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Strategic Planning for a Resilient and Sustainable Energy Future: Analysis of a 100 % Renewable Energy System for Portugal in 2050

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The current energy system of Portugal is heavily reliant on fossil fuels, which accounted for 65.4 % of primary energy consumption in 2021. The low share of renewable energy in the industrial, transportation, and heating & cooling sectors is the primary reason for this dependence. To achieve carbon neutrality and ensure a successful energy transition, the Portuguese government has introduced the "Carbon Neutrality Roadmap 2050", a strategic plan to decarbonise the energy system entirely. This study presents technical solutions to achieve carbon neutrality in the overall energy sector, based on the guidelines of the Portuguese government plans and assuming a high share of green hydrogen utilisation in the industrial and transportation sectors. Hourly energy balances were calculated using the EnergyPLAN software, which revealed the substantial investment required in new renewable electricity sources to achieve decarbonisation of the industrial and transportation sectors. The study's findings emphasise the urgent need to transition to a low-carbon energy system and inform policymakers and energy experts in developing effective strategies towards achieving carbon neutrality.

1. Introduction

The 2015 Paris Climate Treaty effectively and significantly altered the prevailing worldwide paradigm of fossil fuel dependency. This shift was made possible through a collective endeavour, wherein nearly all major global economies were resolute in their commitment to reducing their carbon intensity and a long-term temperature goal of keeping global warming below 2 ºC above pre-industrial levels. As a regional organisation, the European Union (EU) is pivotal in implementing the Paris Agreement. It has been at the forefront of efforts to reduce greenhouse gas (GHG) emissions, and mainly CO_2 emissions. The EU has set a goal of reducing GHG emissions by at least 40 % below 1990 levels by 2030 and a long-term plan to become carbon-neutral by 2050 (Croatian Presidency of the Council of the European Union, 2020). Inside the EU, Portugal has been highlighted as one of the countries with the most ambitious renewable targets, the country has invested heavily in wind, solar and hydropower, which has contributed to a substantial increase in the share of renewable electricity in the energy mix. The country also set an ambitious goal of becoming carbon neutral before 2050. In Portugal's overall energy demand (electricity, transportation, and cooling and heating), fossil fuels accounted for a staggering 68.4 % of the country's primary energy consumption in 2021(Direção Geral de Energia e Geologia, 2022a). Recognising the urgent need for decarbonisation, the Portuguese government has introduced the "Carbon Neutrality Roadmap 2050" (Council of Ministers, 2019), a comprehensive strategic plan to enhance clean energy sources in the energy system. The success of this roadmap lies in an effective energy transition, particularly in the industrial and transportation sectors. This study aims to contribute to realising Portugal's CO_2 emissions reduction goals by presenting technical solutions aligned with the guidelines outlined in the government's roadmap. A key focus of these solutions is the utilisation of green hydrogen in the industrial and transportation sectors, offering a promising pathway for decarbonisation. Numerous authors previously analysed the feasibility of several carbon neutralisation plans and presented technical alternatives to achieve a significant portion of renewable energy supply (Almurisi and Lim, 2022). Several limitations are found in the

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previous literature. Firstly, most studies (Graça Gomes et al., 2020) present technical alternatives on a Portuguese scale for the power system to achieve the target of reducing CO_2 emissions. Still, they do not analyse the transportation and industrial requirements. Secondly, certain studies have utilized simulation models to integrate CO_2 mitigation goals and assess the impact of flexibility measures such as demand response on Portugal's long-term energy strategy (Anjo et al., 2018). Still, these analysis have not taken into account the potential ramifications of hydrogen integration within the system. A similar gap is found in Krajačić et al. (2011), it aimed to achieve a 100% renewable electricity supply in Portugal by 2020 through closed-system simulation. While emphasizing reversible hydro storage due to Portugal's potential, hydrogen and batteries played a minor role. The study's feasibility of a renewable system was highlighted, but economic aspects were suggested for future refinement. To address the mentioned gaps, the main objective of this study is to develop a methodology that certifies optimal penetration of renewable energy in the electric grid, transportation, and industrial sectors by leveraging storage technologies, green hydrogen, and interconnection capacity, considering the 2050 horizon.The work also aims to present a scenario featuring a substantial proportion of renewable energy generation in Portugal, analyse the operational feasibility of the energy system under a high penetration of variable renewable generation through optimising electrical and hydrogen storage management, and identify the investments for a decarbonised energy sector, including the required power capacity. The paper is organised as follows: Section 2 describes the Portuguese energy sector, Section 3 introduces the methodology, and Section 4 the parameters employed in the case study. The results are discussed in Section 5. Finally, the conclusions are shown in Section 6.

