth.

However, as the world begins to recover from the pandemic, vaccinations and widespread fiscal measures have stimulated economic growth and subsequently increased the demand for all types of fuels and technologies. This resulted in a rebound in $CO_2$ emissions during the first quarter of 2021 [5].In 2015, the energy sector emerged as the primary source of GHG emissions, accounting for 70 % of the total. Industrial processes and product uses (IPPU) contributed 11 % to the emissions, while the agricultural sector represented 10 %. Additionally, the waste sector contributed 9 % to the overall GHG emissions.

It becomes clear that, although not enough, a reduction of at least 80 % of GHG emissions requires the decarbonization of the Portuguese energy mix.

Although low-carbon energy sources already account for approximately 60 % of the energy supply in Portugal, further efforts are needed to significantly increase this share in order to meet the objectives set for 2050. One potential option being evaluated globally, including the IPCC, is nuclear energy. Its inclusion in the panel's work agenda indicates the recognition of its potential role in the transition to a low-carbon future.

## 1.2 Objectives and Scope

As a country committed to the Paris Agreement and striving to meet its emissions reduction targets, understanding the feasibility and implications of different energy sources is crucial.

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 achieve these objectives, the thesis employs EnergyPLAN as the modeling system, to develop reference and predictive models. These models allow for the comparison of different scenarios and their implications, including the installed capacities of various technologies such as wind, solar photovoltaic (PV), and nuclear power.

By achieving these objectives, the thesis aims to provide valuable insights and recommendations to policymakers, energy planners, and stakeholders involved in Portugal's energy transition. It aims to contribute to the ongoing discussions and decision-making processes regarding the country's pathway to decarbonization, offering a different perspective. The findings of this thesis can inform evidence-based policymaking, facilitate informed discussions, and support the development of a sustainable and resilient energy system in Portugal.

## 1.3 Thesis Outline

This chapter serves as an introduction, presenting a comprehensive description of the problem and the underlying objectives of this work, while also outlining the structure of the thesis.

Chapter 2 provides an in-depth overview of Portugal's power sector, with a specific emphasis on energy consumption and the country's reliance on fuel imports. It delves into the electricity sector's structure, encompassing aspects such as the transition towards a liberalized market, electricity transmission and distribution. It analyzes energy consumption patterns within the transportation and heating/cooling sectors. Additionally, the chapter introduces nuclear energy, its advantages and disadvantages, and sheds light on its global applications.

Moving forward, Chapter 3 introduces the software utilized for modeling energy scenarios, presenting a comprehensive overview of the data considered for energy demand, energy supply, and costs across the different models.

Chapter 4 showcases the results obtained from each model, undertaking an extensive comparison and analysis of these findings.

Finally, Chapter 5 provides a conclusive summary of all the results derived throughout this thesis, culminating in the formulation of recommendations for future research and work.

# Chapter 2

# Portuguese electricity sector framework

This chapter provides a comprehensive overview of the electricity sector in Portugal. It explores primary and final energy consumption (FEC), highlighting the country's heavy reliance on fuel imports.The chapter delves into the structure of the electricity sector, examining the transition to a liberalized market and the role of regulatory entities. It discusses the evolution of electricity production, includingthe growth of RES. The transmission and distribution of electricity are examined, along with the importance of interconnection capacity. The chapter also analyzes energy consumption patterns in the transportation and heating/cooling sectors. Finishes by providing insights into nuclear energy applications and its role in the energy mix.

## 2.1 Power sector

To comprehensively assess Portugal's energy consumption, it is essential to consider both primary energy and FEC. Primary energy consumption encompasses the energy used directly or transformed into other forms, including imports and domestic production, while excluding stock variations and exports. On the other hand, FEC represents the observed consumption at the end-use level, derived from primary energy consumption but excluding energy utilized for other purposes like raw materials and energy sector consumption.

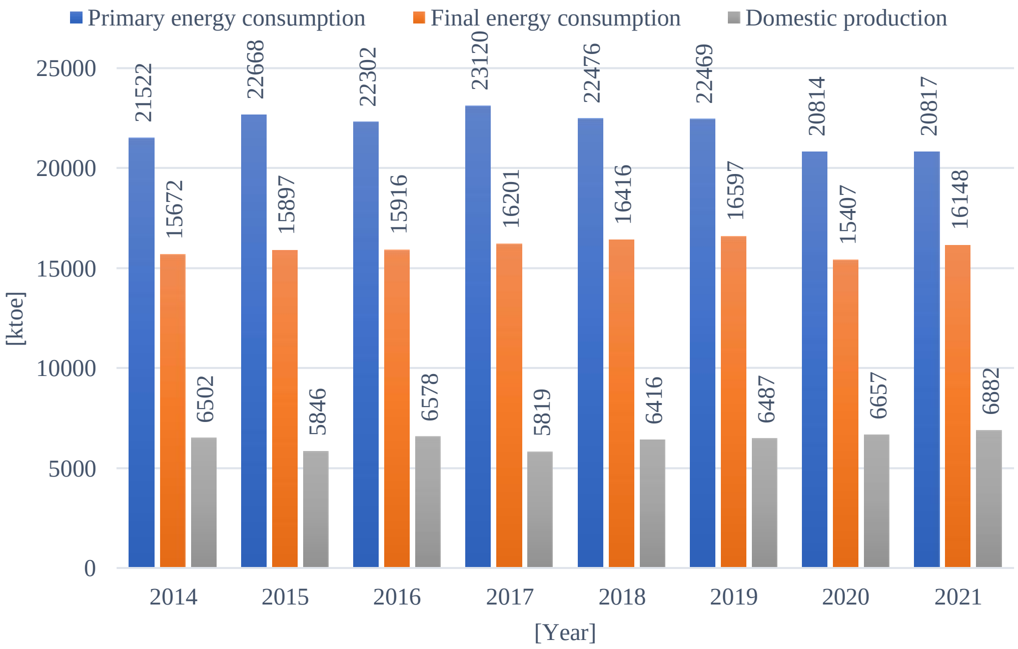

*Figure 2 - Primary energy consumption, final energy consumption and domestic production from 2014 to 2021, adapted from [6], [7].*

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.

Portugal's energy dependence (ED) remains significant within the EU, despite a notable decrease in fossil fuel consumption. The ED indicator measures the level of reliance on imports to meet the country's energy needs. It is computed according to equation 1 taking into consideration total values forall energy sources.

$$ED[\%] = \frac{(IMP - EXP)}{FEC + IMN + IA} \times 100 \tag{1}$$

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.

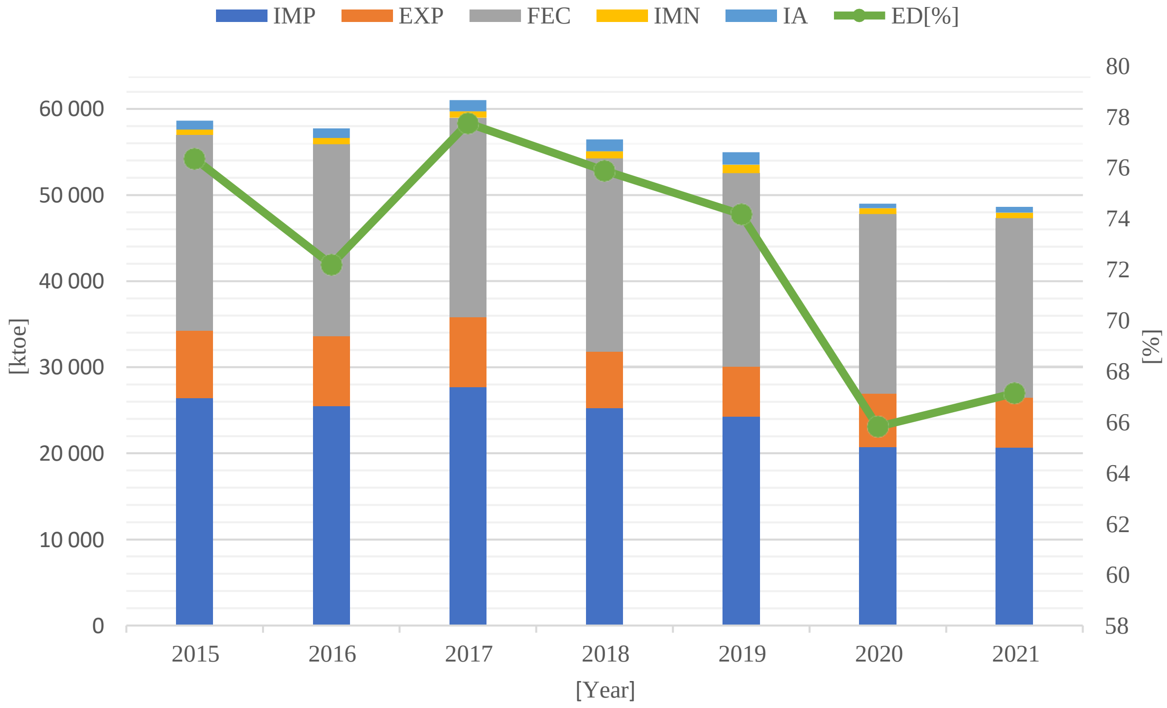

*Figure 3 - Imports, Exports, FEC, IMN, IA and ED in Portugal from 2015 to 2021, adapted from [6].*

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. In 2020, the energy content of imports, especially coal and road fuels, decreased by 22 %, leading to an 8.4 percentage point reduction in ED from 2019 to 2020 [6], [7].

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, as shown by Figure 4.

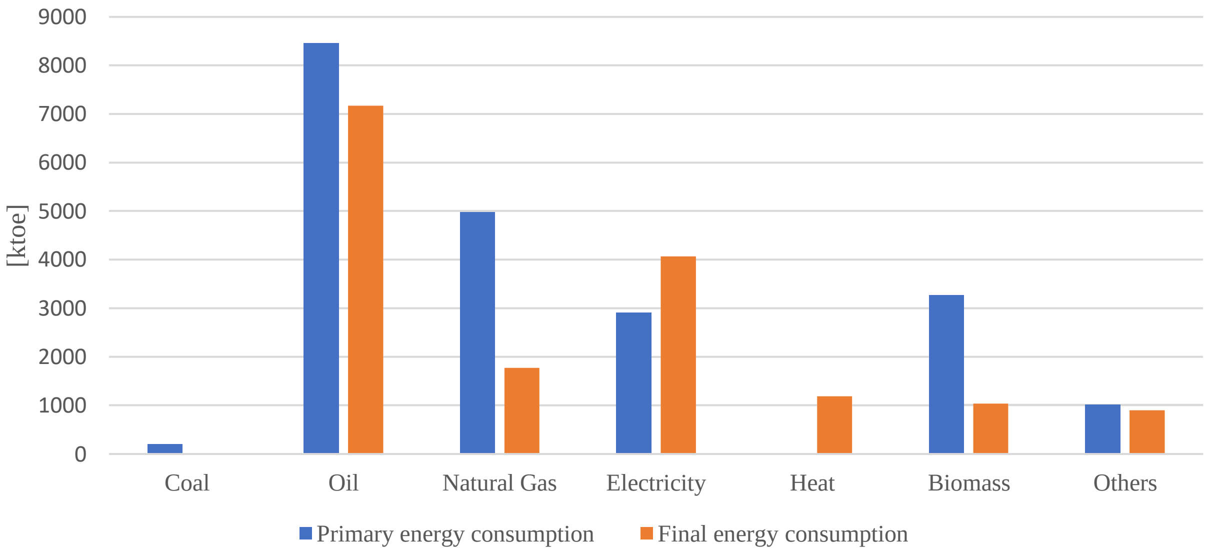

*Figure 4 – Primary and final energy consumption by source in 2021, adapted from [6].*

The industry and transportation sectors collectively account for over 60 % of Portugal's FEC. According to Figure 5, 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.

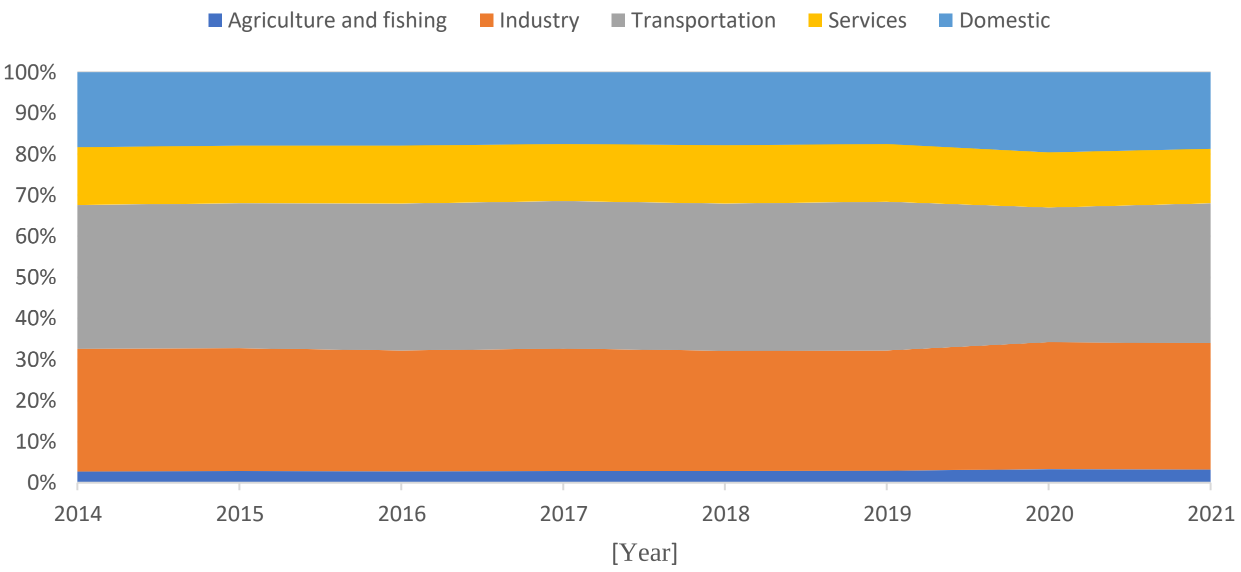

*Figure 5 - Share of the FEC by sector from 2014 to 2021, adapted from [6], [7]*

### 2.1.1 Electricity sector

Prior to 1996, the electricity sector in Portugal was overseen by the state-owned company (*"Eletricidade de Portugal"),* which was responsible for electricity promotion and infrastructure development. However, significant changes occurred in 2006 when the monopolistic model was dismantled, and a liberalized market was established with government support for private initiatives.

