Portugal's Transition to a 100 % Renewable Energy Sector by 2050

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Abstract

The study developed an energy system for Portugal that solely relies on renewable energy for the year 2050. As Portugal is aiming to reduce its GHG emissions by at least 80 % to avoid climate change, tremendous efforts need to be made. As the main cause of GHG in Portugal, the energy sector plays a major role to achieve this goal. At first, the current situation in Portugal in the energy sector is explained focusing mainly on the sources of energy. Afterwards, previous studies are briefly discussed to show what has been done and how it differs to the underlying study. The methodology introduces the two programs that were used in the design of the future energy system, namely EnergyPLAN and MATLAB. It also compares the reference model with reality to ensure that the model is calibrated. Furthermore, the optimization model is explained and how the sectors are expected to evolve in this study. Due to Portugal's high reliance on hydropower it is necessary to model different scenarios simulating a wet, an average and a dry year. These scenarios are compared in terms of installed capacity, energy demand and production, import and export, storage, and costs. The final future energy system is then created to provide enough energy regardless of the water availability. The future system will rely greatly on electricity with wind and solar being the main contributors. The system will be considerably less expensive than the current system and use around 30 % less of primary energy.
Keywords: Renewable Energy, 100 % RES, Portugal, EnergyPLAN, Optimization

1. Introduction

As counter measurement against the threat of climate change, most of the countries in the world signed the Paris agreement in 2015. These countries pledged to strongly reduce its greenhouse gas (GHG) emissions to limit the anthropogenic climate change to ideally 1.5°C. According to the EU this translates to a necessary reduction of at least 80 to 90 % of GHG emissions by 2050 in comparison to the base year 1990 for every European country [18]. Therefore, Portugal's path is set. The more difficult issue is how to achieve this goal. Figure 1 shows the GHG emissions in Portugal from 1990 to 2015 as well as the minimum goal of an 80 % reduction by 2050. It can be noted that GHG emissions have risen by 12 % in comparison to 1990. Thus Portugal needs to undergo tremendous efforts to stop them from rising and decrease its GHG emissions. The main contributor is the energy sector with a share of 70 % in 2015. The smaller rest of 30 % is split up into the categories industrial processes and product use (IPPU) (11 %), agriculture (10 %) and waste (9 %) [2]. Considering the role of the energy sector, it becomes clear that Portugal's reduction goal requires a fully decarbonized energy system.

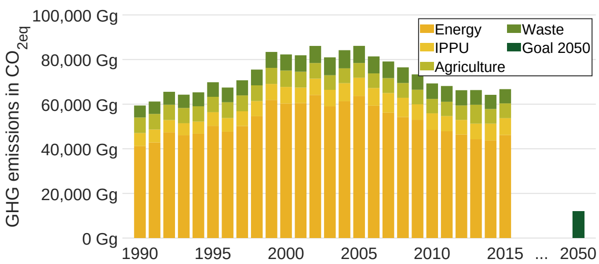

Figure 1: GHG emissions in Portugal 1990 – 2015 and minimum goal for 2050 [2, 18]

This paper is divided into seven sections. The first is the introduction that explained the need for the decarbonization of the energy sector. The second chapter explains the current situation of the energy sector in Portugal split into the sectors electricity, transportation and heating & cooling. The main focus is the share of fuels used in each sector. The third discusses previous scientific papers and studies that talked about the transformation of the Portuguese energy sector. The fourth section contains the methodology that was used for the design of the future energy system. It is split into the program used for the model creation, the optimization approach and the reference model. The fifth part presents the future model that was created for the optimization process. It also talks about what restrictions and parameters were implemented in the optimization process to obtain more realistic results. The sixth section contains the results of the optimization process. At first the three scenarios, which represent a wet, average and dry year, are compared with each other. Afterwards, the findings of the scenarios are used to design a reliable energy system that can provide enough energy across all scenarios. The last part draws the conclusion and gives recommendations for future studies.

2. Portugal's Current Situation

Portugal is in general highly dependent on fuel imports to supply its energy sector as it does not produce fossil energy itself since 1994 [25]. It only produces 5.90 Mtoe of its consumption of 15.51 Mtoe. Oil is the most important source of energy covering 42.7 % of Portugal's primary energy consumption [45]. This section goes into more detail and explains the situation of each energy sector.

2.1. Electricity

Portugal's electricity sector has one of the highest shares of renewable sources in Europe. This is mainly based on hydro and wind power. In 2016 57 % were renewable as shown in Figure 2 [54]. However, due to Portugal's strong reliance on hydropower, the share varies significantly from year to year. In 2017 only 40 % of the electricity were from renewable sources as the production from hydropower fell by 64 % [55]. The electricity demand in Portugal was 49.3 TWh in 2016 [54]. In the last 10 years this value has stabilized after increasing over the decades [25].