2. Portuguese Energy Sector Profile

Over the past two decades, Portugal has experienced a notable decline in its primary energy consumption, amounting to a reduction of 17.8 % (from 25.324 to 20.817 ktep). This downward trend has been accompanied by a decrease in oil and coal consumption, while the demand for natural gas and renewable energy sources has witnessed an upward trajectory. In 2000, renewable energy sources accounted for approximately 16 % of the total energy consumption, by the end of 2021 this figure had doubled to 32 % (Figure 1). This increase can be attributed to the expanded power capacity of hydropower, wind, and solar photovoltaic (PV) installations. The decline in oil consumption can be primarily attributed to reduced fuel oil usage for electricity production. Coal consumption in Portugal has nearly reached zero by 2021, largely due to the country's decommissioning of coal power plants. It is important to acknowledge that fossil fuel sources dominate the primary energy consumption (65.4 %), emphasising the urgent need to diversify the energy supply.

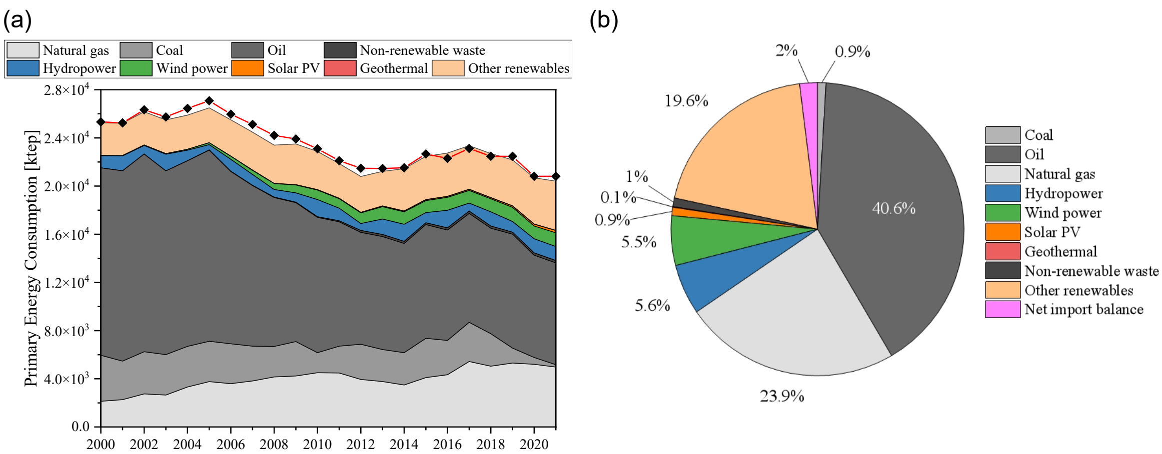

Figure 1: Primary Energy Consumption in Portugal a) Historical trend, 2000-2021 b) Percentual results in 2021.

