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

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Abstract

The thesis' objective is to develop an energy system for Portugal that solely relies on renewable energy for the year 2050. As Portugal is aiming to reduce its greenhouse gas (GHG) emissions by at least 80 % to avoid climate change, tremendous efforts need to be made to achieve this goal. Since the energy sector is responsible for 70 % of the country's emissions, it needs to undergo drastic changes and become completely carbon-free.

At first the generation and storage technologies that will play a role in the future energy system are introduced. Afterwards, closer attention is given to Portugal's energy system. The current system is explained as well as the challenges it is facing in the effort to switch to renewable energy sources. Furthermore, the thesis discusses the technical potential of the country for the respective technologies. After a brief introduction to modeling and optimization, a reference model is created to calibrate the system and to be used for comparison. This is followed by the creation of the optimization model for 2050, which differs significantly from today's with the key feature of greatly relying on electricity as energy carrier.

The model is optimized for three different scenarios where the hydro capability index is varied to see how the system reacts. The results are compared against each other and the reference model. Using the obtained information from the scenarios, a future energy system is created that is capable of providing sufficient energy for Portugal under any scenario. The future system will rely greatly on wind and solar power while hydropower becomes less prominent in comparison to today. To balance out the system, the storage capacities of dammed hydropower as well as carbon-neutral gas burnt in gas power plants will be used. The system will be considerably less expensive than the current system and use around 40 % less of primary energy while the electricity demand increases by around 120 %.

Keywords: 100 % RES, EnergyPLAN, Optimization, Portugal, Renewable Energy

Resumo

O objetivo desta tese é o desenvolvimento de um sistema energético para Portugal que dependa unicamente de energias renováveis no ano 2050. Portugal visa diminuar as emissões dos gases de efeito de estufa em pelo menos 80 % para evitar os efeitos das alterações climáticas. O setor energético é responsável por 70 % dos emissões do país e por isso tem que passar por mudanças fundamentais e tornar-se completamente livre de carbono.

Inicialmente as tecnologias de geração e armazenamento são introduzido uma vez que vão ser importante para o futuro sistema energético. Depois o sistema português é descrito em mais detalhe. O sistema atual é explicado e também os desafios colocados pela mudança para fontes de energia renováveis. Adicionalmente, a tese analisa o potencial técnico do país para cada tecnologia. Depois de uma introdução curta sobre modelação e otimização, um modelo de referência é criado para calibrar o sistema e usar para comparação. Depois o modelo de otimização para 2050 é desenhado, o qual difere significamente do sistema atual porque confia consideravelmente em electricidade para transporadora energética.

O modelo é otimizado para três cenários diferentes onde o índice de produtibilidade hídrico é variado para descobrir como o sistema reage. Os resultados são comparados entre eles e com o modelo de referência. As informações obtidas dos cenários são usadas para desenhar um sistema energético futuro, capaz de produzir energia suficiente para satisfazer o abastecimento de Portugal em qualquer cenário. O sistema vai ter um uso significativo de energia eólica e solar, no entanto a parcela de energia hídrica irá diminuir em importância em comparação com os dias de hoje. Para equilibrar o sistema, usam-se as capacidades de armazenamento hídrica de barragem, assim como gases carbono neutro em centrais eléctricas térmicas. O sistema vai ser consideravelmente mais barato em comparação com o sistema atual. Adicionalmente, vai precisar de 40 % menos de energia primária e 120 % mais de energia eléctrica.