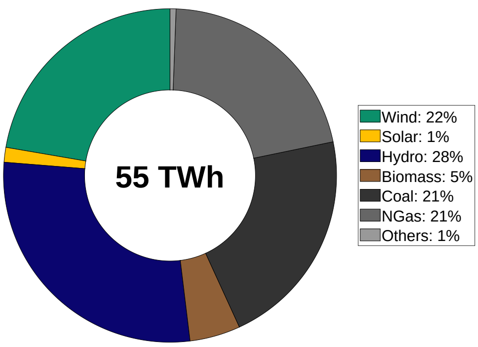

Figure 2: Share and total electricity production in 2016 [54]

By 2017 around 3 GW were installed for exporting of electricity to Spain [25]. With the currently installed generation capacity of 19.8 GW in 2017 [55], this represents 15.2 % and therefore suffices the European requirement of a transmission capacity of 10 % of the installed capacity [17].

2.2. Transportation

36 % of Portugal's final energy consumption is attributed to the transport sector. 73 % of the total oil demand is used in the transport sector [59]. As Portugal imports 99.8 % of its oil, it exposes the sector to variations of the international fuel prices [28]. In 2016 there were 6.2 million fossil-fueled vehicles, of which the main part was powered by either diesel or petroleum with 64 % and 35 %, respectively [44]. Light-duty vehicles are responsible for 72.5 % of the national energy demand in the transport sector. Heavy-duty vehicles have a share of 22.5 %. The remaining 5 % are shared by railway (0.8 %), domestic air traffic (2.6 %) and inland navigation (1.6 %) [40].

As can be seen in Table 1, only 5 % of the final energy consumption are covered by renewable sources (excluding renewable share in electricity). The main sources are still fossil fuels with a share of 92 %. Diesel is the main source of energy with 70 % percent. In total Portugal's domestic transport sector used more than 64 TWh in 2016 [27].

Table 1: Share of different energy sources of the final energy consumption in the transport sector in 2016 [27, 13]

Energy source	**ktoe**	**TWh**	**Share**
Fossil fuels	6.377	61,0	92%
Gasoline	1.140	13,3	20%
Diesel	3.964	46,1	70%
Jet fuel	1.273	1,6	2%
Renewable fuels	274	3,2	5%
Electricity	33	0,4	1%
Others	89,2	1,0	2%
Sum	**6.773**	**64.6**	**100%**

2.3. Heating & Cooling

Due to its favorable geographical position, Portugal has had traditionally low demands for heating and cooling [23]. However, housing insulation was long neglected in the building sector resulting in low efficiencies [35]. The majority is heated with individual heaters that are mainly powered by electricity and wood. These two types alone account for 87.5 % of the heating systems. The rest is mainly petrol and gas based heating systems, which are to a large extent central heating systems. Other systems such as geothermal or solarthermal only make up less than 1 % [26]. Cooling is done exclusively via electricity. The total demand for heating & cooling (excluding industrial energy consumption) is 26.2 TWh, of which heating is responsible for 21.6 TWh [23].

Figure 3 shows the energy efficiency of Portuguese buildings. The majority of the existing building stock is energy inefficient. 82.5 % have a rating of C or worse. All new buildings are a B- or better due to new legislations that require a minimum efficiency of B-. Existing buildings have to achieve a rating of at least C when they undergo major renovations, however renovation rates are low [1].

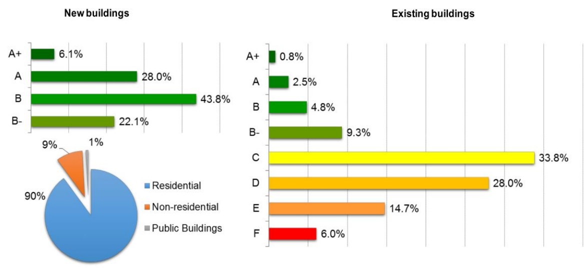

Figure 3: Current situation of the dwelling stock and new buildings [1]

3. Previous Studies

Several scientific papers [21, 4, 58, 30, 43] and reports [36, 7] have been published that investigate the transformation of Portugal's energy system. This section introduces them briefly and outlines the differences to this study.

Krajačić et al. tried to answer the question how to achieve a 100 % renewable electricity supply in Portugal by 2020. The simulation was carried out as a closed system. Furthermore, sector coupling was not considered and the demand was kept steady at the level of 2006. The study considered the necessary energy storage to obtain a reliable system. Due to Portugal's high potential in reversible hydro storage, this was the main measure with hydrogen and batteries only making up a smaller portion. The study showed that a completely renewable electricity system was possible by 2020. However, cost data was not used in the model and therefore the authors suggested to refine the model in the future to also verify the economic feasibility [30].

Similarly, Fernandes et al. aimed to achieve a 100 % renewable electricity system by around 2022. Other sectors are not included in this study. The results show that new capacity is needed, especially to produce enough electricity during the summer months when production from hydro and wind is low. Storage systems besides hydro storage are not considered resulting in high amounts of exported electricity and critical excess energy production (CEEP). The results show that an entirely renewable electricity sector would have higher costs [21].

Amorim et al. focused on creating a cost-effective road map to achieve a carbon-free Portuguese electricity sector by 2050. Another focus point was if the interconnection with Spain was beneficial or if designing the Portuguese energy system should be done as an isolated island. The study considered an increase in electricity consumption but did not specifically consider the transport and heating sector and their characteristics. The open system showed that the future electricity system made Portugal a strong exporter with more than 18 TWh (37 % of the current demand) being exported in 2050. The results suggested that governments should not plan their energy system development in isolation but communicate with affected countries to increase the efficiency and decrease costs. Thus the transmission infrastructure is expected to play a crucial role in the future [4].