3. Methodology

This study employed the software EnergyPLAN, a deterministic program that manages production and energy needs with a sequential discretisation that provides full granularity, such as hourly time intervals (Lund et al., 2021). EnergyPLAN is a computer tool focused on the planning of large energy systems; the main data to be input in the model comprise the energy consumption, production technologies type, and the energy generation pattern, as output, it provides the demand and energy generation diagram, system cost, and its correspondent CO_2 emissions. As EnergyPLAN only optimizes the technical side of the system, the software was coupled with an optimization algorithm that prioritises renewable power electricity production (Figure 2) in MATLAB. To accomplish this objective, international interconnections and large-scale energy storage, green hydrogen, and battery storage are used to accomplish periods where the generation of renewable sources surpasses or is scarce to satisfy the need. Fossil sources cope with demand peaks and safeguard a continual electricity supply in renewable resource shortage. The fossil power plants, assumed to be combined heat and power (CHP) plants, and green hydrogen (H_2) will simultaneously generate useful heat for the industry. The transportation sector demand will be supplied by both H_2 and electricity. The model makes it feasible to analyse the attained load profile and installed power capacity for 2050.

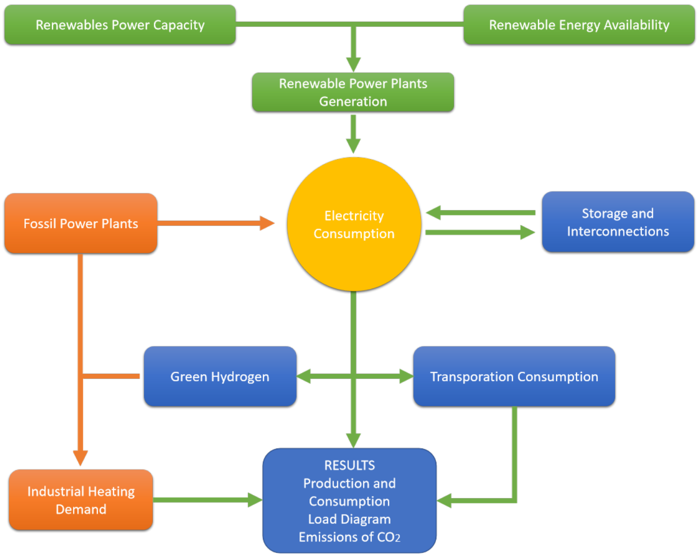

Figure 2: Flowchart of the methodology employed.

The objective function of the optimization algorithm is to minimise fossil fuel consumption. The minimisation of fossil power in the electricity sector and electrical transport can be represented by Eq(1):

$$\text{Min } \sum_{h=1}^{h=8760} F_h = Load_h + Trans_h^{elect} - RES_h - Hydro_h^{reser} - Hydro_h^{pump} - BES_h - I_h \quad (1)$$

Where F_h defines the electricity produced in CHP plants; $Load_h$ represents the electricity requirements; $Hydro_h^{reser}$ designates the power from the hydropower stations with reservoir; $Hydro_h^{pump}$ is the energy accumulated by the pump power plants, BES_h is the energy stored of the battery storage, and I_h is the interconnection capacity between the Portuguese electricity system and other electricity systems, all units are in GWh. RES_h signifies the RES-E generation, and is a result of Eq(2):

$$RES_h = PV_h + Wind_h^{onshore} + Wind_h^{offshore} + Bio_h + Hydro_h^{run-of-river} + Ocean_h \quad (2)$$

Where PV_h,$Wind_h^{onshore}$,$Wind_h^{offshore}$,Bio_h ,$Hydro_h^{run-of-river}$,$Ocean_h$, symbolise the solar PV, wind onshore, wind offshore, bioenergy, hydro run-of-river, and ocean power plants generation, respectively. The H_2 generation is signified by $GH_{2\,h}$ (in GWh_{th}) and is given by the surplus of renewable electricity generation, as defined by Eq(3):

$$GH_{2\,h} = RES_h + Hydro_h^{reser} - Load_h - Trans_h^{elect} \quad (3)$$

The heating generated (in GWh_{th}) in the CHP plants (F_h^{heat}) is defined by Eq(4):

$$F_h^{heat} = \frac{F_h}{\eta_{CHP}^{heat}} \quad (4)$$

In Eq(4) η_{CHP}^{heat} defines the overall efficiency of the conversion process, accounting for losses and waste heat. The minimisation of emissions in the industrial sector can be translated by Eq(5):

$$\text{Min } \sum_{h=1}^{h=8760} F_h^{heat} = Ind_h^{heat} - (GH_{2\,h} \times \eta_{H2}^{heat}) \quad (5)$$