Palavras-Chave: 100 % RES, Energia Renovável, EnergyPLAN, Otimização, Portugal

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List of Abbreviations

BEV Battery Electric Vehicle

CAES Compressed Air Energy Storage

CCS Carbon Capture and Storage

CEEP Critical Energy Excess Production

CES Chemical Energy Storage

CHP Combined Heat and Power

CI Capability Index

CSP Concentrated Solar Power

DSM Demand-side Management

ECES Electrochemical Energy Storage

EES Electrical Energy Storage

EPC Energy Performance Certificate

ESS Energy Storage System

EV Electric Vehicle

FiT Feed-in Tariff

G2V Grid-to-vehicle

GA Genetic Algorithm

GES Gravity Energy Storage

GHG Greenhouse Gas

GWO Gray Wolf Optimization

HDR Hot Dry Drock

ICE Internal Combustion Engine

IPPU Industrial Processes and Product Uses

LCOE Levelized Cost of Energy

LPES Liquid-piston Energy Storage

LPG Liquefied Petroleum Gas

MATLAB Matrix Laboratory

MES Mechanical Energy Storage

nZEB Nearly Zero Energy Building

P2G Power-to-gas

P2L Power-to-liquid

P2P Peer-to-peer

PCM Phase Change Material

PHES Pumped Hydroelectric Storage

PRE Special Generation Regime

PRO Ordinary Generation Regime

PSH Pumped Storage Hydropower

PSO Particle Swarm Optimization

PTC Parabolic Trough Collector

PV Photovoltaics

R&D Research and Development

RE Renewable Energy

SHP Small Hydropower Plant

SMES Superconducting Magnetic Energy Storage

ST Solar Tower

SynGas Synthetic Gas

TES Thermal Energy Storage

toe Tons of Oil Equivalent

V2G Vehicle-to-grid

List of Institutions, Companies & Policies

AdC Portuguese Competition Authority

ADENE Energy Agency

APA Portuguese Environmental Agency

APREN Renewable Energy Association

DGEG General Administration of Energy and Geology

DSO Distribution System Operator

EC European Commission

EDP Energy of Portugal

ERGEG European Regulators' Group for Electricity and Gas

ERSE Energy Services Regulatory Authority

EU European Union

FPC Portuguese Carbon Fund

GDP Gas of Portugal

IEA International Energy Agency

KfW Reconstruction Loan Corporation

MIBEL Iberian Electricity Market

NEEAP National Energy Efficiency Action Plan

NES2020 National Energy Strategy 2020

NRA National Regulatory Authority

NREAP	National Renewable Energy Action Plan
PETI3+	Strategic Plan for Transport and Infrastructure
PNBEH	National Program of Dams with High Hydroelectric Potential
REN	National Power Networks
SlovSEFF	Slovak Energy Efficiency and Renewable Energy Finance Facility
TSO	Transmission System Operator

Chapter 1

Introduction

This chapter serves as the introduction to the thesis. At first it discusses the relevance of the topic and the motivation behind it. Afterwards, it outlines the scope of the thesis to allow the reader to know what to expect. The last section briefly explains the structure of the thesis.

1.1 Motivation

Since the last glacial period over 20,000 years ago, temperatures have risen by almost 4 degrees. As can be seen in Figure 1.1, this increase took more than 10,000 years and ever since then the climate has somewhat stabilized, allowing humanity to evolve and prosper. However, due to the industrial revolution and its reliance on fossil fuels, the temperature has risen drastically within the last 200 years. If the