Simões et al. considered the economic development of Portugal for their case study for 2050. Six different scenarios were created that varied the minimum amount of GHG saved, economic evolution and a minimum of fossil electricity that had to be used in the system. The results show an increase of the share of RE from 15 % in 2005 to 56-59 % by 2050. RE was found to be cost-effective, even when no GHG cap was imposed. The study also integrated the transport and heating sector into their analysis. According to their results Portugal would fail to meet the reduction goal of 80-95 % [58].

Pina et al. created a hybrid framework for planning high shares of RE using Portugal's electricity system as case study for a time period from 2010 until 2050. The goal of the study was to minimize CO_2 emissions but not to achieve a completely renewable electricity system. For this reason coal and natural gas are used throughout the entire period. Only the electricity sector was investigated while transport and heating were neglected. The obtained results allowed a decrease by 70 % in comparison to 2005 while almost achieving 90 % of RE generation [43].

APA published a study in 2012 investigating different scenarios of GHG reduction. The study evaluated every source of GHG emissions, i.e. electricity, transport, buildings, industry, refinery, agriculture, forest and land use, and waste. The change in emissions ranged from +22 % to -60 % by 2050. According to the study, Portugal would exceed the allowed GHG emissions by around 150 % in 2050 [36].

The most recent study was conducted by APREN. The report looks at GHG emissions from all sectors of the energy system and furthermore addresses the changes that are expected to occur in the future in the Portuguese energy system. The report creates three different scenarios for the reduction of GHG emissions in the energy sector. One of them is created without specific targets, while the other two aim at 60 and 75 % of RE, respectively.To balance out variations in the renewable energy production, natural gas with carbon capture & storage (CCS) was deployed. However, the study hinted that in the future storage technologies might be more sensible. Both reduction scenarios turn out to be cheaper than the conservative approach by at least more than 20 % [7].

4. Methodolgy

The methodology section is split into three subsections. At first the modeling tool, EnergyPLAN, is introduced. The subsequent subsection talks about optimization and the program that was used MATLAB. Lastly, the results for the reference model are compared to ensure the model's validity.

4.1. EnergyPLAN

EnergyPLAN is a deterministic input/output simulation model [33]. Its main use is the assistance in the design process of national or regional energy systems [9]. EnergyPLAN includes transport, heating, electricity, gas, and industry in its energy system analysis and can thus be seen as a holistic model. It simulates an entire year using an hourly time step. This short time step allows a realistic inclusion of fluctuating renewable energy as wind and solar, as well as the means to balance them out with storage systems [60]. Outputs are energy balances containing information such as annual electricity production, CO_2 emissions, fuel consumption and import/export.

The program does not separate the energy sectors but allows the simulation of an intertwined smart energy system [32]. EnergyPLAN is highly optimized and thus it only takes a few seconds for the simulation of an entire energy system [33]. This is crucial for using optimization algorithms, as they require to run hundreds to thousands of different configurations to find the ideal system.

4.2. Optimization

EnergyPLAN is a deterministic program that evaluates the system implemented by the user. However, it has only very rudimentary abilities to optimize a system [32]. Thus, the optimization was conducted using MATLAB (Version 9.4). For this study an adaptation of the gray wolf optimization (GWO) algorithm was chosen, which is based on the hunting behavior of gray wolves [39]. The algorithm allows a single- [37] as well as multi-objective optimization [38]. In this case, the single-objective algorithm was used as the main goal was to minimize the costs of a carbon-free energy system. The advantage of MATLAB is that EnergyPLAN already offers a toolbox for the coupling of the two programs, which can be downloaded on the website of EnergyPLAN [6]. The toolbox allows to change the input of EnergyPLAN within MATLAB, run the simulation in EnergyPLAN and obtain the results in MATLAB for analysis and optimization.

4.3. Reference Model

For this paper 2016 was used as reference year. The main sources for the model creation were [54, 15, 56, 5, 19, 13]. The results are shown in Table 2. It is apparent that oil is the main source of energy in Portugal, having a share of around 44 % of the total demand. The other sources follow in the order natural gas, coal, biomass, hydro, wind and solar. The results of EnergyPLAN are almost identical with those of the official statistics. The highest deviation is 2 % in the case of coal. Overall the total deviation is 0 %, thus proving that the created reference model is adequate and the energy system is correctly modeled in EnergyPLAN.

Table 2: Comparison of total national primary energy demand split by energy source between the official values and the simulation results in TWh [13, 19, 54]

Energy Source	Official	Model	Error
Oil	111.08	111.06	0 %
Gas	50.47	51.05	1 %
Coal	33.08	33.77	2 %
Biomass	29.26	28.97	-1 %
Hydro	16.63	16.65	0 %
Wind	12.19	12.19	0 %
Solar	0.78	0.78	0 %
Sum	**253.49**	**254.47**	**0 %**

5. Future Model

Creating realistic input is crucial to obtain a reliable scenario. There are many factors to consider. Furthermore, since the model was created for a very distant future many forecasts had to be made. The following subsections discuss these changes and the implementation in EnergyPLAN.