These reforms resulted in the unbundling of the electricity sector into separate activities, including production, transmission, distribution, and retail, each operated by different entities. The Regulatory Entity for Energy Services (ERSE) plays a crucial role in the national regulation of electricity and natural gas, ensuring that operators in these sectors comply with public service obligations while fostering a competitive market environment [8].

#### Production

Figure 6 shows the evolution of the installed capacities from 1944 to 2021. In the early 1940s, the Central Tejo coal-fired power plant and the Lindoso hydraulic (hydro) power plant were the primary sources of electricity production in Portugal.

However, in 1944, hydro power was prioritized by law, and its share of the total installed capacity reached nearly 94 % by 1966. Over the following decades, there was a significant increase in fossil fuel generation capacity. Gas-fired power plants were introduced in 1997, and as coal-fired power plants were gradually phased out, they now represent almost 100 % of all fossil fuel-based generation, accounting for 24 % of the total installed capacity as of 2021. In 2005, the introduction of subsidized tariffs led to the proliferation of wind farms and other RES. By 2021 Portugal had 5,368 MW (28 %) of installed wind power capacity [9], [10].

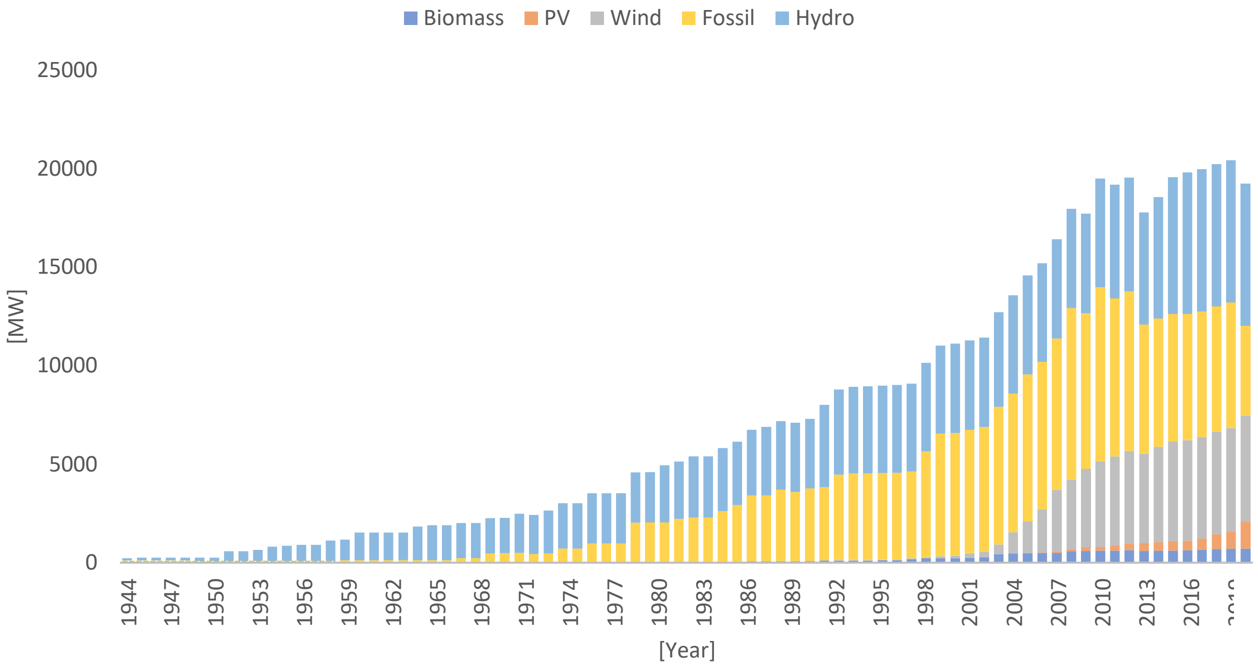

*Figure 6 - Portuguese installed capacity 1944-2021, adapted from [9], [10], [66]–[71]*

Portugal has implemented two distinct mechanisms, namely the ordinary production regime and the special production regime, to provide compensation to electricity producers. With the establishment of the Iberian Electricity Market (MIBEL), power plants that possess a production license, issued by the Directorate-General for Energy and Geology (DGEG), started offering their energy on a unified platform.

The ordinary electricity production regime primarily applies to non-renewable-based production and large water-producing centers. Under this regime, these producers participate in the market on equal terms with other conventional producers. They compete based on market dynamics and are subject to market prices.

On the other hand, the special production regime pertains to electricity generation through cogeneration and renewable resources, as well as micro and mini production without adding substantial power to the grid. Producers operating under this regime benefit from a guaranteed remuneration plan, which ensures a price and a feed-in tariff that is deemed more than adequate. This mechanism aims to provide stability and support for producers utilizing these specific technologies.

It is anticipated that as renewable energy (RE) technologies continue to develop and become more competitive, producers under the special regime will gradually offer their energy on the market under comparable terms to regular producers. This signifies a shift towards a more market-oriented approach as RE plays an increasingly prominent role in the country's energy mix [11].

Figure 7 illustrates the gross electricity production from 2014 to 2021. 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. 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 favored imports, which accounted for 10 % of domestic consumption [6], [7].

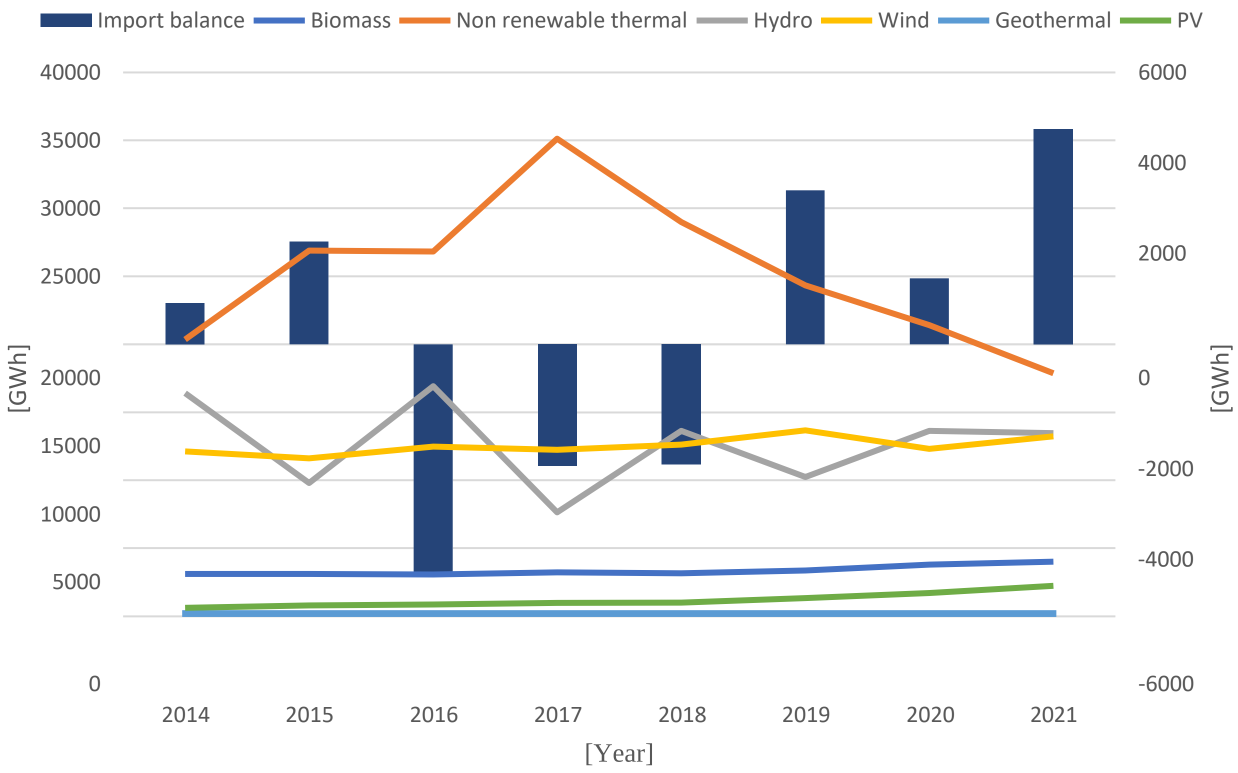

*Figure 7 - Import balance and electricity generation by source from 2014 to 2021, adapted from [6], [7]*

## Transmission and Distribution

Transport of electricity, from power plants to consumers, is divided in transmission and distribution according to the voltage at which is conducted.

Long-distance transport of electricity (transmission) makes use higher voltages in order to reduce losses in transport to the different points of the Portuguese territory. Closer to the consumer, transport is done at lower voltage (distribution) allowing for safer usage of electricity. The national transmission network is operated, under concession, by the transmission system operator which currently is *“Rede Eléctrica Nacional”*, responsible for its planning, construction and maintenance. The distribution is carried out, also under public concession, by exploitation of the national distribution network of electricity. The public service concession for high and medium voltage was granted to *“EDP Distribuição”*, low voltage distribution is assigned to the municipalities which can operate the distribution network or concession the activity. All municipalities have this activity under concession and *“EDP Distribuição”*has the highest market share [8], [12].

Regional electricity markets were created as a step towards a single European energy market. For the MIBEL to function properly and to enable cross-border integration, neighboring nations must be connected. Future expansion of the interconnection capacity between Portugal and Spain is anticipated, as expanding interconnection capacity is thought to be the best way to boost efficiency for small markets like the Portuguese. In 2021 there were nine interconnection lines between Portugal and Spain [9].

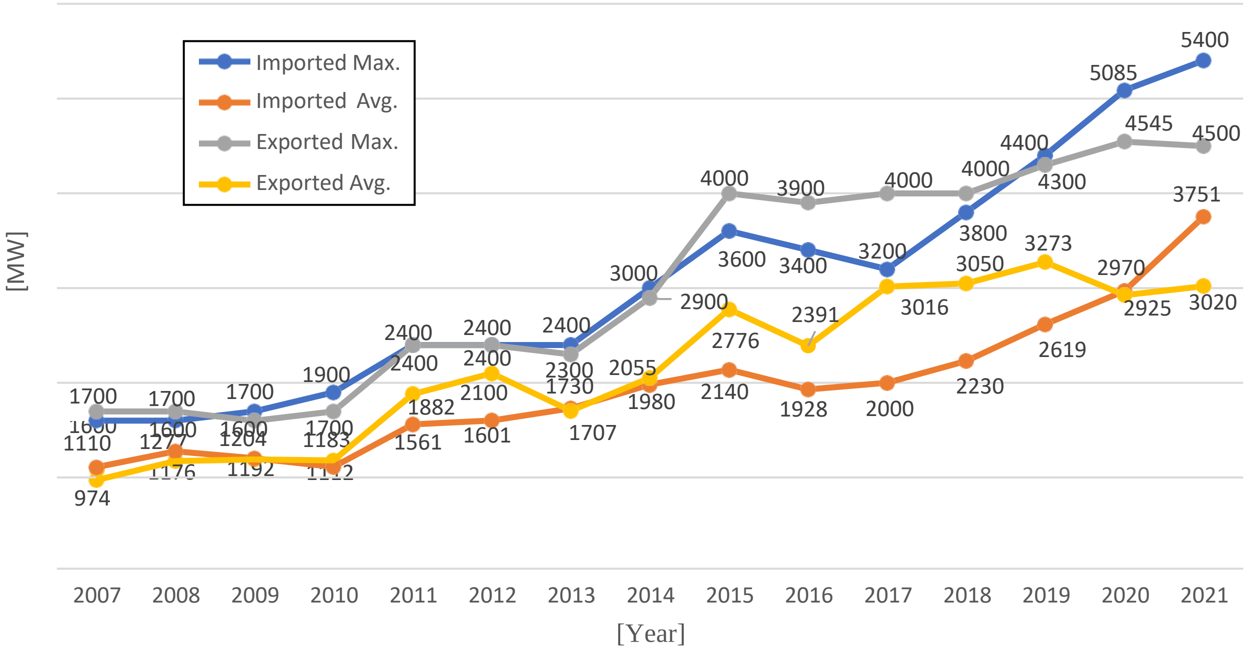

*Figure 8 - Evolution of interconnection capacity available for commercial purposes, adapted from [13]*

Figure 8 shows the development of the, commercially used, interconnection capacity in the import and export directions between the year MIBEL began operating (2007), and 2021.

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 [13].

### Consumption

As of 2006, the liberalization of the electricity sector in Portugal has allowed consumers to choose their retail supplier and switch between providers without any additional charges. Retailers compete on pricing and contract types since the end product, electricity, is not differentiated. Producers sell electricity through the wholesale market to suppliers, who then sell it to customers, with regulated grid access tariffs set by ERSE. In case the liberalized market fails to provide electricity, a last resort supplier ensures the continued supply to consumers [14].

Figure 9 illustrates the fact that consumers switched to the liberal market over the years and in 2022 the regulated market is only responsible for about 5 % (1.93 TWh) of the supplied electricity. It also shows that low tension consumers are responsible for almost 50 % of the 45.52 TWh consumed in 2022 [15].