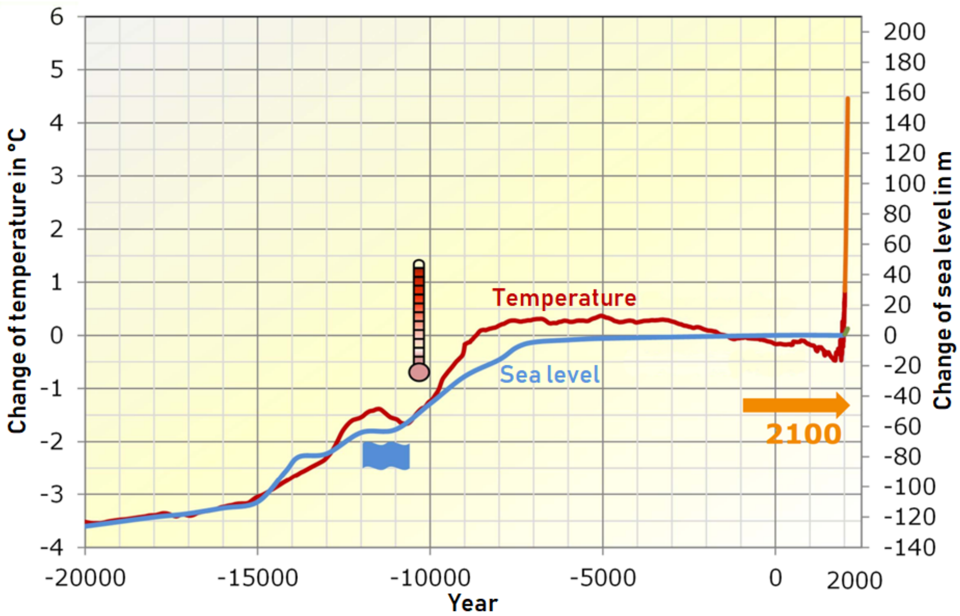


Figure 1.1: Temperature evolution since the last ice age until today and the forecasted evolution until 2100 for a business-as-usual scenario [1]

greenhouse gas (GHG) emissions are not strongly reduced quickly and the world continues to depend on CO_2 emitting energy sources, temperatures will rise by more than 4°C – a stronger increase than in the previous 20,000 years altogether. The accompanied rise of the sea level in combination with the increased temperatures would have devastating consequences with vast areas of the earth becoming uninhabitable and millions of people becoming climate change refugees [1].

To tackle this threat, the Paris agreement was signed by most of the countries in the world in 2015. These countries pledged to strongly reduce its GHG emissions to limit the anthropogenic climate change to ideally 1.5°C but at maximum 2°C. According to the European Union (EU) this translates to a necessary reduction of at least 80 to 95 % of GHG emissions by 2050 in comparison to the base year 1990 for every European country [2]. Therefore, Portugal's path is clear on what to do. The more difficult issue is how to achieve this goal. Figure 1.2 shows the GHG emissions in Portugal from 1990 to 2015. It also shows the minimum goal of an 80 % reduction by 2050. The first thing that can be noted is that emissions have not fallen but increased having their peak in 2005. Although levels have decreased since then, GHG emissions were still 12 % higher in 2015 than in 1990. It is clear that Portugal is still far away from its minimum goal by 2050. The main contributor to these emissions is the energy sector with a share of 70 % in 2015. The remaining 30 % are split up into the categories industrial processes and product uses (IPPU) (11 %), agriculture (10 %) and waste (9 %) [3]. Considering the role of the energy sector, it becomes clear that Portugal's reduction goal can only be reached with a fully decarbonized energy system because even if emissions are considerably reduced in the other sectors, it would still not come even close to the minimum reduction of 80 let alone the aim of 95 %.

To achieve this goal, the energy system has to change profoundly. The sectors electricity, transport and heating & cooling cannot be seen as separate anymore, as they are nowadays, but need to be combined under a so-called smart energy system. This system will mainly be based on electricity for all sectors and solely powered by renewable forms of energy generation [4]. Only then will it be possible to create an entirely renewable energy system in Portugal and mitigate the effects of climate change to solve this serious problem that humanity is facing.