In Eq(5) Ind_h^{heat} symbolises the industrial heating demand of Mainland Portugal (in GWh_{th}), and η_{H2}^{heat} the combustion efficiency of H_2; For last, the problem minimises the consumption of the remaining non-electric transportation. Eq(6) establishes that the energy demand of the transportation sector should be supplied mainly by the $GH_{2\,h}$:

$$\text{Min } \sum_{h=1}^{h=8760} Trans_h^{comb} = GH_{2\,h} \times \eta_{H2}^{veh} - F_h \quad (6)$$

Where $Trans_h^{comb}$ corresponds to the energy requirements of the Portuguese hydrogen transportation fleet (in GWh) and η_{H2}^{veh} is the efficiency of the combustion of H_2 in a vehicle.In the proposed research, the equations will be tackled sequentially, with a primary focus on solving the electricity-related equations first, followed by addressing industry consumption and concluding with transportation-related demand.

4. Case Study

This study's parameters are extrapolated from the Portuguese Energy Action Plan (Presidência do Conselho de Ministros, 2020) and the Portuguese Electricity System Safety Monitoring Report (Direção Geral de Energia e Geologia, 2022b). On the 2050 horizon, an increase in electrical interconnection capacity (ranging from 4 to 6 GW) is estimated, as well as substantial growth projections for offshore wind and solar PV power in Portugal and the potential expansion of electrical storage options. The study analyses various combinations of installed wind and solar PV power capacities, comparing them against a baseline scenario. These simulations assess the benefits different energy mix configurations can offer the Portuguese energy system. A scenario that accounts for high load demand, predicated on assumptions of increased electrification within the industrial sectors, is presented. The capacity factor for each technology is found in (Graça Gomes et al., 2020b). Table 1 introduces the simulation parameters, it comprise the load (*Load*$_h$), electrical ($Trans_h^{elect}$) and hydrogen ($Trans_h^{comb}$) transportation demands, and industrial needs (Ind_h^{heat}). It is also stated the parameters of wind capacity onshore ($Wind_h^{onshore}$) and offshore ($Wind_h^{offshore}$), solar PV (PV_h), biomass (Bio_h), ocean ($Ocean_h$) and hydro storage ($Hydro_h^{pump}$) and run-of river ($Hydro_h^{river}$). It considers 5 case studies, the initial case, which corresponds to linear extrapolations from the government plans, the pro-offshore case, which has an increased offshore wind capacity, the pro-solar, assumes a surge in solar PV capacity, the interconnection case, states Portugal develops new electrical interconnections with foreign countries.

Table 1: Simulation Parameters.

Parameter	Initial Case (GW)	Pro-Offshore (GW)	Pro-Solar (GW)	Interconnection (GW)	High Demand (GW)
$\mathrm{Load_h}$	68.2 TWh	68.2 TWh	68.2 TWh	68.2 TWh	72.26 TWh
$\mathrm{Trans_h^{elect}}$	11.68 TWh	11.68 TWh	11.68 TWh	11.68 TWh	11.68 TWh
$\mathrm{Trans_h^{comb}}$	44.64 TWh	44.64 TWh	44.64 TWh	44.64 TWh	44.64 TWh
$\mathrm{Hydro_h^{reser}}$	6.4	6.4	6.4	7.5	6.4
Max $(\mathrm{Hydro_h^{pump}})$	4.6	4.6	4.6	4.6	6
Max $(\mathrm{BES_h})$	1	1	1	1	3
Max $(\mathrm{I_h})$	4	4	4	6	4
Max $(\mathrm{PV_h})$	17	17	23	17	26
Max $(\mathrm{Wind_h^{onshore}})$	12	12	12	12	12
Max $(\mathrm{Wind_h^{offshore}})$	1	10	1	1	10
Max $(\mathrm{Bio_h})$	1.2	1.2	1.2	1.2	1.5
Max $(\mathrm{Hydro_h^{river}})$	2.5	2.5	2.5	2.5	2.5
Max $(\mathrm{Ocean_h})$	0.2	0.2	0.2	0.2	0.5
$\mathrm{Ind_h^{heat}}$	35 TWh_{th}	35 TWh_{th}	35 TWh_{th}	35 TWh_{th}	28 TWh_{th}