5.1. Electricity Generation and Storage

Only renewable sources can be used in the future. The only limitation to the technologies investigated in the optimization is set by EnergyPLAN as it does not model all types of generation and storage technologies. The generation technologies considered for the model are shown in Table 3. The table contains the minimum and maximum values that the optimization has to stay within. Most of the minimum values are based on the installed capacities in 2017 except for hydropower and thermal plants. The maximum capacities are based on the geographical limitations of Portugal. As there is currently no study for the potential of tidal power a conservative value of 1 GW was used. The maximum value for thermal plants was set to around 250 % of the value of maximum load in 2016 [54]. In terms of industrial CHP there was no optimization done.

Regarding storage EnergyPLAN's options are somewhat limited. It only allows a limited amount of different storage technologies to be used in the model. The technologies that are explicitly modeled are the storage of the dammed hydro power plants, hydrogen storage and gas storage. Another generic model exists that allows the implementa-

Table 3: Setup of the available capacities in EnergyPLAN.

Technology	Min [MW]	Max [MW]	Capacity Factor	Sources
Wind Onshore	5,090	7,500	0.35	[16, 54, 42]
Wind Offshore	0	10,000	0.39	[16, 42]
PV	490	13,000	0.27	[24, 54, 42]
CSP	0	12,000	0.30	[24, 42]
Wave Power	0	7,700	0.08	[24, 42]
Tidal Power	0	1,000	0.42	[42]
River Hydro	3,189	3,441	—	[10, 24, 55, 25, 42]
Dammed Hydro	5,210	6,400	—	[10, 55, 25, 42]
Geothermal	0	980	0.85	[16]
Thermal Power	3,123	20,000	—	[14, 55, 42]
Industrial CHP	560	560	—	[12, 56]

tion of another technology, which was CAES in this study. Thermal storage of CSP cannot be modeled. Regarding the storage of dammed hydro power, a linear increase based on the installed capacity in 2016 was used.

Portugal has a maximum capacity of 1,973 Mm^3 for the storage of gases [15]. As CAES, hydrogen and gas storage all use this available storage, an interdependency between these variables was created in the optimization to ensure that the maximum capacity is not exceeded.

Concerning the interconnection capacity the European goal of 15 % of the installed generation capacity was used. Regarding grid stability the issue was considered as non-existent in the future since RE generation systems are already increasingly able to take over grid services as well as other technologies.

5.2. Heating & Cooling

The change for the future system of individual heating in comparison to today's is shown in Table 4. The reference year in this case was 2015 due to a lack of information for 2016. The following assumptions were made for heating & cooling:

- steady total heating demand (21 TWh)
- heat production shifted to biomass and electricity
- 15 TWh of total demand covered by electricity
- 13 TWh covered by heat pumps (COP = 3) and 2 TWh covered by direct electric heating
- minor improvements of the housing insulation
- unchanged use of district heating due to missing central heating infrastructure and low renovation rates
- district heating uses biomass
- 80 % of households use additional solarthermal systems
- cooling only done via electricity
- cooling demand increases by 40 %

5.3. Transport

Biofuels are not capable of replacing the entire fossil fuel demand and especially road-based transport will transform towards electrically powered vehicles. The forecasts for the future of the transport sector are based on [47] and adapted to Portugal's situation, which are shown in Table 5. The following assumptions were made.

- unchanged demand
- high electrification of transport sector
- one third of electricity demand available for smart charging

5.4. Industry

The industry is listed separately in this paper. 11 % of the GHG emissions in Portugal are mainly caused by high temperature processes [20]. Previously much of that energy came from CHP from fossil sources. The following assumptions were made for the future energy model:

- 30 % decrease of total energy demand of the industry through efficiency measures
- only CHP powered by biomass continued to be used
- direct use of electricity to cover demand
- no use of heat pumps due to high temperatures

5.5. Energy Demand

Table 6 contains the information about the electricity demand for 2016 and 2050. The new demand is 83 % higher due to other sectors relying increasingly on electricity as source. Regarding the consumption that already existed before the sector coupling a constant demand is considered. The difference is that a share of the electricity is considered as flexible demand to model demand-side management (DSM) in the future energy system. This demand was estimated to be 22 % of the uncoupled and industry demand, using a conservative adaptation of [31]. The heating demand will stay constant but the electricity demand will decrease due to more efficient heating system technologies. Cooling will increase by 40 % due to climate change [41]. The industry's energy demand for

Table 4: Fuel demand for individual heating for the years 2015 and 2050 EnergyPLAN.

	2015 [TWh]			**2050 [TWh]**		
Fuel	**Fuel Input**	**Heat Demand**	**Solar**	**Fuel Input**	**Heat Demand**	**Solar**
Oil	4.97	3.98	0	0	0	0
Gas	2.94	2.97	0.50	0	0	0
Biomass	8.89	5.96	0	2.02	3.20	1.58
Electricity	5.62	5.66	0	3.21	15	7.41
Total	22.36	18.56	0.50	5.23	18.20	8.99

Table 5: Fuel demand by each sector and type in 2050.