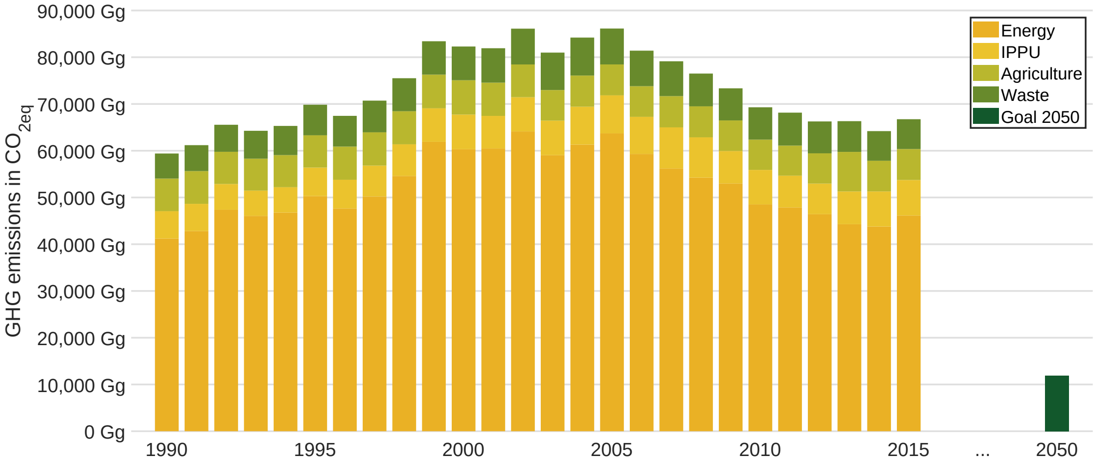


Figure 1.2: GHG emissions in Portugal 1990 – 2015 and minimum goal for 2050 [2, 3]

1.2 Objectives and Scope

The objective of this work is the modeling and optimization of a 100 % renewable energy system in Portugal. Please note that this thesis only considers the Portuguese mainland due to the negligible amounts of GHG emissions of the islands in comparison to the mainland. However, several studies have already discussed how to make the transition for islands in general and Portugal's in particular [5–8].

At first a thorough investigation of the characteristics, challenges and potential of the Portuguese energy system was conducted. Afterwards, a model is created to reproduce the current system using the program EnergyPLAN, which serves as reference point for future system. The chosen year is 2016. For the future Portuguese energy system the following objectives were set for the year 2050:

1. Create a demand model for all energy sectors
2. Model a 100 % renewable system using EnergyPLAN
3. Optimize the 100 % renewable system using MATLAB
4. Analyze the behavior of a 100 % renewable system given varying circumstances
5. Design a 100 % renewable system able to provide enough energy under all circumstances
6. Create a list of recommendations on future steps to take

1.3 Thesis Outline

This thesis is split into six chapters and three annexes. The first chapter serves as introduction to the topic by explaining the motivation for the transition of the Portuguese energy system. Furthermore, it contains the objectives of the thesis and outlines its scope.

The second chapter introduces the reader to the various forms of renewable energy generation and storage that have already reached maturity or are close. The first section discusses the generation side of the future energy system by explaining the characteristics of each technology. Special emphasis is put on the variance in output of non-dispatchable generation systems, at which timescale they occur and what effect they have on the overall system. Afterwards, the different storage technologies that can play a role in the future energy system are introduced.

The third chapter's focus is Portugal. It first discusses the characteristics of the country's current energy system. It continues to list the challenges that Portugal is facing and shows solutions that can help overcome these issues. Lastly, it investigates the technical potential of the country for the various types of renewable energy (RE) to assess its possibilities for a successful transition.

The fourth chapter contains the modeling part of the thesis. At first, modeling itself is introduced as well as modeling tools, especially EnergyPLAN as it is used in this thesis. This is followed by a short introduction to MATLAB and optimization algorithms. Furthermore, the reference model is created in

EnergyPLAN and compared to the actual energy consumption in Portugal for the reference year 2016. Lastly, the optimization model is created considering the current situation and the necessary changes in the system to create a renewable smart energy system.

The fifth chapter presents the results of the optimization process for different scenarios, each of them representing a different output from hydropower in Portugal. It first explains the results of each scenario in detail and afterwards continues to compare the results using various criteria such as installed capacity, electricity demand, costs, etc. Using the findings from the scenarios and their comparison, an energy system is created for Portugal that allows to provide enough energy for any given scenario. This is accompanied by a list of recommendations regarding the steps that need to be taken to achieve a successful transition until 2050.

The sixth chapter is the conclusion. It summarizes the content of the thesis and highlights the most relevant aspects of the findings towards a renewable energy system. Furthermore, it contains suggestions towards future work.

The first of the three annexes contains the MATLAB code that was used for the optimization of the model. The second lists the cost values that were used for the cost evaluation of each scenario and the third annex contains further information about Portugal's roadmap for the transition of the energy system.