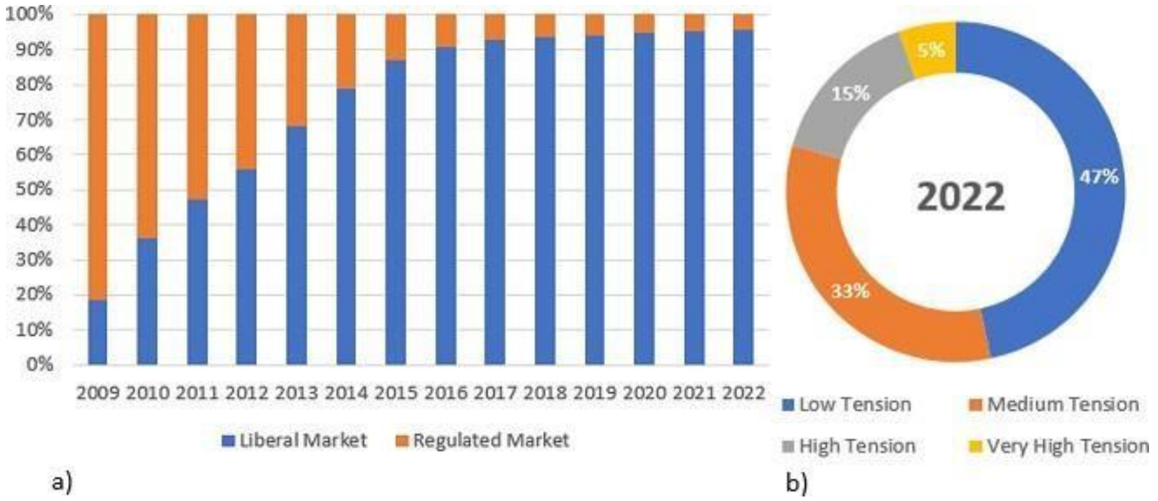

*Figure 9 - a) Evolution of the supplied electricity by market from 2009 to 2022 and b) electricity consumed by tension levels for the year 2022, adapted from [15]*

Deregulation is the final step to achieve a fully liberalized electricity market. Although there were plans for the regulated market to cease by 2020, the regulated tariff (defined by ERSE) is expected to be in force until the end of 2025 and will be reviewed annually [16]. Regulation and price limitations are abolished in order to improve competition. But greater competition and cross-border flow do not conduct to a lower electricity price for end-consumers. Retailers shield their clients from the wholesale price volatility risks by offering fixed retail prices, which do not necessarily follow the adjustments on wholesale market price [17], [18].

### 2.1.2 Transportation & Heating/Cooling sectors

From 2015 to 2021, FEC in Portugal displayed a slight growth trend. However, this pattern was disrupted by the impact of the COVID-19 pandemic, resulting in a decrease in 2020 and 2021. In 2021, the FEC was approximately 16.15 Mtoe, with the transportation sector accounting for 34 % of the total energy consumption.

Table 1 showcases the breakdown of energy consumption by different transport modes in Portugal. Road transport dominates the sector, representing 94.9 % of the total share in 2019. Domestic aviation follows with a share of 2.8 %, domestic navigation accounts for 1.45 %, and rail transportation constitutes 0.85 %.

*Table 1 - Portuguese FEC, for transportation and each type from 2015 - 2021 (in ktoe) , adapted from*[6], [7], [19]–[23]

| | **2015** | **2016** | **2017** | **2018** | **2019** | **2020** | **2021** |
|---|---|---|---|---|---|---|---|
| FEC | 15,897 | 15,915.9 | 16,200.7 | 16,415.6 | 16,597.4 | 15,407.4 | 16,147.7 |
| **Transportation** | 5,607 | 5,698.6 | 5,819.1 | 5,882.6 | 6,020.3 | 5,047 | 5,504 |
| Domestic Aviation | 123.2 | 150.2 | 168.4 | 178.9 | 166.4 | 87 | 120.7 |
| Domestic Navigation | 85.6 | 81.8 | 98.5 | 102.8 | 88.1 | 62.9 | 73.8 |
| Rail | 47.3 | 45.9 | 51 | 51 | 51.9 | 45 | 47.3 |
| Road | 5,350.9 | 5,420.7 | 5,501.1 | 5,550 | 5,713.9 | 4,852.1 | 5,262.1 |

Table 2 shows that in 2021 oil and its derivatives represented 98.8 % of the FEC by the transport sector with electricity having a share lower than 1 %, mostly due to the partial electrification of rail transport responsible for over 96 % of the electricity consumption in the transport sector [24].

*Table 2 - Transportation FEC per energy source type in 2021 (in ktoe), adapted from* [6]

| **2021** | **Oil and derivatives** | **Natural gas** | **Electricity** | **Biomass** |
|---|---|---|---|---|
| **Transportation** | 5,439.3 | 23.8 | 40.1 | 0.78 |
| Domestic Aviation | 120.7 | 0 | 0 | 0 |
| Domestic Navigation | 73.8 | 0 | 0 | 0 |
| Rail | 8.7 | 0 | 38.6 | 0 |
| Road | 5,236 | 23.8 | 1.5 | 0.78 |

Historically, Portugal has had minimal heating and cooling demand due to its advantageous geographical location. However, due to low demand, house insulation has been overlooked in the construction industry. Thus, energy efficiency in Portugal's housing sector is low [25].

According to the Survey on Energy Consumption in Households, result of the collaboration between DGEG and Statistics Portugal (INE) and co-financed by the European Commission, in 2020, cooking accounted for the greatest percentage of home energy consumption, 34.6 % of total energy consumption. Followed by ambient heating at 23.2 %, electrical equipment at 19.9 %, and water heating at 19.7 %. In contrast, the energy consumption in houses was marginal for cooling (1.0 %) and lighting (1.6 %). In Portugal, 78.3 % of households have ambient heating equipment. Although central heating has increased from 10.5 % in 2010 to 16.6 % in 2020, the majority (61.2 %) of domestic heating is done with individual electric heaters. Only 22.6 % of the households used ambient cooling equipment [26], [27].

## 2.2 Nuclear Energy

When employing the term nuclear energy, the writer refers to its applications in terms of nuclear power plants, which most resort to nuclear fission. In conventional power plants the burning of fossil fuels is used to heat up water, generating steam that goes through a turbine which produces electricity. Nuclear power plants work in a similar way.

Inside the reactor, nuclear fuel, in the form of rods, is used for the atomic reaction (fission). Control rods are used to control the process or stop it if need be. Water usually used both as moderator, to slow down the neutrons generated in the fission reaction, to a range in which they are more efficient at causing further fissions, and coolant which circulates through the reactor keeping temperature within normal ranges and transferring heat. Heated water from the reactor goes through a steam generator to produce steam used by a turbogenerator to produce electricity. The steam then goes through a condenser transferring heat with another water source which is then sent to a cooling tower.

Except for hydrogen, which consists of a single proton, atomic nuclei are composed of a combination of elementary particles, namely protons and neutrons. The number of protons in a nucleus is a unique characteristic of each element, while the number of neutrons can vary. This variation gives rise to different types of nuclei for a single element, known as isotopes. Isotopes can be stable or undergo radioactive decay. The term half-life pertains to the duration required for fifty percent of the nuclei in a radioactive isotope to decay, emitting electromagnetic radiation and/or nuclear particles. The range of half-lives can vary from fractions of a second to millions of years.

In nature, stable isotopes are typically long-lived. However, through nuclear reactions, short-lived artificial isotopes can be created, such as those involving heavier elements like plutonium, which are heavier than uranium. Uranium is the heaviest naturally occurring element and is composed primarily of uranium-238, which consists of 92 protons and 146 neutrons. Another isotope, uranium-235, represents a small fraction (0.718 %) of natural uranium. It is the only fissile isotope available in significant quantities for industrial use, capable of sustaining a self-sustaining chain reaction. As a result, most nuclear reactors are specifically designed for the fission of uranium-235.

Distinct combinations of radioactive fission products can be formed by fission of different nuclei, these products and the results of their radioactive decay represent a relevant share of high-level nuclear waste. The majority of the energy liberated during the reaction manifests as kinetic energy possessed by fission products that interact with neighboring atoms, converting their kinetic energy into heat, which is then harnessed for the production of electricity. On average, only one of the neutrons released from the reaction ends up colliding with another fissile nucleus leading to a chain reaction, consequence of their level of kinetic energy. To decrease the kinetic energy of neutrons released to a more efficient level, nuclear power plants make use of a moderator (frequently water). The remaining free neutrons can either escape the reactor (leakage), simply bounce off a nucleus (scattering) or collide not causing fission (capture), which can create radioactive isotopes part of high-level nuclear waste such that of plutonium element (which can be used as nuclear fuel).

When a neutron impacts with heavy nuclei (nuclear collision), such as that of plutonium or uranium isotopes, the nucleus splits into two fragments (fission products) releasing energy and neutrons. This is the so-called nuclear fission by neutrons reaction, the key basic reaction for todays' commercial use of nuclear energy, in which atomic nuclei split, by collision with a neutron, producing heat and releasing neutrons which, under specific conditions, cause further fissions [28], [29].

Nonetheless, there is currently a fusion reactor under construction, in France, expected to be commissioned in the late 2020s. A jointly (EU, United States of America, Russian Federation, Republic of Korea, China, India and Japan) funded project, called international thermonuclear experimental reactor, which attempts to replicate what occurs in the core of stars, including our sun, a fusion reaction. The most efficient one, in a laboratory setting, and thus the most studied, was the fusion reaction of two hydrogen isotopes, tritium and deuterium [30], [31].

If fusion reactors become a reality, they could bring several benefits to current nuclear power:

- Energy efficiency – 1 kg of fusion fuel has the potential to produce an equivalent amount of energy as that derived from 10 million kg of fossil fuel;
- Fuel resources – Even with widespread implementation of fusion reactors, fuel resources would last for thousands of years;
- Reliability – designed to continuously supply large amounts of energy at costs like other energy sources;

- Safety – The amount of fuel used at one time is minimal, making it impossible for a large-scale nuclear accident to happen;
- Carbon emissions – Helium is the only by-product of the referred fusion reaction, an inert gas that can be safely released;
- Radioactive waste – the fusion reaction doesn't produce radioactive waste, only the reactor materials become radioactive, for which research is being carried to use materials with shorter decay times;

### Advantages and disadvantages

One of nuclear powers' primary drawbacks with worldwide consequences is the potential of radioactive pollution due to nuclear reactor accidents and nuclear waste management.

Throughout the history of nuclear power, there have been two significant accidents that obtained a maximum score of 7 out of 7 on the International Nuclear and Radiological Event Scale. These accidents were the Chernobyl disaster in 1986 and the Fukushima incident in 2011. These events had a notable impact on how countries worldwide perceived nuclear power.

The aftermath of the Chernobyl disaster had such a profound effect on public opinion that Germany passed a resolution in the same year to phase out nuclear energy by the end of the decade. Italy followed suit by completely discontinuing its nuclear energy program, while Kazakhstan and Lithuania made similar decisions. After the Fukushima accident in March 2011, the Japanese government, with a 31 % nuclear power share, decided to shut down all nuclear reactors, concluding by May 2012. Japan began restarting its nuclear reactors in 2015 under new safety standards.

Despite the understanding that nuclear power plants are equipped with multiple physical barriers to prevent the release of radioactive isotopes into the environment, large-scale catastrophic events have a lasting impact on public perception.

According to America's National Aeronautics and Space Administration nuclear power has a 0.085 % percentage of the total deaths per TWh produced, while power from fossil fuels has a share of 22.1 % to 39.2 % (depending on the source) and natural gas 3.38 % [32].

Nuclear power also threats the environment due to the complicated management of nuclear fuel waste. Nuclear waste consists of Uranium particles that failed to enter the fission process, other fission products, and Plutonium. Plutonium has a half-life of about 24,000 years and is extremely dangerous and toxic. Although spent nuclear fuel reprocessing can help solve this problem by reducing the volume of nuclear waste that needs to be stored, the amount of nuclear waste being produced annually around the world is still about double of that being reprocessed.

Long term waste disposal is the most pressing matter, for which the global consensus on the most viable solution is the storage of nuclear waste, in specially designed containers, at natural occurring locations (tectonically stable, several hundred of meters underground and almost null permeability surroundings). Finland, France and Sweden are in the process of building such sites [33].

Regarding the advantages of nuclear energy, according to the IPCC, nuclear power is secure, stable and reliable. With a median global emission of 12 g/kWh on a lifecycle basis, it is also one of the lowest $CO_2$ footprint generation technologies, comparable to wind energy and almost 4 times lower than the lifecycle emissions of solar PV. While the carbon footprint associated with the complete nuclear cycle may presently be undervalued, several studies indicate that the average emissions produced by this form of energy amount to 66 g $CO_2$/kWh. These calculations take into account indirect emissions, which surpass the commonly acknowledged estimates. However, these emissions remain significantly lower in comparison to those generated by fossil fuels [34], [35].

Taking their low variable costs and high fixed costs into consideration and given that continuous operation of nuclear reactors at rated power levels is usually more efficient, nuclear reactors have been operated as a baseload technology which could complement intermittent renewable sources. Incorporating nuclear energy within a mixed framework, alongside renewable energies, presents a promising option for globally transitioning away from fossil fuels.

With uranium reserves being estimated sufficient for another 100 years of operation (not considering alternative fuels) and the ease of securing fuel for years of operation (6 g of uranium fuel produces as much energy as one ton of coal), Portugal could strengthen the resilience of its energy system against unforeseen and exceptional events that pose risks to the continuity of energy supply or cause sudden and unrelated spikes in energy prices, irrespective of economic factors [36].

## Tracking nuclear power

The first nuclear reactor became operational in a laboratory environment in the United States of America in the early 1950s. A major milestone in the history of nuclear energy unfolded globally from 1970 to 1985, characterized by a substantial surge in the total count of nuclear reactors. During this period, the number of reactors surged almost fourfold, soaring from over 80 to surpass 360. At the same time span, their installed capacity increased 14-fold, from around 18,000 MW to approximately 250,000 MW.