Means of Transportation		**Share**	**Efficiency Factor**	**Demand**
Light-duty vehicles	**47.3 TWh**			
BEV		95 %	3.25	13.83 TWh
P2G		5 %	1.3	1.82 TWh
Heavy-duty vehicles	**14.7 TWh**			
electric, overhead lines		70 %	3.25	3.17 TWh
P2G		30 %	1.3	3.40 TWh
Railway transport	**0.5 TWh**			
electric, overhead lines		100 %	1	0.50 TWh
Maritime and aviation transport	**2.6 TWh**			
biofuels		100 %	1	2.57 TWh

process heat and other processes as well as the decreased energy output from industrial CHP plants will have to be replaced resulting in an additional demand of 24.39 TWh. The electricity demand of the transport sector is 17.49 TWh. Additionally, it has a demand of 5.21 TWh for hydrogen and 2.57 TWh for biofuels, which are not shown in the table.

Table 6: Electricity demand by sector in 2016 and 2050

	Demand [TWh]	
Sector	**2016**	**2050**
Uncoupled	38.71	38.71
Heating	5.62	3.21
Cooling	4.59	6.43
Industry	0	24.39
Transport	0.38	17.49
Total	**49.30**	**90.23**

5.6. Costs

The cost database for 2050 used in this study is that provided by EnergyPLAN [8]. The only changes that were made were for the generic storage system as it models PHES by default but in this study CAES was used. For the investment costs [34] was used while [29] was used for the life time of the respective components. The resulting database was used for both the reference and the future model.

5.7. Other Considerations

Due to Portugal's high reliance on hydropower three different scenarios were created each with a different hydro capability index (CI). For the wet year, the reference year 2016 was chosen, which has a CI of 1.33. For the dry year, 2017 was chosen with an index of 0.47. Lastly, an average year with an index of 1.00 was modeled.

For stability and reality purposes further parameters were set for the optimization:

- max. import: 5 % of the total electricity demand (90.23 TWh)
- max. export: 10 % of the total electricity demand (90.23 TWh)
- max. total use of biomass: 42.5 TWh [22]
- max. total storage potential: $1,973\,\mathrm{Mm}^3$

6. Results & Discussion

This section discusses the results of scenarios for the wet, average and dry year. The comparison allows to gather more information about the behavior of Portugal's future energy system, which helps to ensure that the future power matrix is robust under any circumstances.

6.1. Installed Capacities

Figure 4 shows the recommended installed capacities for each scenario. Some of the technologies show the expected behavior, while others require further study to understand the results.

For onshore wind the capacity stays constantly at the maximum technical potential across all scenarios. Offshore wind power does not have a constant value but increases as the CI decreases. The minimum capacity is 7 GW. The results suggest that both technologies will play major roles in the future.

Regarding PV, the case is identical with that of onshore wind power. The installed capacity is always at its maximum of 13 GW. Therefore, Portugal needs to strongly increase their current capacity. The results of CSP suggest that it is not viable. Based on current cost predictions, the technology is simply not cost-effective and other technologies are more favorable in the case of Portugal. However, it needs to be noted that EnergyPLAN simulates CSP without storage. The case might be different once EnergyPLAN considers storage for CSP plants.

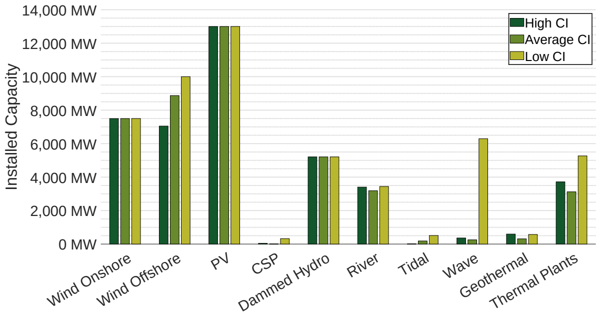

Figure 4: Comparison of the installed capacities of each scenario

Dammed hydropower is always kept at the minimum. Regarding run-of-river plants, in two scenarios the capacity is kept at the maximum, while the average scenario recommends to not further build this type of plant. This is likely to be caused by the mechanism of the optimization algorithm as the change is very little and the algorithm pays less attention to this part of the optimization.

Tidal power shows a somewhat linear behavior in the scenarios while wave power shows a strong spike in the dry scenario. In terms of tidal, the behavior is typical as it simply increases as the energy demand increases. However, it is difficult to make an assessment for Portugal as there is currently no evaluation of the technical potential. The sharp increase for wave power is understood when considering the capacity factor from Table 3. The small capacity factor requires much greater capacities to produce the same amount of power.

The capacities of geothermal power vary but every scenario has at least a share of 2 %. Therefore, geothermal could play a minor role in the energy system of Portugal's mainland. An advantage is that Portugal already has competences in the use of geothermal power since it is already used for electricity production in the Azores.

The last technology is that of thermal power plants. Normally, an increase would be expected as the hydro CI decreases. However, the capacity is lowest for the average scenario. This suggests that the capacity in the other two scenarios could be lowered. This was confirmed when manually decreasing the installed capacity of thermal power plants to 3,500 MW in the low CI scenario. However, this increased the amount of imported electricity from 2.79 to 6.74 TWh, which is above the 5 % threshold. Thus this would increase the reliance on other countries and their ability to provide power in moments of low domestic production. Therefore, it needs to be decided politically, if this dependence is acceptable or not.