Chapter 2

Renewable Energy Technologies

The energy sector of the future will be significantly different from today's. To achieve a carbon-free energy sector, the old technologies will have to phase out and be replaced by sustainable ones. These technologies have different characteristics and are at varying levels of maturity. This chapter introduces the main technologies that can play a significant role in the future.

2.1 Power Generation

Nowadays power is traditionally generated by fossil fuel power plants that emit CO_2. Their advantage is their dispatchability that allows them to adjust their power output according to the current demand. Renewable generation technologies work differently. Adjusting their output is difficult for most of them. Instead they naturally vary given changes in the resource availability at different timescales, which are shown in Figure 2.1 [9]. This section discusses the specific characteristics of each generation technology and goes into detail how the timescales are different for each technology and how they affect the future energy system.

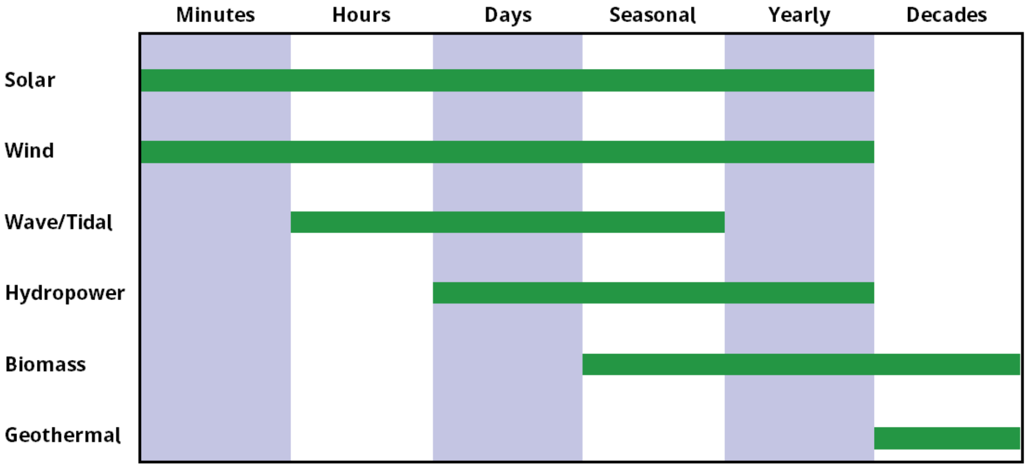


Figure 2.1: Timescales of natural cycles of renewable energies [9]

2.1.1 Hydro

Hydropower is the oldest and most established renewable form of power generation. In Portugal the first hydropower plant was established in 1894 [10]. As the name suggests (from the Greek word for "water"), hydropower uses the power of the moving water in rivers to generate electricity. The kinetic power of the water is converted into mechanical energy via a turbine. The turbine is connected to a shaft that powers a generator, which converts the mechanical energy into electrical [11]. There are different types of turbines that are specialized for different situations, i.e. Pelton, Francis, Kaplan, Bulb and Ossberger. The type of turbine that is used for a project depends on the flow rate, the drop height and the capacity of the plant. There are three different types of hydropower plants: Run-of-river, storage and pumped hydroelectric storage (PHES). PHES will be discussed in section 2.2.1 as it is rather a storage than a generation technology. The principle of run-of-river power plants is shown in Figure 2.2. This type of plant can be built wherever there exists a sufficient difference in elevation in a river. The height difference is caused by a weir. As the height difference is usually only a few meters, most of the run-of-river hydropower plants do not exceed installed capacities of 100 MW [12]. As a matter of fact many run-of-river power plants are so-called small hydropower plants (SHPs), which have typically a capacity below 10 MW. Their big advantage is their low impact on the environment while being technologically mature [13].