When assessing the cumulative growth of atomic energy from 1955 to 2015, this particular period represents approximately 65 % of the overall expansion observed during the span of six decades. The decline in nuclear development after 1985 can be attributed to a series of global events, with two major factors standing out. Firstly, there was a surge in interest in oil due to significant price drops after 1980. Additionally, the Chernobyl nuclear disaster had a profound impact on how nations across the world perceived nuclear power, leading to a notable shift. However, some governments in Eastern Europe and Asia chose to continue their nuclear energy programs after 1990, steadily expanding their nuclear capacity up to the present day. Consequently, nuclear energy technology has continued to advance and is currently experiencing a renaissance period. This resurgence can be attributed to increased investments in new power plants in developing nations, escalating fossil fuel prices, and growing concerns about climate change [37], [38].

According to the Power Reactor Information System of the International Atomic Energy Agency (IAEA), one of the most complete and reputable platforms for statistics data on nuclear power reactors globally, as of 2021, the global operational count of nuclear reactors stood at 437, collectively providing a net capacity of 389.5 GW(e). Furthermore, there were 56 reactors in the planning phase, intended for construction, with a combined net capacity projected to reach 58.1 GW(e).

With a total of 2,653.3 TWh produced by nuclear power worldwide, IAEA estimates 1.26 Gt of $CO_2$ emissions were avoided. As shown, the pressurized water reactor (PWR) represents almost 70 % of the operational nuclear reactors with a load factor, from 2010 to 2020, of 86 %.

Although not the most efficient one the PWR is still the most used reactor due to the lower costs of construction. Of the reactors which began construction in 2021, 90 % are of PWR type [39]. Among operational nuclear reactors, 14 % are boiling water reactors (BWR), 10.8 % are pressurized heavy water reactors (PHWR), 2.5 % are light water graphite reactors (LWGR), 2.5 % are gas-cooled reactors (GCR), 0.7 % are fast reactors (FR), and 0.2 % are high-temperature gas-cooled reactors (HTGR). Table 3 summarizes the most relevant information on the operational nuclear reactors in 2021.

*Table 3 - Operational reactors, load factor, net capacity and electricity produced for the different type of nuclear reactors, adapted from* [40]

| Type of reactor | Operational Reactors [%] | Load factor [%] | Net capacity [GW(e)] | Electricity Produced [TWh] |
|---|---|---|---|---|
| **PWR** | 69.3 | 86 | 288.2 | 2,026.1 |
| **BWR** | 14 | 89 | 61.8 | 369.1 |
| **PHWR** | 10.8 | 84.2 | 24.3 | 159.7 |
| **LWGR** | 2.5 | 71.3 | 7.4 | 56.1 |
| **GCR** | 2.5 | 58.5 | 6.1 | 35.1 |
| **FR** | 0.7 | 63.8 | 1.4 | 7.2 |
| **HTGR** | 0.2 | - | 0.2 | 0.1 |

Figure 10 illustrates the nuclear net capacity and the corresponding share in the energy mix for the 35 united nations members that used nuclear energy commercially in 2021.

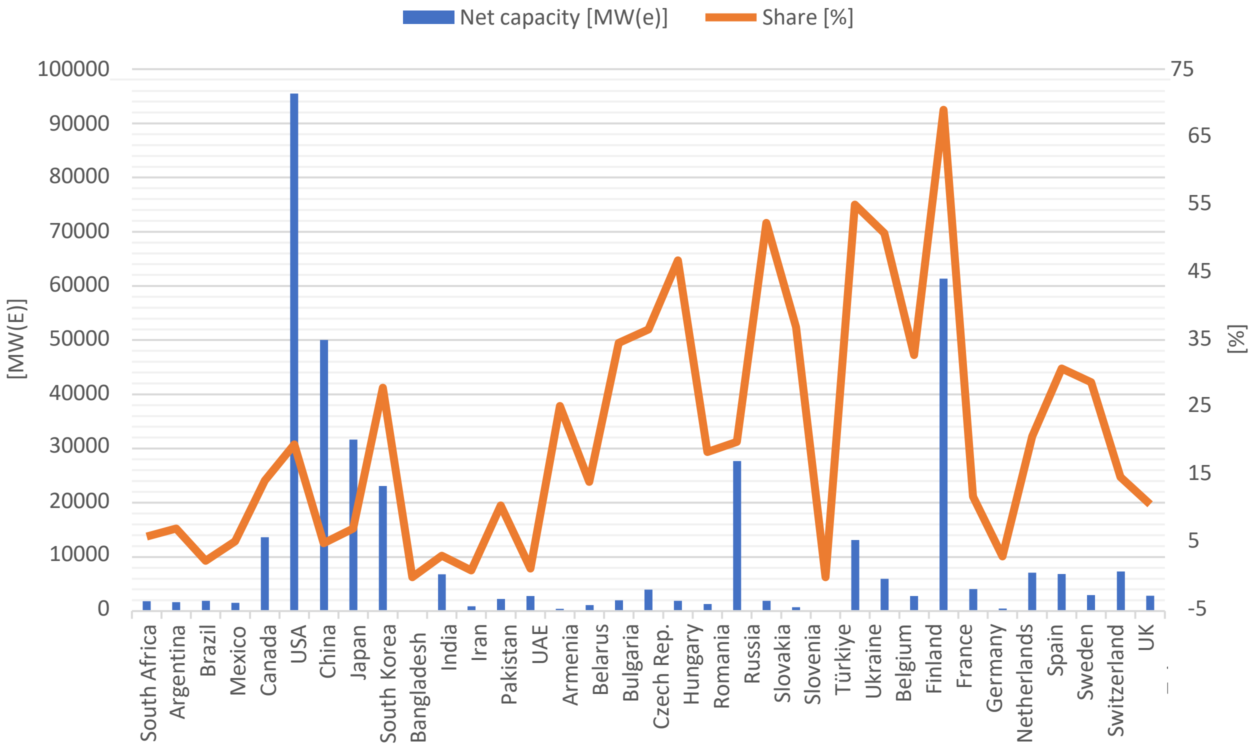

*Figure 10 - Nuclear net capacity and corresponding share for UN member countries, adapted from [40]*

Of the 35 countries (considering Taiwan), in 2021, the United States of America had by far the highest net capacity, 95,523 MW(e) with 93 operational reactors, followed by France (61,370 MW(e), 56 reactors), China (50,034 MW(e), 53 reactors), Japan (31,679 MW(e), 33 reactors), Russia (27,727 MW(e), 37 reactors) and South Korea (23,091 MW(e), 24 reactors). In terms of nuclear power share in the energy mix, the ranking is led by France with share of almost 70 % and 363.4 TWh of electricity produced by nuclear power, followed by Ukraine (55 %, 81.1 TWh), Slovakia (52.3 %, 14.6 TWh), Belgium (50.8 %, 48 TWh) and Hungary (46.8 %, 15.1 TWh).

In 2021, the planned construction of 56 reactors was primarily spearheaded by China, accounting for nearly one-third of the total (16 reactors) and projecting a net power capacity of 15,967 MW(e). Following closely, India had plans for 8 reactors with a projected capacity of 6,028 MW(e), while Russia and South Korea each had 4 reactors in the pipeline, with capacities of 3,759 MW(e) and 5,360MW(e) respectively. Additionally, Turkey and Bangladesh had plans for 3 reactors, projecting a net power capacity of 3,342 MW(e), while the latter two countries were set to incorporate 2 reactors into their energy mix, with a combined capacity of 2,160 MW(e) [39].

# Chapter 3

# Modeling energy systems with EnergyPLAN

This chapter provides an introductory overview of EnergyPLAN and highlights the reasons behind its selection as the modeling tool. The chapter also covers key considerations related to energy demand and supply in different models. Additionally, it discusses the assumptions made regarding costs. The information presented in this chapter sets the groundwork for the subsequent analysis and exploration of Portugal's energy scenario.

## 3.1 EnergyPLAN - Advanced Analysis of Smart Energy Systems

Defining the type of analysis to be conducted is crucial when selecting a software to accomplish such task. There are countless energy tools accessible, each distinct in terms of the objectives fulfilled, the regions they analyze, and the technologies considered. Assessing the different tools (some of which are disseminated at EnergyPLAN's website [41]) would go beyond the scope of this work. To simulate the behavior of the Portuguese energy system 20 to 30 years into the future, subject to the introduction of new technologies such as nuclear power, the EnergyPLAN software was chosen.

EnergyPLAN is a comprehensive and integrated energy systems modelling tool that has been developed to support decision-makers in the transition to a more sustainable and RE system. The software enables the simulation of various energy scenarios, analyses their impacts, and compares them based on various criteria such as environmental, economic, and technical aspects. Initially developed by the Aalborg University in Denmark in the late 1990s, the first version of the software was released in 2000, and since then, it has been continuously updated and improved to meet the evolving energy systems' challenges. The software's development team is composed of a group of interdisciplinary researchers and experts in energy modelling, policy analysis, and system optimization.

EnergyPLAN's general schematic is shown in Figure 11, it is evident that the program enables for the modeling of an integrated smart energy system.

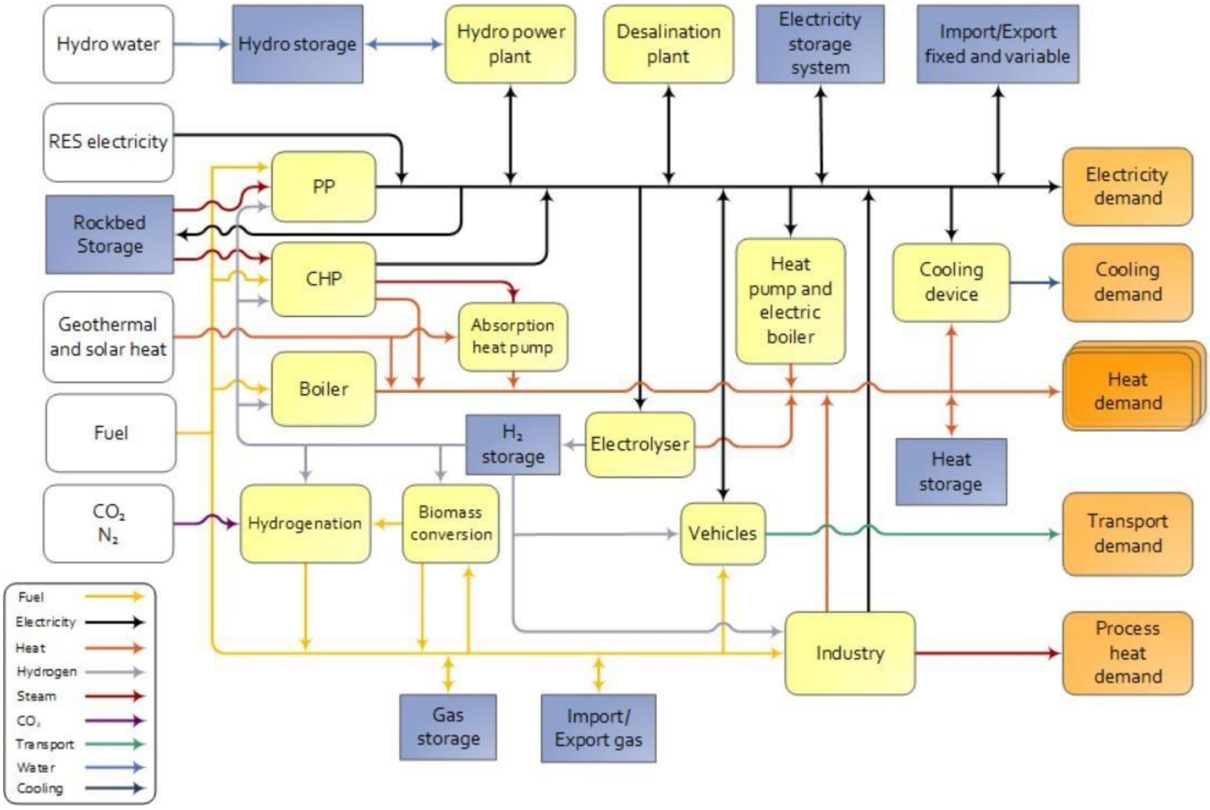

*Figure 11 - EnergyPLAN's overall schematic [41]*

EnergyPLAN has several advantages over other energy system modeling tools, such as:

- User-friendly interface: EnergyPLAN has a user-friendly interface that allows non-experts to use the software without extensive training or expertise in energy system modeling;
- Flexibility: EnergyPLAN is highly flexible and customizable, allowing users to tailor the software to their specific needs and requirements;
- Integration of environmental impacts: EnergyPLAN integrates environmental impacts into the modeling process, enabling users to assess the environmental sustainability of energy systems;
- Integration of heat and transportation sectors: EnergyPLAN integrates the heat and transportation sectors into the modeling process, enabling users to optimize the whole energy system, including the interactions between different sectors;
- Transparency and open-source: EnergyPLAN is open-source and transparent, allowing users to understand and modify the underlying assumptions and calculations of the software;

However, EnergyPLAN also has some disadvantages relative to other tools and software. Given its bottom-up approach, the software requires a considerable amount of input data, which can be timeconsuming and challenging to collect. Moreover, the software is greatly conditioned by the quality and accuracy of the input data, which can significantly affect the simulation results. Replication of an energy system through calibration is beneficial for proving the capacity of the software to adequately mimic existing systems, hence confirming the output. Nevertheless, it is constrained by nature when the simulated circumstances expand outside the scope of observable conditions [42]. Energy planning models are commonly employed to evaluate potential future scenarios involving significant shifts in the composition of the energy system. However, it is important to note that there is no guarantee that future systems will align exactly with these projections, as there are no existing data or metrics available for direct comparison.

In Figure 12, which illustrates the geographical application of EnergyPLAN in academic literature, it can be observed that all EU member countries have been studied. Generally, the application of EnergyPLAN has been global, although there is a notable lack of representation in Africa and Asia.