6.2. Electricity Demand

The total electricity demand is higher than that of Table 6. It varies between 105 and 120 TWh from wet to dry scenario. The difference is explained by the production of hydrogen and SynGas, which was not considered previously as the demand could not be estimated. Unlike the electricity consumption, the primary energy demand has clearly fallen. In the reference model it lies at 256 TWh in comparison to 146 – 151 TWh for the future scenarios.

6.3. Electricity Production

The other part of the energy demand is the energy production. Figure 5 gives information about the share of each technology in the electricity production for every scenario. The electricity production is that to cover the demand shown in Table 6 and not the total electricity demand. Overall, the scenarios show very similar behavior.

The share of onshore wind power is very consistent. However, the share is slightly higher in a wet year, although the installed capacity is always the same. This is due to the lower total electricity demand as less synthetic gas (SynGas) is needed. For offshore wind, the share is comparable as increase in capacity and electricity demand go hand in hand. PV shows the same behavior as onshore wind since it is also always has the same capacity. CSP is only noticeable in the scenario with a low hydro CI (dry year), due to its high electricity demand. The same can be said for both tidal and wave power.

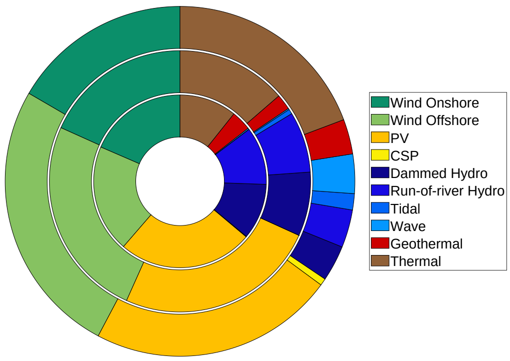

Figure 5: Comparison of the share of each technology in the energy production from a wet (inside) over an average (middle) to a dry (outside) year

As the capacities of dammed and run-of-river vary only marginally, their share is only influenced by the availability of water. Nonetheless, this is a huge factor as can be seen. Geothermal power is used across all scenarios to some extent, which suggests that it might be of interest in the future. The share of thermal power increases strongly as the hydro CI decreases and demand increases.

6.4. Import and Export

Figure 6 shows the amounts of imported and exported electricity for each scenario in both absolute and relative values. It can be seen that in all three scenarios the system can be easily kept within the given restraints. In the dry scenario the higher import is caused by the overall higher demand while in the average scenario it is needed to balance out the lower total capacity of thermal power plants.

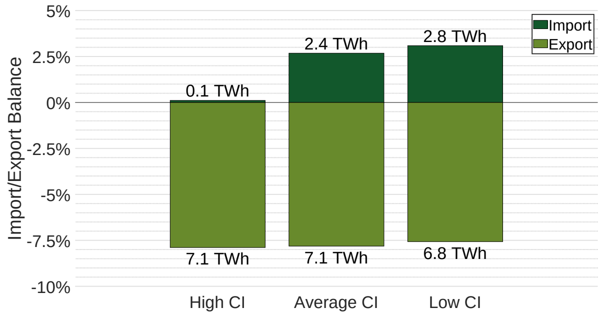

Figure 6: Imported and exported electricity of each scenario

As an additional note, it can be said that it turned out that a transmission capacity of 15 % of the total installed capacity proves to be sufficient under all circumstances. In the three scenarios the value ranged from 6.1 to 7.8 GW. The value for the average-year scenario is 6.2 GW and therefore in accordance with Rodríguez et al. that calculated a necessary capacity of 6.2 GW to cover the demand 99 % of the time [57]. In conclusion, the trade-off between thermal power plant and interconnection capacity needs to be made as they are inversely related.

6.5. Storage

The storage methods that were optimized by the program were hydrogen, CAES and SynGas storage. Other storage methods are not discussed here as they were not optimized but simply extrapolated. The results showed that large scale hydrogen storage, which ranged from 0 to 9 GWh, does not seem to be necessary in the system. This can be attributed to the fact that only very small amounts of hydrogen are needed and most of it is directly converted to SynGas. The same applies to CAES, which was not needed to balance out supply and demand. Thus both storage types are of little importance in the future system.

The last type of storage is gas storage. The country already possesses 333 Mm^3 of storage capacity, which translates to 3,967 GWh [54]. This amount would already suffice in the first two scenarios. The low CI scenario, on the other hand, states a much higher need for storage capacity at over 12 TWh, however, it is never used to its maximum capacity. This is an imprecision of the optimization as the size has very little influence on the total annual costs.

The main issue with EnergyPLAN for the modeling of energy systems with high dependencies on hydropower is the fact that it only models for one year at a time. Furthermore, the storage content within a year has to be the same at the beginning and end. If EnergyPLAN was able to simulate several years, it would be possible to model the behavior of the gas storage content throughout years of different CIs.