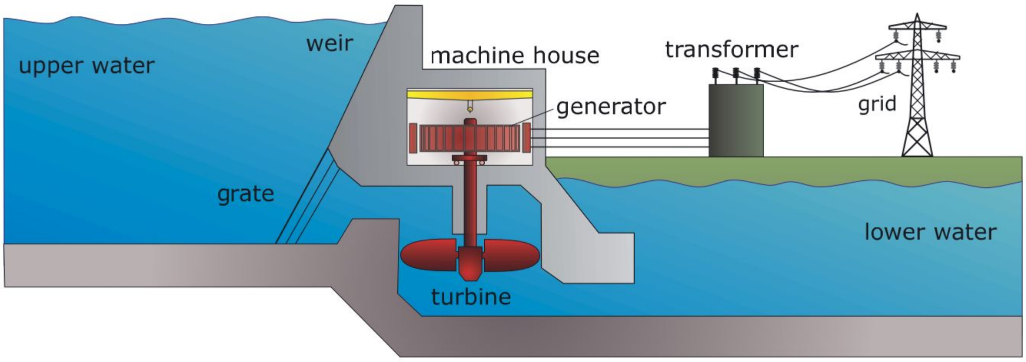


Figure 2.2: Principle of a run-of-river plant [12]

The second type are storage or dammed power plants. Unlike the run-of-river plants they store huge amounts of water that is held back by a dam. Thus they can match their production to the demand very well. As big areas will be flooded behind the dam, they cannot be built everywhere. Typical locations are in the mountains. Despite their higher environmental impact, they are highly advantageous as they can use the stored water to balance out changes in the water supply. This allows them to adjust their production somewhat to the current demand. Typically storage power plants have higher capacities [14]. Portugal's biggest hydropower plant is currently Venda Nova III with an installed capacity of 781 MW. However, an even bigger plant is being built at the moment with 880 MW in Gouvães [15].

As shown in Figure 2.1, hydropower underlies different timescales of power output. While their variations are negligible regarding minutes and days, they become more relevant when looking at days and even more so for seasons and years. The changes in days are still not too relevant as they are of minor influence and foreseeable. The changes in output per season are more significant as they are rather big [9]. For example the average output in February 2016 was 47 % of the installed capacity while in September of the same year it was only 16 % [16]. This is caused by the variation in rainfalls throughout the year. However, as these variations are very similar each year, the output curve throughout the seasons is still somewhat foreseeable. The biggest issue with hydropower plants is on a yearly timescale [9]. Figure 2.3 shows the capability index (CI) for each year from 2008 to 2017. The CI describes how much more or less energy was produced in comparison to the average. The figure makes it clear that the output varies greatly from year to year. Unlike the seasonal output, the yearly output is much more difficult to forecast. This means that in a dry year other means of generation need to replace hydropower generation but it is unknown to what extent they need to be replaced. Thus other technologies need to be highly flexible. As Portugal greatly relies on hydropower, these variations can be significant. As an example of this issue, in 2016 hydropower produced 15,413 GWh. However, it was only 5,536 GWh in 2017, despite an increase in capacity. The difference had to be compensated by other plants, which are currently mainly fossil fueled types [17].

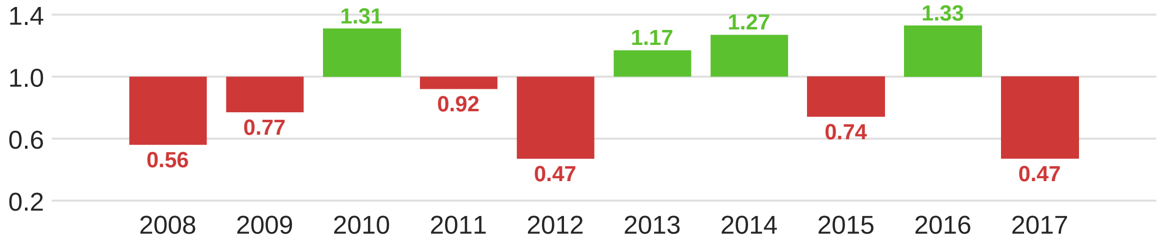


Figure 2.3: CI of hydro in the recent years in Portugal [17]