5. Results and Discussion

After analysing the model's application to Portugal’s energy sector, it became noticeable that achieving a fully decarbonised energy system was not feasible based on the initial case study (Figure 4). Although the model successfully demonstrated the ability to meet the entire power load demand, including electrical transportation, through renewable energy power plants and backup from electrical interconnections, it was unable to address the substantial requirement for H_2 to decarbonise the industry using endogenous energy sources. Consequently, fossil fuels account for 31.5 % of the country's total energy needs. Among the renewable technologies considered, onshore wind and solar PV emerged as the most relevant, each contributing 18.5 % towards meeting the total energy demand. Hydropower, despite accounting for 11.9 % of the energy supply, played a key role in managing the variability in renewable power. This highlights the significance of maintaining pump storage capacity within the energy system. The model underscored the importance of interconnections in ensuring a secure energy supply, mainly in the last semester of the year, when it is verified a reduction in PV generation. The availability of Spanish electricity interconnections was assumed in 80 % of the time, any reduction in these interconnections would result in a heightened dependence on fossil fuels.

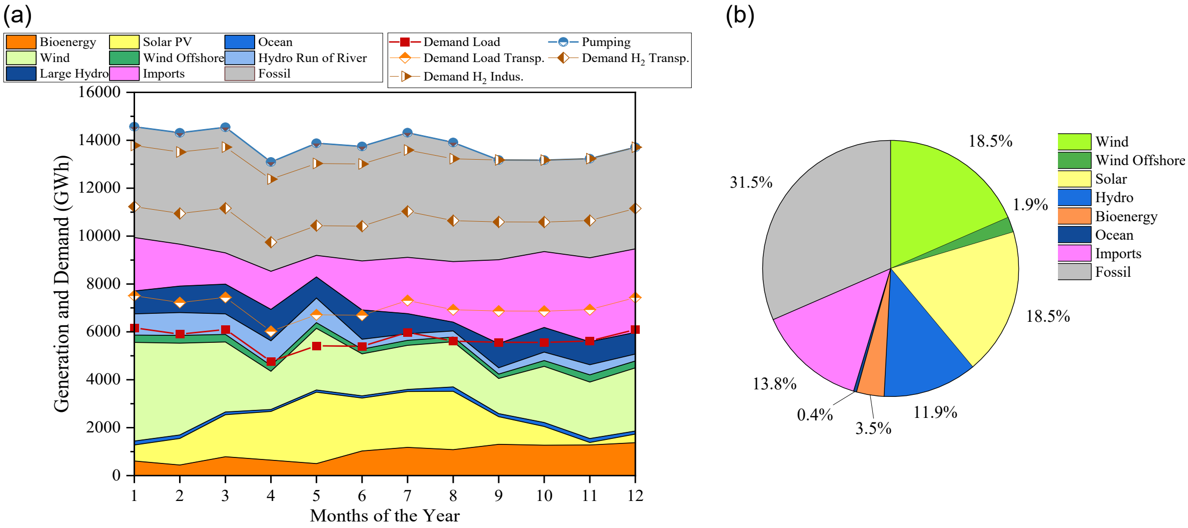

Figure 4: Initial case model results for Portugal - 2050 a) Yearly energy profile. b) Primary energy demand.