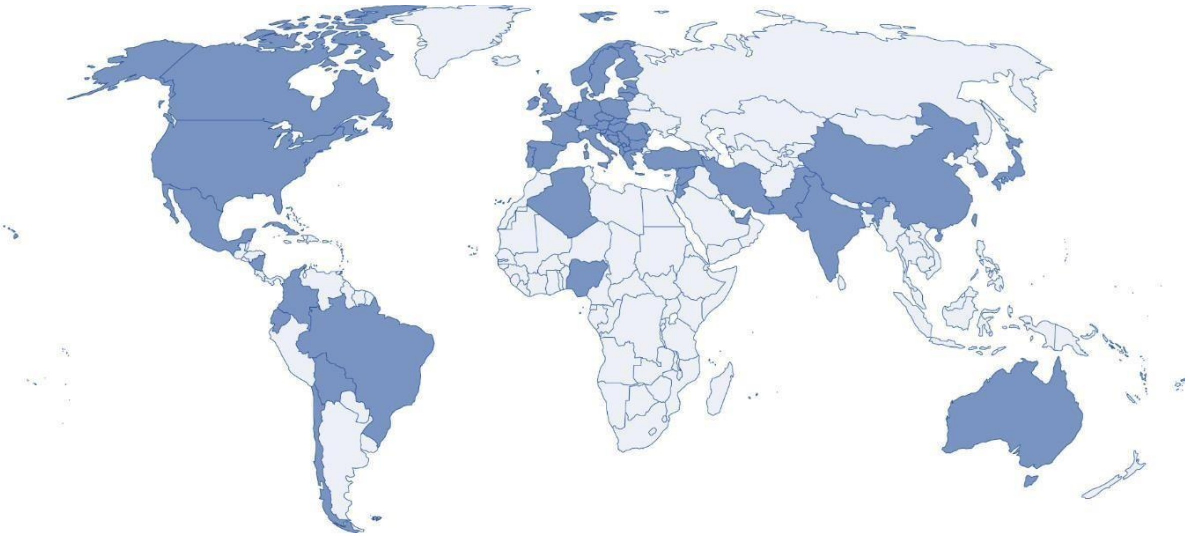

*Figure 12 - Countries studied with EnergyPLAN (dark blue)[41]*

From the early studies, which focused on the addition of combined heat and power and RES into conventional systems with minor sector integration [43], to some of the most recent analyses, in which EnergyPLAN has been integrated with other modeling tools to establish intricate simulation environments. These environments are designed to address the integration of national energy systems or incorporate a combination of design optimization and simulation methodologies [44], [45]. By the end of 2022, EnergyPLAN was referenced over 315 times in journal literature with the top cited articles focusing on RES integration [46]–[50], an overview can be found at EnergyPLAN’s webpage [41].

Through extensive testing, researchers have determined that EnergyPLAN is not only capable of accurately modeling specific systems but also of producing reliable and trustworthy findings. The large-scale use of EnergyPLAN, across many nations and energy system development phases, was considered when validating the program.

Regarding the Portuguese energy system, the application of EnergyPLAN was scarce. Nevertheless, the following studies depict the type of considerations and analyses made for the case of Portugal.

Fernandes et al. [51] focused solely on achieving a 100 % renewable electricity system by 2022, thereby leaving out other sectors. Their study reveals a need for increased capacity, especially for energy generation during summer periods when the outputs from hydro and wind are less substantial. In contrast to the EU's ambitions for expansion, the study maintains the transmission capacity at 3 GW. The substantial quantities of exported power and significant incidents of Critical Excess Electricity Production (CEEP) are mainly due to the limited exploration of storage alternatives beyond hydro storage. Their findings also suggest that systems with greater RE contributions may be costlier than those with lesser ones. Notably, this study did not employ any optimization method.

Soares [52] conducted a comprehensive analysis, considering multiple scenarios to evaluate thepotential proportion of RE over a ten-year period. The outcomes ranged from 37 % to 86 % RE. The model concluded that achieving higher proportions of RE within the given constraints was not feasible.Notably, the costs associated with the 86 % RE scenario were significantly higher, exceeding 150 % of the costs in the 37 % scenario. However, this higher RE scenario resulted in a remarkable reduction of 98 % in $CO_2$ emissions. It's important to note that the study did not incorporate a smart energy system due to the limited observation period. To achieve a fully renewable system, the author suggested strengthening collaboration with Spain.

Garret [53] developed two distinct models for the Portuguese energy system by 2030. The first scenario aligned with the government's predictions, projecting a substantial increase of 46 % in energy demand and a 43 % rise in $CO_2$ emissions compared to the 2010 levels. The second aimed to enhance energy security by reducing Portugal's import dependence, leading to a higher proportion of RE. However, despite these efforts, $CO_2$ emissions still experienced a moderate increase of 19 %. Notably, the thesis did not include a scenario focused on reducing GHG emissions in 40 % from 1990 levels by 2030 or specifying a particular target for RE utilization.

Simões et al. [54] conducted a study considering Portugal's economic growth and explored six potential scenarios with varying levels of GHG reduction, economic progression, and fossil-based electricity consumption. The findings of the study indicate a significant upsurge in the proportion of RE from 15 % in 2005 to an estimated range of 56-59 % by 2050. This transition not only resulted in a substantial reduction in GHG emissions, ranging from 49 % to 74 %, but also demonstrated the cost-effectiveness of adopting RE, even without imposing a GHG cap. In contrast to many other studies, this report also took into account the transportation and heating sectors in its analysis. However, it should be noted that the evaluation did not specifically examine the necessary changes required in these sectors to achieve Europe's GHG emission reduction targets by 2050. According to the study, Portugal is projected to fall short of the target range of 80 - 95 %. The analysis underscores the importance of minimizing the generation of fossil fuels in future energy systems to align with European emission targets.

Amorim et al. [55] aimed to develop a cost-effective strategy to achieve a carbon-free electrical sector in Portugal by 2050. It specifically focused on exploring the advantages of interconnection with Spain versus designing an isolated energy system for Portugal. While the study took into account increased power consumption, it did not incorporate the transportation and heating sectors. The results indicated that adopting an open system approach would transform Portugal's future electrical grid into asignificant exporter, with a projected export capacity exceeding 18 TWh by 2050. The findings underscored the importance of governments moving away from isolated energy system planning and instead fostering collaboration with neighboring countries to enhance efficiency and reduce costs. Therefore, transmission infrastructure is anticipated to play a key role in facilitating such collaboration and supporting the future energy system.

In 2022, Fortes et al. [56] conducted a study on the influence of climate change on the interplay between wind, solar PV, and hydro power in achieving a power sector neutral in carbon for Portugal by 2050. The findings indicated that climate change is projected to result in a 20 % reduction in hydro power generation. By incorporating improved geographical and temporal resolution, as well as integrating future climatic patterns, the study revealed that the cost-effectiveness of solar PV systems was lower than initially anticipated in the Portuguese roadmap for carbon neutrality for 2050 (RNC2050). Furthermore, the study indicated that climate change is expected to have minimal impact on onshore wind output, while offshore wind generation is anticipated to experience positive effects.

## 3.2 Energy demand

To develop an energy system model, it is critical to understand energy needs and what sort of energy is demanded. To better evaluate the impact of new technologies in the production of electricity, the energy demands were kept the same for the reference and predictive models.

### Electricity demand

In accordance with the Paris Agreement, to which Portugal agreed to hold global average temperature rises to well below 2 °C, over pre-industrial levels, and to work toward keeping increases to 1.5 °C or below. Portugal has made a commitment to reduce its GHG emissions so that, by 2050, a net zero carbon footprint is achieved (carbon neutrality).

According to the RNC2050 [57] and the national plan for climate and energy 2021-2030 [58], there will be a reduction between 22 % and 25 % of the FEC, compared to 2015 and a growing electrificationof 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 4 summarizes the demands considered for this work.

*Table 4 - Total and electricity FEC for 2015, 2040 and 2050*

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

When you download the EnergyPLAN model, it comes with several included distributions. In many studies, these distributions are sufficient as the results obtained from the EnergyPLAN model may not significantly improve with a more precise distribution. Hence, it is advisable to analyze the impact of different distributions on your results before investing considerable time in creating new ones. For the case of electricity demand, a new distribution file was created illustrated by Figure 13.

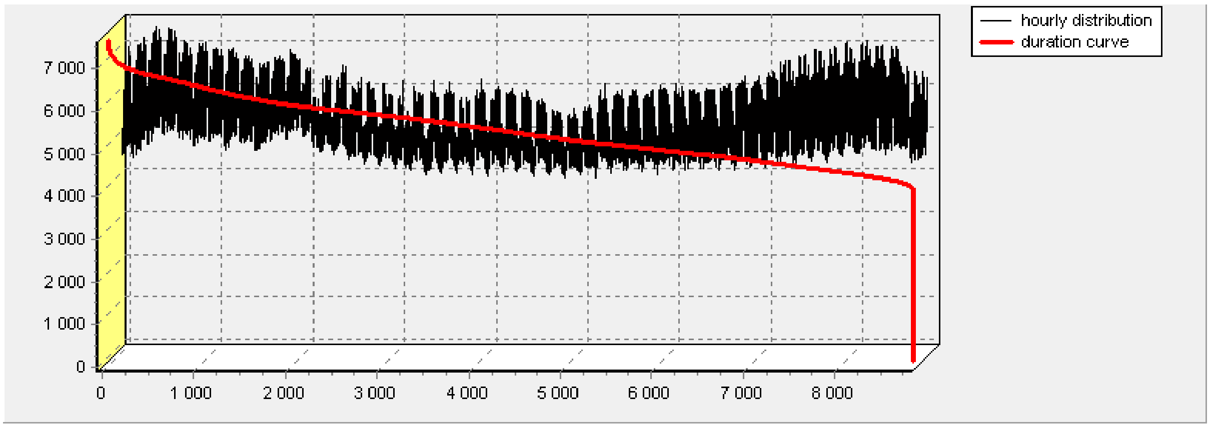

*Figure 13 - Hourly distribution and duration curve for the total electricity demand*

Equation 2 is the linear approach for the load duration curve considered for the Portuguese electricity demand.

$$P = -0,4046h + 7524 \, [MW] \qquad (2)$$

## Heating & Cooling

Climate change will greatly impact Portugal's future heating and cooling needs, winters will experience less severity, while summers will become hotter. Therefore, it is expected that heating needs decrease while cooling needs increase. However, future improvements to heating systems are likely to first tackle the heating gap (aiming at decreasing) so, for this work, it was considered that the heat demand will be the same as in 2020 (most recent information), the biggest change will be how heat is produced.

Figure 14 shows the hourly distribution and duration curve considered for heat demand. It was selected from the several distribution files included with the software.

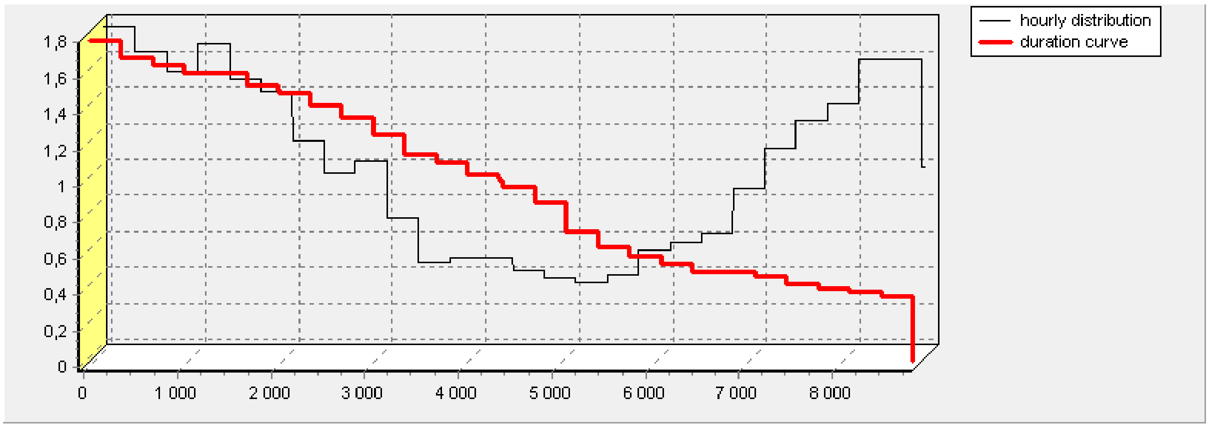

*Figure 14 - Hourly distribution and duration curve for heat demand*

Figure 15 shows the selected distribution for cooling demand and the corresponding duration curve.

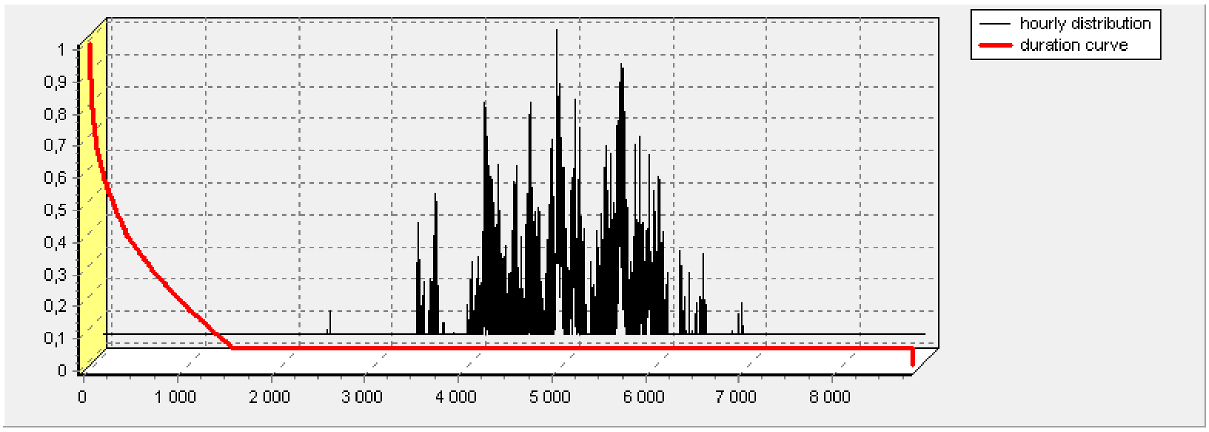

*Figure 15 - Hourly distribution and duration curve for cooling demand*

According to INE [59], it should be noted that more than a third of the biomass used to heat the accommodations was not purchased, hence the cost associated with this source of energy was significantly lower than the costs associated with the others. Also, although present in a lot of households, heat pumps and solar thermal panels, found an inexpressive rate of use for environment heating in 2020. Taking this into consideration, the heat demand covered by biomass was kept the same and in 2040 and 2050 it is considered that the heat demand covered by oil and natural gas (0.75 TWh), in 2020, will be covered by heat pumps, as shown by Table 5.