Another issue that was not considered in the optimization process is security. France, for example, stores enough gas to supply the domestic consumption for 91 days [15] in comparison to 21 days in Portugal [55]. A development plan exists at Carriço to expand the capacity by 1,250 Mm^3. This would allow the storage of almost 19 TWh, which is enough to cover 27 % or 99 days of the total national demand of 2017 [55]. By 2050 the gas demand will drop due to the increased use of electricity as shown by the results of the simulations. The highest demand is 26 TWh in the low hydro CI scenario. Thus the supply security would increase even further and the storage could cover 267 days. This leads to the conclusion that current expansion plans are more than sufficient to ensure a reliable gas supply.

6.6. Costs

All scenarios have proven to be technically viable, however, if their direct costs exceed those of the fossil based system, the likeliness of the system to change decreases. The costs are shown in Figure 7, which splits the costs into variable, fixed operation and annual investment. It shows that all three scenarios are significantly less expensive than the reference model, which has a total cost of almost 20,000 M€. The costs of the future scenarios range from 12,800 M€ to 15,400 M€.

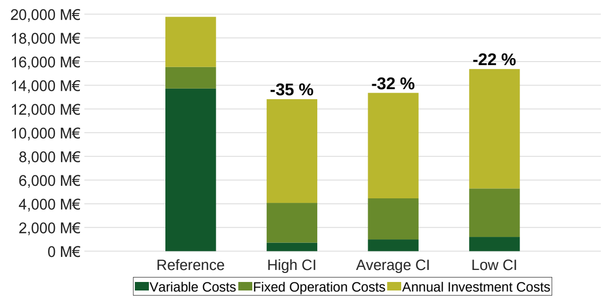

Figure 7: Comparison of the total annual costs in 2050

It can be clearly noted that the share of the different cost types is very different between the developed and the reference model. In the reference model, the dominant costs are the variable ones, accounting for 69 % of the total annual costs due to higher fuel and CO_2 emission costs. This is only natural as the reference system relies strongly on fossil fuels, which are expected to increase in costs in the upcoming decades. The cost types that are more significant in the future scenarios are the fixed operation and especially the annual investment costs. The latter has a share of 66 to 68 %.

6.7. Future Energy System

The previous subsections have investigated different scenarios for the future of Portugal's energy system, paying special attention to the high influence of hydropower. This part combines all the results to give recommendations for the development of the Portuguese energy system. Based on the results from the previous sections an energy system is created that considers Portugal's dependence on hydropower to ensure that enough energy can be produced regardless of the available water supply.

To design the future system it is first necessary to know what the average yearly electricity demand will be. A demand of 110 TWh is considered, which is set higher than that of the average CI scenario due to conversion losses for the gas production.

The proposed power matrix for 2050 is shown in Figure 8. The corresponding electricity production of each technology is found in Table 7. Portugal will rely strongly on wind and solar power to cover its demand. With a combined share of 75 % the two will become the backbone of the system. As it has shown across all scenarios that hydropower is less favorable, the proposed increase is moderate. Run-of-river hydropower plants exploit their full technical potential, while dammed hydropower is not increased beyond the capacities that are already under construction. As their costs are higher than those of run-of-river plants, their unreliable yearly energy production makes them less interesting. However, it needs to be noted that this optimization was created for the year 2050 and did not consider the development up to that point. Overall, the contribution of hydropower will shrink to an average of around 16 %. As the results showed very low usage of biomass in thermal plants, it was not considered for further usage apart from CHP. Therefore, the usage of biomass is restricted to the CHP capacity of 560 MW. Biomass and waste have a combined electricity production of around 4 TWh.

All before mentioned technologies will produce on average 104 TWh, which leaves a gap of 6 TWh. This gap can be filled through various measures. One possibility is the promotion of further energy efficiency measures that have not been considered yet in the model. However, as further savings are not considered it is recommended to use wave and geothermal power to bridge the gap. The reason why these two were chosen is due to Portugal's expertise in these technologies. Geothermal energy is already common in the Azores. Therefore, it will be easier to install capacities on the mainland as a construction infrastructure already exists. Wave power was chosen due to Portugal's heavy investment in the technology. The country already pursues plans to develop the technology to commercial maturity by 2030 [46]. To build up a wave power industry in Portugal, high domestic demand is crucial to enable the technology's breakthrough.

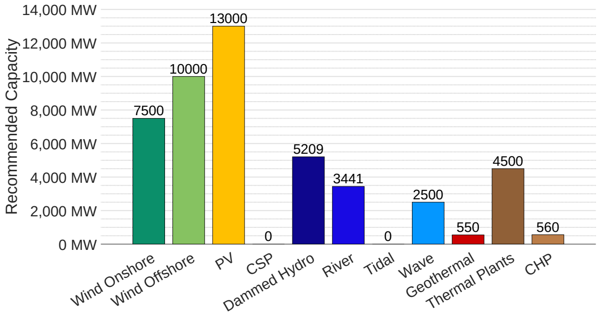

Figure 8: Recommended installed capacities for Portugal by the year 2050

These capacities will be built up linearly. Instead several factors need to considered. One of them is existing expansion and demolition plans for hydropower and thermal plants as each plant adds considerable capacity. Furthermore, onshore wind power is currently more economical than offshore wind and should first be exploited. The last point is the level of maturity of some generation technologies. Wave and HDR geothermal power are not yet commercially available and cannot be used right away.