In the second scenario, the high demand scenario, it becomes notorious that renewable energy sources are capable of meeting Portugal's energy needs entirely. Solar PV emerges as the primary energy source, contributing 26.9 % of the total energy supply, followed closely by onshore and offshore wind, accounting for 18.4 % and 18.2 %, respectively. While the dominance of renewable energy in this scenario is a positive development, it is important to note that electrical interconnections continue to play a crucial role in ensuring a reliable electricity supply for the country. These interconnections contribute 16.9 % towards meeting Portugal's total energy needs. It is worth highlighting that in this scenario, the maintenance and expansion of electrical interconnections remain essential.

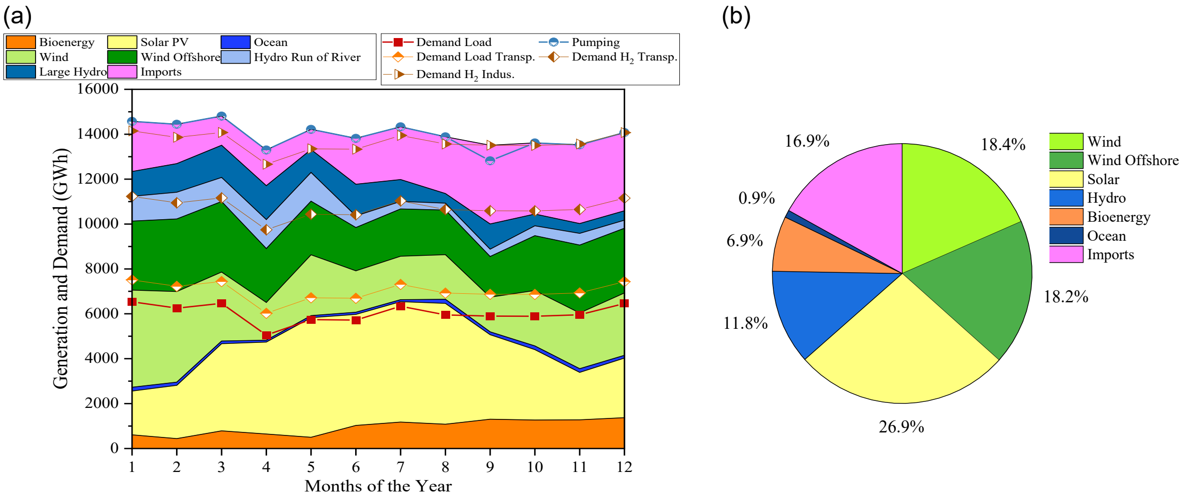

Figure 5: High scenario model results Portugal - 2050 a) Yearly energy diagram. b) Primary energy demand.

6. Conclusion

This study aimed to assess the feasibility of attaining a fully supplied renewable energy system in Portugal, considering the transportation, heating and cooling, and electricity sectors, while considering the Government targets for the 2050 horizon. The results highlight two contrasting scenarios. In the first scenario, following the current trends in power plant installations until 2040, Portugal would be unable to achieve a decarbonized energy sector. Fossil fuels would still represent over one-third of the country's total energy needs. This underscores the need for substantial changes and efforts to transition away from fossil fuel reliance, and an investment in new power generation technologies. In the high-demand scenario, assuming a more rapid electrification of the industry and increased investments in solar PV and offshore wind, Portugal could achieve complete decarbonization. Achieving this goal would require continued investment in and maintenance and increase of the electrical interconnections with neighbouring countries, Spain and Morocco. The analysis emphasizes the vital role of these interconnections in fully meeting the country's energy demands and supporting renewable energy integration. The following directions are critical for future studies: comparing the total costs of installing different renewable technologies, exploring the economic surplus from selling oxygen created as side product from hydrogen production, and incorporating a wider range of scenarios to account for different consumption trends.

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