*Table 5 - Fuel Input and Heat demand according to fuel type for 2020 and 2040/2050*

| | **2020** | | **2040/2050** | |
|---|---|---|---|---|
| **Fuel** | **Fuel Input** | **Heat Demand** | **Fuel Input** | **Heat Demand** |
| Oil | 0.35 | 0.3 | 0 | 0 |
| Natural gas | 0.5 | 0.45 | 0 | 0 |
| Biomass | 6.29 | 5.03 | 6.29 | 5.03 |
| Electricity | 0.6 | 0.6 | 0.85 | 1.35 |
| **Total [TWh]** | **7.74** | **6.38** | **7.64** | **6.38** |

Portugal has a low renovation rate, thus for this work it was considered that cooling needs will indeed increase. According to INE, in 2020 environment cooling represented 2.2 % of electricity total consumption in the household. Considering a 40 % increase in cooling demand, it is assumed that in 2040 and 2050 the cooling needs will be of 0.44 TWh.

### Transport

In the ensuing decades, the transport sector will require to undertake significant changes. Due to the introduction of new technology and mobility concepts, predicting the transformation of the transport sector is extremely difficult. Despite the numerous studies on different fuels for maritime, aviation and haulage transportation, there is a lack of literature evaluating the operational needs of each sector and, as a result, the different energy carriers and powertrains that are relevant and for what reason [60].

Therefore, this thesis considers the total electrification of the transport sector while keeping the sum of kilometers of every technology the same as in 2021, a task which is made easier by EnergyPLAN's design tool. It was considered that fossil fuel-based transportation consumes 1 kWh per 1.5 km while electric vehicles will achieve 5 km with the same energy consumption. Any technological advancements in efficiency are presumed to be balanced out by a bigger desire to travel [61].

By doing so, the FEC in the transport sector will decrease from 64 TWh in 2021 to 20.55 TWh between 2040 and 2050. EnergyPLAN can differentiate between smart and dump charging, for this work only dump charging was considered. Figure 16 shows the considered distribution for transportation and the corresponding duration curve.

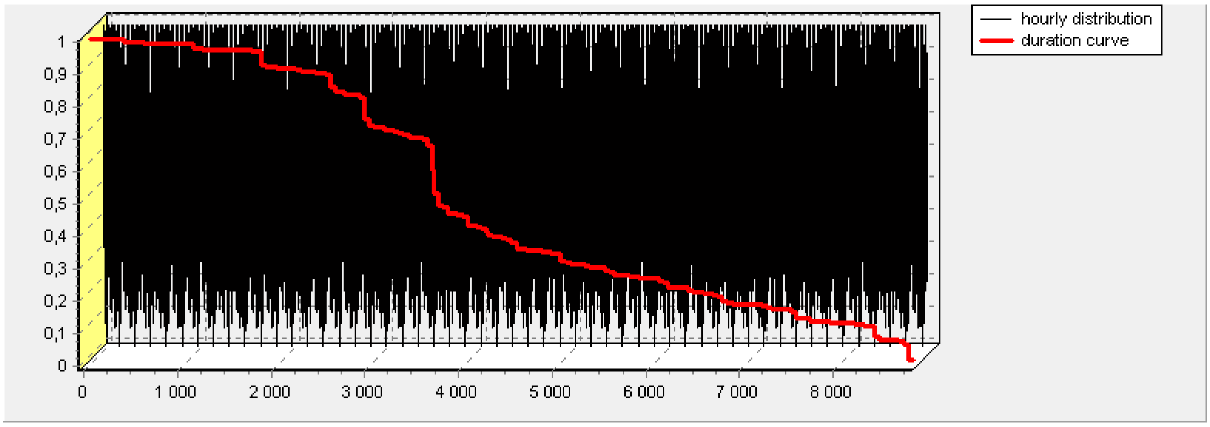

*Figure 16 - Hourly distribution and duration curve for transportation*

### Industry

The industry sector accounts for a significant portion of GHG emissions in Portugal (13 %) [62]. Mainly due to the use of fossil fuels for high temperature required by industrial processes. It was considered that any improvements in efficiency were balanced out by the growth of the sector. Energy consumption was kept the same as in 2021, but coal and oil were replaced by hydrogen as Table 6 presents [63].

*Table 6 - Industry energy demand by fuel source for 2021 and 2040/2050*

| Energy demand [TWh] | 2021 | 2040/2050 |
|---|---|---|
| Coal | 0.12 | 0 |
| Oil | 9.43 | 0 |
| Natural gas | 14.2 | 14.2 |
| Biomass | 5.2 | 5.2 |
| Hydrogen | 0 | 9.55 |

The industry hydrogen and natural gas demands follow a constant distribution shown in Figure 17.

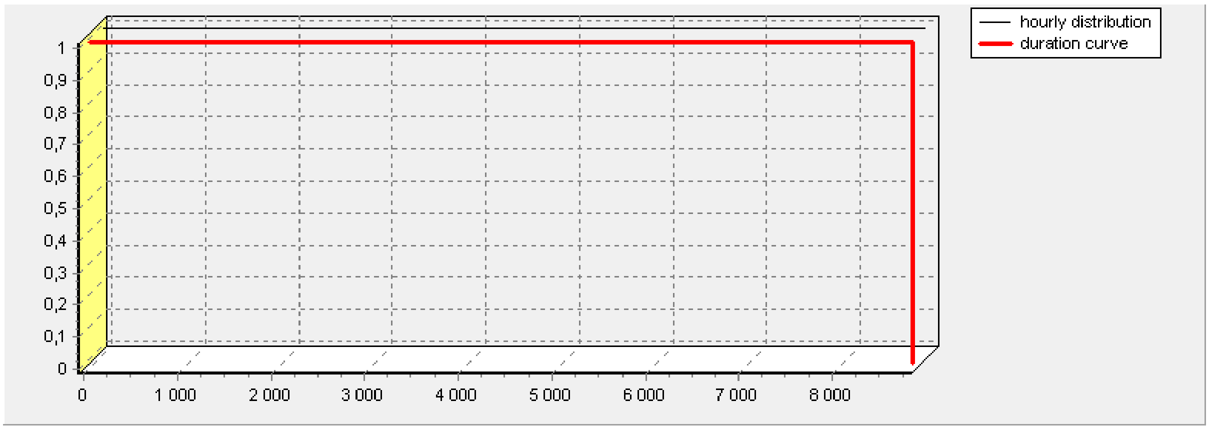

*Figure 17 - Hourly distribution and duration curve for the industry demands*

## 3.3 Energy supply

In this study, the reference models (R-2040 and R-2050) align with the guidelines outlined in the RNC2050. Portugal has already halted coal-based electricity production as of the end of 2021. The government's plan aims to achieve total decarbonization of the electricity generation sector by 2050, with solar PV and wind technologies accounting for 50 % of electricity generation in 2030 and 70 % in 2050. To address the intermittency of these renewable resources and ensure dispatchability and supply security, Portugal plans to retain natural gas on the grid until 2040 and anticipates the cost-effectiveness of batteries as early as 2025. By 2050, a combination of batteries and pumped hydro is projected to comprise approximately 14 % of Portugal's installed capacity. The reference models use a regulatory strategy that focuses on reducing production from conventional power plants to avoid CEEP. Table 7 summarizes the installed capacities for the different energy supply models.

*Table 7 - Installed capacities by technology considered for the different models*

| | **Reference models** | | **Predictive models** | | |
|---|---|---|---|---|---|
| **Installed Capacity [GW]** | **R-2040** | **R-2050** | **P-2040** | **P-2050** | **P-2050R** |
| Coal | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Natural gas | 2.40 | 0.20 | 0.00 | 0.00 | 0.00 |
| Oil | 0.10 | 0.00 | 0.00 | 0.00 | 0.00 |
| Hydro | 8.50 | 8.50 | 7.10 | 7.10 | 7.10 |
| Wind | 10.00 | 13.25 | 10.00 | 10.00 | 12.00 |
| Solar PV | 16.95 | 26.20 | 5.00 | 5.00 | 7.50 |
| Geothermal | 0.10 | 0.00 | 0.10 | 0.00 | 0.00 |
| Biomass | 1.40 | 1.60 | 1.40 | 1.60 | 1.60 |
| Batteries | 2.00 | 4.00 | 2.00 | 4.00 | 4.00 |
| Nuclear | 0.00 | 0.00 | 4.00 | 6.00 | 4.00 |
| **Total** | **41.45** | **53.75** | **29.60** | **33.70** | **36.20** |

The predictive models (P-2040, P-2050, and P-2050R) aim to analyze the integration of nuclear power in Portugal's energy mix. By utilizing equation 2 as a linear approximation of Portugal's load duration curve, the minimum nuclear installed capacity required is 4,000 MW to meet the electricity demand for all 8760 hours of the year. Model P-2050 expands nuclear capacity by 50 % to fulfill the demand in 2050, while model P-2050R focuses on increasing wind and solar PV capacities to meet the higher demand in 2050, while maintaining the 4 GW nuclear capacity from 2040. Batteries, biomass and geothermal capacities were kept the same for each year independent of the model to allow for a better comparison. For the predictive models, hydro installed capacity was limited to the current 7.1 GW due to the anticipated decline in hydro availability. Also, for that reason, dammed hydro water supply was constrained to achieve an estimated 6.36 TWh electricity production (dry year of 2022) across all models. The predictive part load nuclear power to avoid CEEP.

It is worth mentioning that the study adopted an optimistic viewpoint on RES and a more pessimistic view on nuclear power. Specifically, the study focused on the PWR type of nuclear reactor, which is not the most efficient. Details of the PWR reactor, including a 33 % efficiency and a load factor of 0.86 (these values do not consider future improvements), were provided in section 3.2. The hourly distribution was considered constant, as depicted in Figure 17.

This study explored the maximum deployment potentials of wind and solar PV power by 2050, considering technology capacity factors (TCF) specific to Portugal. The TCF values provided in Table 8 are generic for the respective technologies and do not account for potential climate variability, as per the study supporting the RNC2050. It is important to note that climate change is anticipated to have a detrimental effect, particularly on solar PV power [56].

*Table 8 - Generation capacity and TCF for wind and solar PV in 2020 and maximum deployment potentials in 2030 and 2050 for the Portuguese electricity system, adapted from* [56]

| | **2020** | | **2030** | | **2050** | |
|---|---|---|---|---|---|---|
| | **[GW]** | **TCF [%]** | **[GW]** | **TCF [%]** | **[GW]** | **TCF [%]** |
| Wind Onshore | 5.48 | 27 | 7.0 | 32 | 12.0 | 32 |
| Wind Offshore | 0.03 | 40 | 4.0 | 43 | >30.0 | 50 |
| Solar PV (utility-scale) | 0.61 | 20 | 5.0 | 21 | 13.0 | 22 |
| Solar PV (rooftop) | 0.42 | 17 | 2.5 | 18 | 12.0 | 19 |

The hourly distribution, and corresponding duration curve, for wind power production is illustrated in Figure 18 and for solar PV in Figure 19.

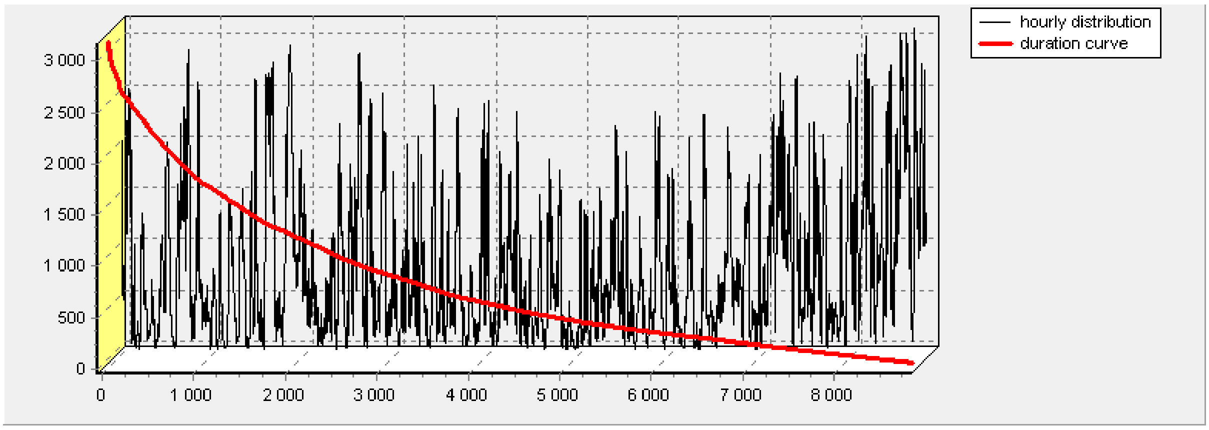

*Figure 18 - Hourly distribution and duration curve for wind power production*

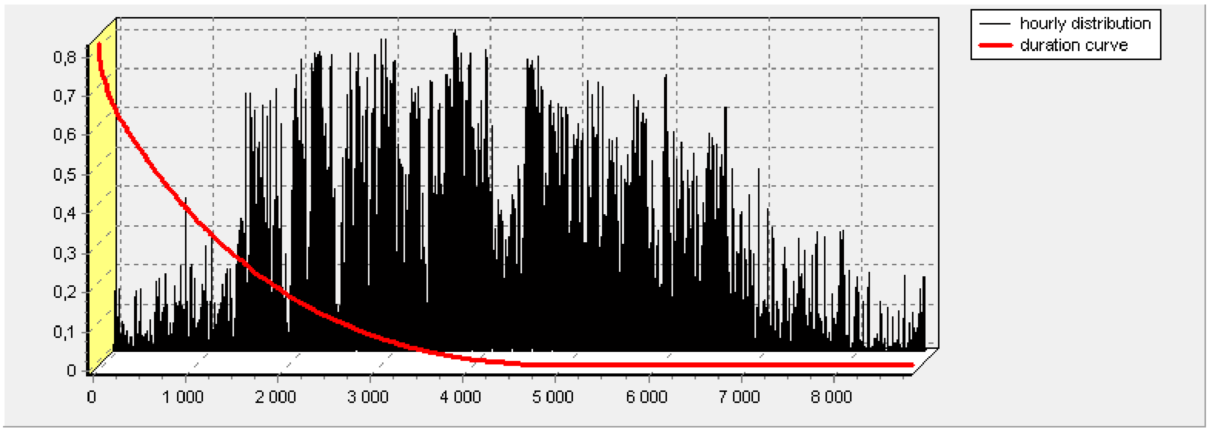

*Figure 19 - Hourly distribution and duration curve for solar PV production*

## 3.4 Costs

There are several sources for cost forecasts. Lund et al. [64] 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 willbe able to attain accurate figures. This thesis makes use of the EnergyPLAN's cost database for 2050 [65]. 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.