All these considerations were taken into account to generate Figure 9, which shows the according capacity evolution of each technology in Portugal. Due to the consideration to first exploit Portugal's onshore wind potential, offshore wind does not need

Table 7: Development of the Portuguese renewable electricity generation until 2050

Technology	Electricity Production [TWh]
Wind Onshore	21
Wind Offshore	32
PV	29
Dammed Hydro	9
River Hydro	9
Wave	2
Geothermal	4
Biomass & Waste	4
Total	**110**

to be used before 2024. PV is heavily used and has a somewhat linear behavior. The dents in the curve are caused by the introduction of wave and geothermal power. The technology is currently the most undervalued in Portugal and needs to be heavily increased. Regarding, hydropower there is very little change expected. There are three plants scheduled to be connected to the grid between 2021 and 2023 with a total capacity of 1,154 MW [14]. The remaining 285 MW for run-of-river plants are scheduled to be operational by 2030 in this roadmap. Wave power is expected to be mature by 2030. From then on its capacity is increased linearly by 119 MW per year. The situation is similar for geothermal potential, where the necessary capacity is installed from 2040 on at a yearly rate of 50 MW. The biomass capacity is decreased linearly by 2 MW per year as the capacity needs to be decreased from 624 to 560 MW. However, the type of biomass plants needs to be changed as the currently installed capacity consists of both CHP and non-CHP plants [55]. According to Portugal's roadmap, coal power will be phased out until 2030. Currently, there are two coal power plants with a combined capacity of 1,756 MW. Regarding gas power, there are currently four major plants in Portugal. However, 990 MW of capacity are scheduled to go offline by 2025. This reduces the capacity to 2,839 MW, which would be the only remaining capacity of major thermal power plants due to the decommission of all coal plants by 2030 [14]. To counteract this lack of capacity, the roadmap considers the installation of new gas power plants with a total capacity of around 1,000 MW until 2030. Another smaller plant with 661 MW is scheduled to go online by 2040 to improve Portugal's flexibility further and raise the total installed capacity to the recommended 4,500 MW. The usage of gas power plants guarantees a smooth transition from fossil to renewable fuels as natural gas can simply be gradually be replaced by SynGas. In the future they will serve as a backup system when other measures fail to cover the demand resulting in less full-load hours in comparison to today [3]. The remaining

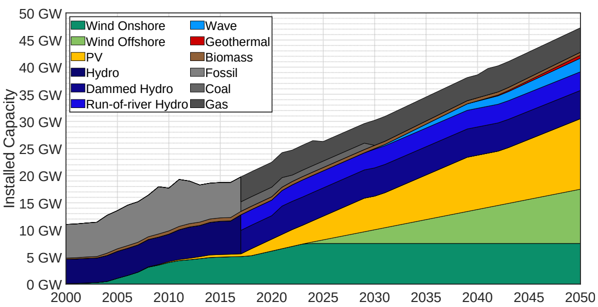

Figure 9: Portugal's evolution of the installed capacities until 2050 [11, 48, 49, 50, 51, 52, 53, 54, 55]

capacity which consists mainly of industrial CHP power plants will need to be decommissioned. As explained in subsection 5.4, their electricity and heat generation will be covered otherwise. The plan expects them to start being decommissioned from 2030 on. By 2050, this will leave Portugal with a total installed capacity of 47,260 MW, which is an increase by almost 140 %.

Other major parts of the future energy system are the transmission capacity as well as the gas generation and storage. Table 8 shows the recommended capacities. The transmission capacity is 15 % of the total capacity in accordance to European requirements. The gas production is split into biogas and SynGas. The capacity for biomass is around 1 GW. SynGas has an intermediate step as it is produced from hydrogen. Thus capacity for electrolyzers is naturally higher at 4.2 GW while that for SynGas is 2.4 GW. The minimum installed capacity for gas storage is 6.5 TWh.

Table 8: Capacities for the interconnection and storage aspects of the future energy system

Interconnection Capacity	7,089 MW
Biomass Gasification Capacity	1,036 MW_{Gas}
Electrolyzer Capacity	4,200 MW_{e}
SynGas Capacity	2,400 MW_{Gas}
Gas Storage Capacity	6,500 GWh

7. Conclusions

This study investigated how to turn Portugal's entire energy sector sustainable in order to contribute to the worldwide goal of limiting the temperature increase to 1.5°C. The results have proven that the country is well able to achieve a green, yet economical energy system that allows it to become energy independent.

The future energy system will rely heavily on electricity throughout all sectors to form a smart energy system. The demand will increase from 49 to around 110 TWh by 2050. Wind and solar power will become the backbone of the energy system, covering on average 75 % of Portugal's future electricity demand. The role of hydropower will decrease, contributing around 16 %. The remaining 9 % will be covered by biomass, wave and geothermal power. Dammed hydropower alongside with hydrogen and gas production will serve as storage measures and increase the system's flexibility alongside with DSM and smart charging systems.

For future work, it is recommended to further investigate the path towards 2050 to create a more precise roadmap that models Portugal's energy system evolution in a five-year step. This ensures a smooth transition from the old to the new energy system.

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