# Chapter 4

# Results

This chapter offers insights into various aspects, including installed capacities, primary energy consumption, electricity production, interconnection requirements, $CO_2$ emissions, and costs for the different models.

### Installed capacities

The installed capacities of the energy models provide insights into the composition and scale of the energy generation infrastructure. Figure 20 illustrates the installed capacities of the different models.

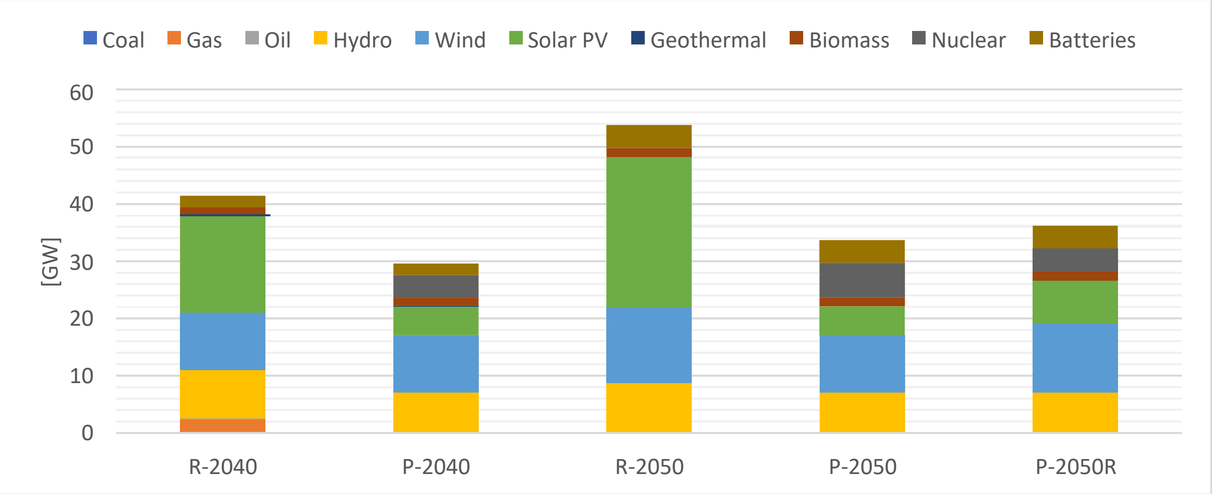

*Figure 20 - Installed capacities [GW] for the different models*

While the reference models emphasized the expansion of solar PV and wind capacities, the predictive models incorporated nuclear power to achieve carbon neutrality.

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.

A lower total installed capacity requirement can potentially reduce infrastructure costs and environmental footprint. These changes in installed capacities set the stage for further analysis.

**Primary energy consumption**

Figure 21 presents a breakdown of primary energy consumption for each model and year and an overview of primary energy consumption.

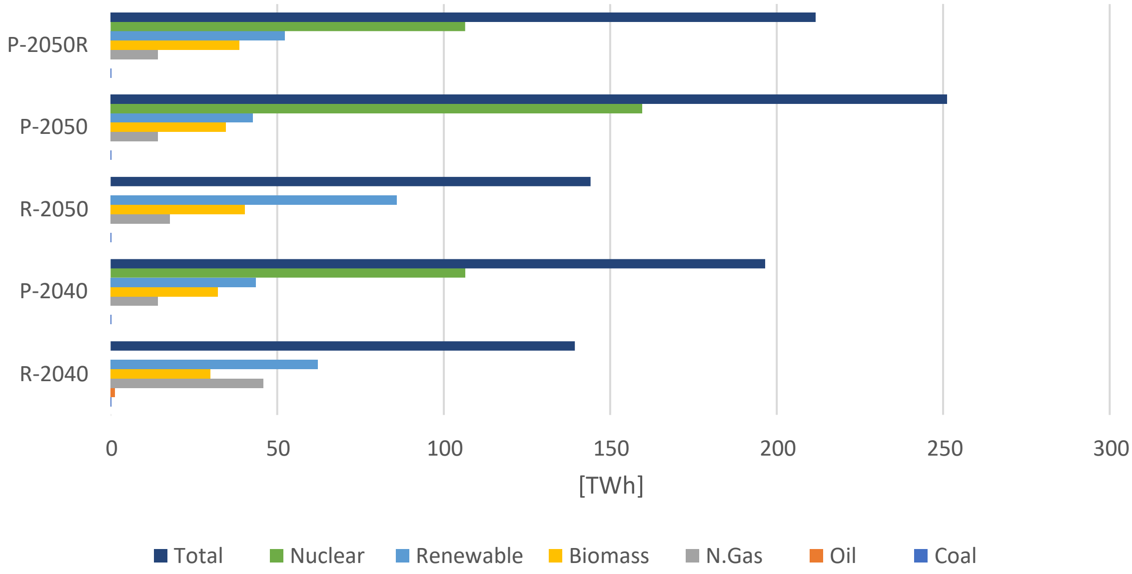

*Figure 21 - Primary energy consumption [TWh] for the different models*

The Reference model for 2040 (R-2040) relies heavily on fossil fuels, specifically natural gas, accounting for nearly 33 % of total primary energy consumption. Other significant contributions come from RE (approximately 45 % of the total, divided among hydro, wind, and solar PV), and biomass (21 %) totaling 139.4 TWh. For P-2040 biomass and nuclear contribute significantly to the total primary energy consumption (196.6 TWh), accounting for about 54 % of the total energy consumptioncombined. It is interesting to note that despite the nuclear power capacity being lower compared to othersources (like wind and solar PV), the primary energy consumption is substantially high due to the highload factor (0.86), consistent power generation of nuclear plants, and the lower efficiency considered.

In the reference model for 2050 (R-2050) total primary energy consumption has slightly increased (144.1 TWh) compared to R-2040. Renewables make up most of the energy consumption, at approximately 60 %. The reliance on oil has dropped to zero, signifying a complete transition away from this fossil fuel. There's a notable increase in biomass and natural gas consumption compared to the R-2040 model, likely making up for the removal of oil. Total primary energy consumption has increased significantly in P-2050 (251.2 TWh), compared to the corresponding reference model, this model relies heavily on nuclear power, which makes up about 63 % of the total primary energy consumption. The reliance on biomass and natural gas remains consistent with the P-2040 model. P-2050R model's total primary energy consumption (211.7 TWh) is less than the previous predictive model but still higher than all the reference models. The contribution from Nuclear is slightly lower than in the P-2050 model but remains the dominant source.

### Electricity production

An overview of electricity production by source, for the different models, is illustrated by Figure 22.

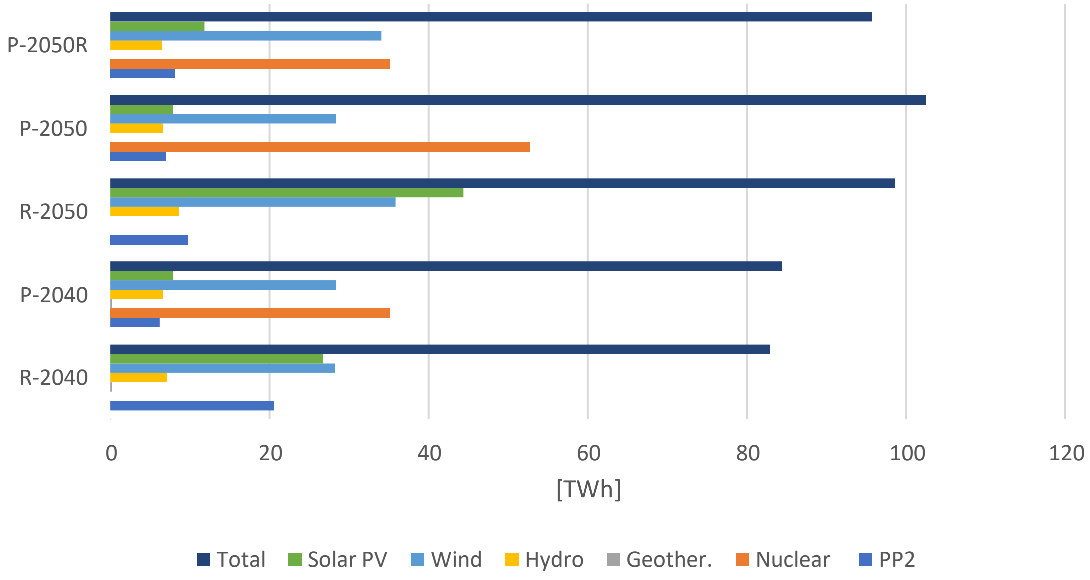

*Figure 22 - Electricity production [TWh] for the different models*

For the model R-2040, the electricity production is dominated by wind and solar PV, collectively accounting for over 66 % of total electricity production (82.9 TWh), reflecting their high installed capacities. Hydro and biomass also contribute substantially. PP2 (oil, natural gas and biomass) account to 24.8 %. In the corresponding predictive model for 2040 (P-2040), nuclear energy has the highest contribution to the total electricity production (84.45 TWh), which is consistent with its high load factor of 0.86 and continuous operation capability. This is despite its lower installed capacity compared to wind and solar PV. Wind also continues to be a significant source of electricity production, almost equal to that of the R-2040 model.

For the reference model R-2050, total electricity production (98.6 TWh) is substantially higher than in the 2040 model, consistent with the higher energy demand for 2050. The trend of reliance on wind and solar PV continues, with their combined output making up nearly 82 % of total electricity production. Model P-2050 shows a contribution of over 50 % from nuclear power generation to the total electricity production of 102.51 TWh. This again showcases the impact of the high load factor of nuclear power. Wind also continues to contribute significantly, albeit less than in the 2050 reference model. For the Predictive model for 2050 which doesn't consider nuclear capacity expansion, P-2050R, nuclear power continues to be the primary source of electricity, although its contribution is slightly less than in the P-2050 model. The electricity production from wind and solar PV has increased compared to the P-2050 model, indicating a higher usage of these renewable sources. For model P-2050R electricity production totaled 95.75 TWh.

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.

### Interconnection requirements

Analyzing Figure 23, 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.

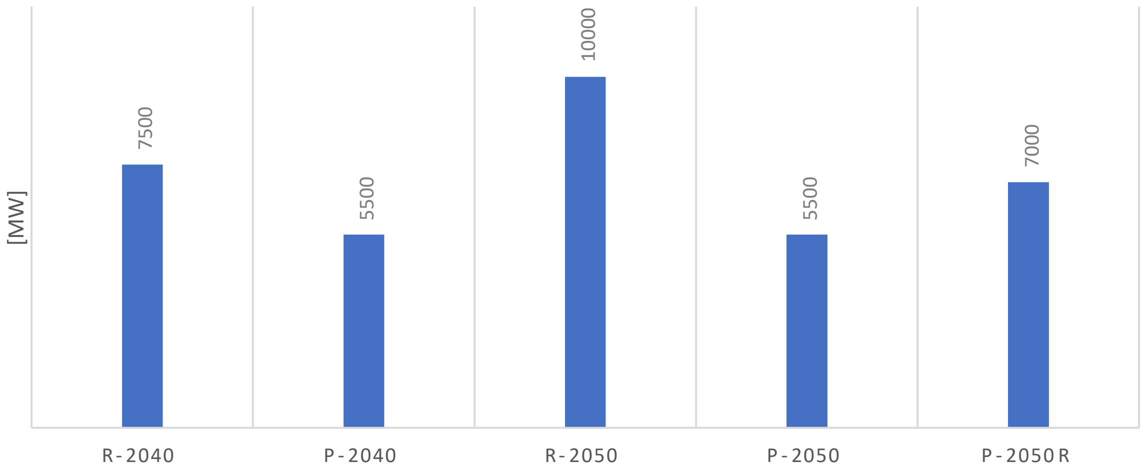

*Figure 23 - Interconnection capacities [MW] for the different models*

In the reference model for 2040 (R-2040), the interconnection capacity is 7,500 MW, which represents 18.1 % of the total installed capacity. For the year of 2050 the reference model's transmission capacity rises to 10,000 MW, or 18.6 % of the total installed capacity. The increase in non-dispatchable renewable sources (wind and solar PV) demand higher interconnection capacity to ensure supply during periods of low generation. In both cases the import/export balance favored exports.

The predictive models, P-2040 and P-2050, both require a lower transmission capacity of 5,500 MW, this still equates to 18.6 % and 16.3 % of the total installed capacity. The significant nuclear component, which is a dispatchable source, allows for a net export of electricity, indicating surplus power during low demand periods. By increasing the electricity supply through non-dispatchable technologies, the model P-2050R requires an increase in transmission capacity to 7,000 MW, representing 19.3 % of total installed capacity and it turns into a net importer of electricity (4.37 TWh net import).

The results suggest that the installed battery capacity is insufficient in all models to fully compensate for the fluctuations in electricity generation and demand, especially with higher penetrations of non-dispatchable renewable sources. While none of the models achieve the desired 15 % target of interconnection capacity to total installed capacity, it appears that a mix of dispatchable sources (like nuclear) and improvements in energy storage, could help to reduce the interconnection requirements. It should be noted that the analysis did not consider external wish for electricity.

### $CO_2$ emissions

Figure 24 illustrates the results for annual $CO_2$ emissions for the reference and predictive models in 2040 and 2050.

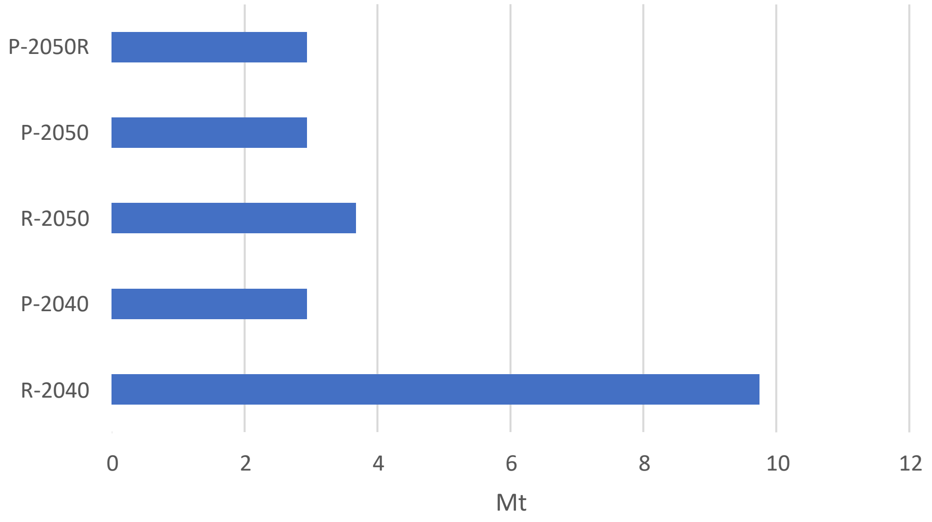

*Figure 24 - $CO_2$ emissions [Mt] for the different models*

In the reference models, annual $CO_2$ emissions experienced a significant reduction from 9.224 Mt in 2040 to 3.492 Mt in 2050. This decline can be attributed to the increased utilization of RES, such as solar PV and wind, which displaced carbon-intensive sources in electricity generation. Nevertheless, despite the lower share of RES in the total installed capacity, the predictive models achieved lower levels of $CO_2$ emissions, with both 2040 and 2050 recording 2.94 Mt annually. In fact, this representsa 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.

## Costs

Figure 25 presents an interesting comparison of the various costs associated with different energy models, showing that nuclear power can offer substantial benefits in certain contexts.

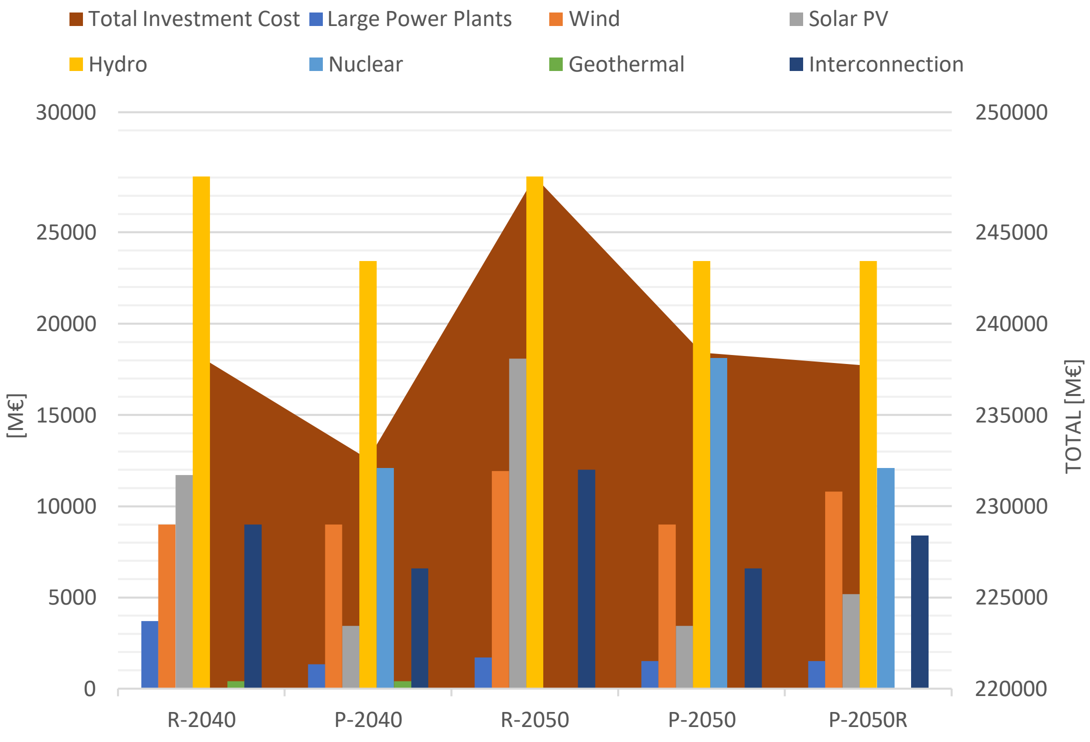

*Figure 25 - Total and individual investment costs [M€] for the considered installed capacities, by each model*

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. 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 interconnectioncapacity 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 2 GW and 2.5 GW respectively proves to be more cost-effective than extending the nuclear installed capacity by 2 GW, 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 26.

*Figure 26 – Annual investment, fixed operations, variable and total annual costs [M€] for the different models*

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 27 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. This analysis was conducted with a null external wish for electricity, meaning that the EnergyPLAN model primarily strives to avoid CEEP, while also managing supply surpluses and deficits through exports and imports as required.

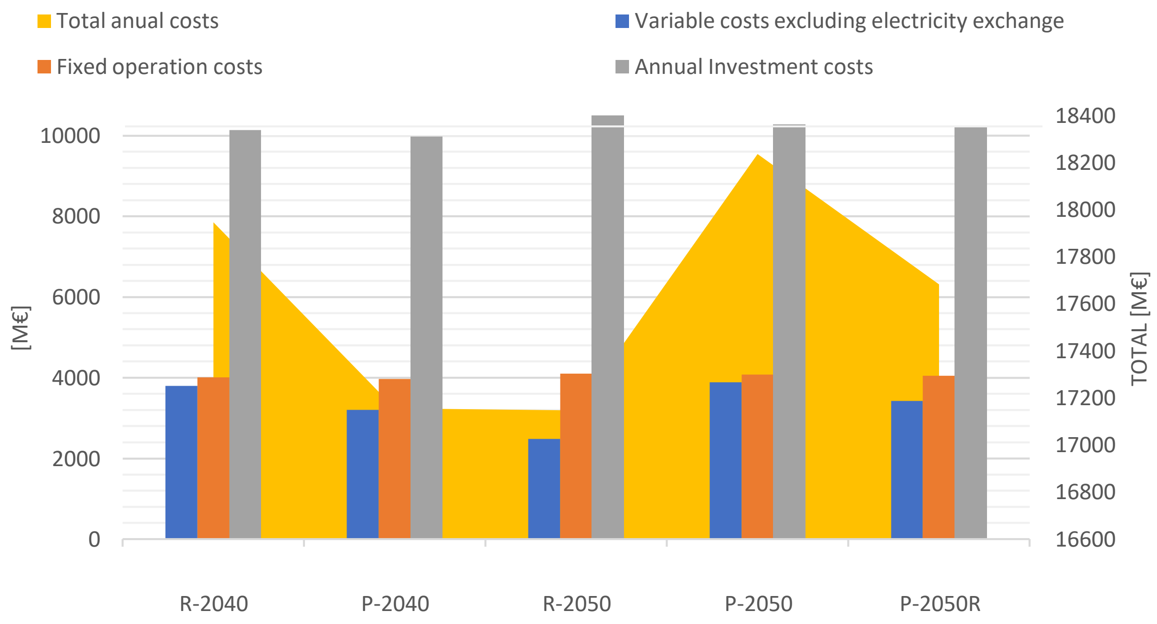

*Figure 27 - Annual investment, fixed operations, total annual and variable costs excluding electricity exchange costs [M€] for the different models*

## Chapter 5

# Conclusion

This thesis aims to analyze the Portuguese plan for achieving carbon neutrality by 2050 and evaluate the potential impact of incorporating nuclear power into the country's energy mix starting in 2040. The study utilizes the modeling system EnergyPLAN to develop both reference and predictive models, allowing the comparison of the different scenarios and their implications.

The reference models are designed to align with the guidelines outlined in the RNC2050. The government's plan emphasizes the complete decarbonization of the electricity generation sector by 2050, with a strong emphasis on RES such as solar PV and wind power. Recognizing the intermittencyof these renewable resources, the plan also includes provisions for retaining natural gas on the grid until2040 to ensure dispatchability and supply security. With batteries and pumped hydro projected to comprise approximately 14 % of Portugal's installed capacity by 2050. The predictive models, on the other hand, seek to explore the potential integration of nuclear power into Portugal's energy mix. The models consider a minimum nuclear installed capacity of 4,000 MW by 2040 to meet the projected electricity demand. Furthermore, two possibilities are examined for meeting the demand in 2050: expanding the nuclear capacity by 50 % or increasing the capacities of wind and solar PV while maintaining the 4 GW nuclear capacity. For the predictive models, hydro installed capacity was limitedto the current 7.1 GW due to the anticipated decline in hydro availability. Also, for that reason, dammedhydro water supply was constrained to achieve an estimated 6.36 TWh electricity production (dry yearof 2022) across all models. Electrochemical storage, biomass and geothermal capacities were kept the same for each year independent of the model to allow for a better comparison.

It is worth mentioning that the study adopted an optimistic viewpoint on RES and a more pessimistic view on nuclear power. The study did not consider nuclear power efficiency improvements. On the other hand, this study explored the maximum deployment potentials of wind and solar PV power by 2050, considering TCF specific to Portugal, that do not account for future climate change, as per the technical study supporting the RNC2050.

## 5.1 Final conclusions

It was 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. A lower total installed capacity requirement can potentially reduce infrastructure costs and environmental footprint. In summary, nuclear power, despite its lower installed capacity, provides a significant portion of electricity at the cost of high primary energy consumption 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.

The results show that employing nuclear power in the Portuguese energy mix would allow for a fully decarbonized electricity generation sector by 2040. Meanwhile, for the government's plan, if electrochemical storage capacity does not increase substantially, natural gas will be required and, no matter how you paint it, the complete decarbonization of the electricity generation sector by 2050 won't be achieved.

The results suggest that the installed battery capacity is insufficient to compensate for the fluctuations in electricity generation and demand, especially with higher penetrations of non-dispatchable renewable sources. The use of dispatchable sources (like nuclear), reduces the interconnection requirements.

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. Making total investment costs lower across all predictive models. The same trend was observed when considering annual investment costs, the fixed operations expenses follow suit, rendering the reference models - which emphasize RES - as the more substantial investment. The major advantage of RES lies in its lack of fuel consumption, which results in lower variable costs. However, the study shows that when electricity exchange costs are considered, the intermittency of RES might lead to higher variable costs too.

In conclusion, the findings of this thesis highlight that the installation of a nuclear power plant, despite the associated increase in ED due to uranium imports, can be economically feasible and has the potential to significantly contribute to the decarbonization of the electricity generation sector by 2040. However, it is important to acknowledge the role of public opinion in shaping policy decisions regarding nuclear power. Positive change in public opinion towards nuclear power can be achieved through effective communication strategies that prioritize transparency, education, and engagement. It is crucial for policy makers to address concerns, provide accurate information about safety measures and waste management, and foster a constructive dialogue with the public. By promoting a better understanding of the benefits, risks, and advancements in nuclear technology, a positive change in public opinion can be achieved, potentially paving the way for a more diversified and sustainable energy mix that includes nuclear power as a viable option for decarbonization.

## 5.2 Future work

Upon completion of this study, it is imperative to address the future research directions that can be pursued. It is crucial to consider the following areas for further investigation:

- Techno-economic analysis of nuclear power: Conduct a detailed techno-economic analysis of nuclear power in the Portuguese context. This analysis should consider factors such as investment costs, operational costs, levelized cost of electricity, and cost competitiveness with other energy sources. Additionally, the study could evaluate the potential for cost reduction through advancements in nuclear technology, construction techniques, and supply chain optimization;
- Environmental impact assessment: Perform a comprehensive assessment of the environmental impacts associated with nuclear power, including life cycle assessments of GHG emissions, water usage, waste generation, and land use. Compare these impacts to alternative energy sources to provide policymakers with a holistic understanding of the environmental trade-offs involved in different energy choices;
- Safety analysis and risk assessment: Undertake a thorough safety analysis and risk assessment of nuclear power plants, considering both natural and human-induced hazards. Evaluate the effectiveness of safety measures, emergency preparedness plans, and regulatory frameworks. This analysis will contribute to enhancing public confidence in the safety of nuclear power and help policymakers make informed decisions;
- Grid integration and system optimization: Investigate the optimal integration of nuclear power into the national grid system. Analyze the impacts on grid stability, reliability, and transmission infrastructure. Consider strategies for maximizing the benefits of nuclear power, such as coupling it with RES, energy storage, and demand-side management techniques. Explore the potential for developing a flexible and resilient energy system that efficiently integrates different energy sources;

Additionally, it would be valuable to analyze the impact of electricity exchange costs in the context of integrating variable RES into the grid. This analysis would provide insights into the economic viability and competitiveness of different energy sources, considering the intermittency of RE generation and the need for cross-border electricity exchange. Understanding the potential fluctuations in electricity prices and the associated costs of intermittency would assist policymakers in making informed decisions regarding the optimal energy mix and the development of interconnection infrastructure.

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