2.1.2 Wind

Just like hydropower, wind power has been used for a long time. 3000 years ago it was already used for irrigation purposes. However, the use for electricity generation is quite recent. This started only in the 1970's during the oil crises when new technologies were explored to decrease the dependence on fuel imports. The energy that the wind contains stems from temperature differences on earth. The density differences of the air cause it to move creating winds that turn the blades of the wind turbine. This rotational movement drives a shaft that is connected to a generator, which produces electricity [14]. Since the first wind turbines the industry has improved the technology greatly, especially since 2008. Greater hub heights and larger swept areas have steadily increased the capacity factors for a given wind resource. Simultaneously, costs have fallen causing the levelized cost of energy (LCOE) of wind to be lower than that of coal fired power plants by now. This trend will continue in the future driving down costs even further while installed capacities increase [18]. Portugal has one of the highest wind shares in Europe. In 2017 23 % of the Portuguese electricity came from wind power [17].

All of Portugal's wind power comes from onshore wind farms. There are two types of wind farms: onshore and offshore. Onshore wind farms are built on land and were invented first. Their advantage is that they are comparatively easy to install as conditions on land are less harsh. As the energy output depends on the surface roughness on the land, onshore turbines are usually built at higher hub heights than offshore turbines to increase the energy yield. Despite this, onshore turbines reach lower full-load hours than offshore ones. Offshore turbines are built off-coast. Presently, their foundation is built into the ground [14]. This will change in the future with floating platforms that allow to explore even bigger potentials of offshore wind. Offshore wind turbines are characterized by higher yields. This is due to steadier winds and lower surface roughness, as the surface is the ocean. In return offshore turbines can be built at lower hub heights. Currently offshore costs are still higher but they are also decreasing, making them increasingly attractive for power generation [19].

Although offshore wind turbines have a steadier output, both types still suffer from fluctuations at various time scales. Although wind is affected by almost all, as suggested in Figure 2.1, they effect the energy system differently [9]. As shown in Figure 2.4, the yearly variations are not too significant. Just like for hydropower plants the exact overall output per year is almost impossible to foresee. However, since the variations are smaller, the issue is less critical. It becomes even less important when capacities of wind and solar power produce similar amounts of electricity. Comparing the CIs of wind in Figure 2.4 with those of solar in Figure 2.6, it can be noticed that they are inversely related [17]. Therefore a lack in wind power in one year is compensated by solar power and vice-versa. Seasonal variations are, similarly to hydropower, well known and can be anticipated in advance. Short-term fluctuations play only a role when there are only a few wind turbines installed as the variation of each can be rather big. However, due to the aggregational effect, this variation becomes negligible on a larger scale. The timescales with the biggest issues are hourly and daily. These variations can be very big despite having many turbines. The effects can be alleviated by distributing the turbines geographically [9] and by having precise forecasts [20]. The bigger the area the smaller the issue becomes. However, one country alone is generally not big enough and fluctuations will occur that need to be balanced out [9].

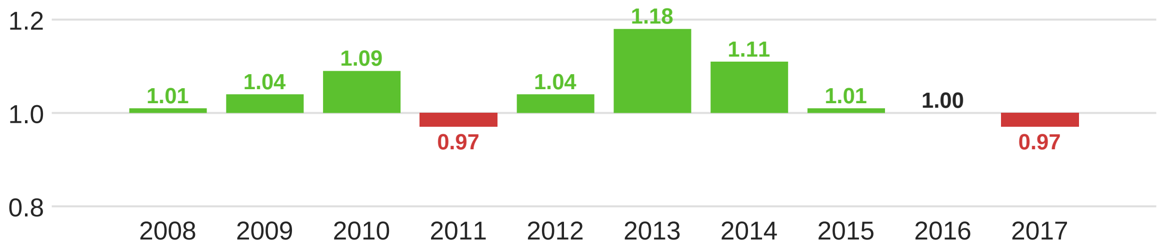


Figure 2.4: CI of wind in the recent years in Portugal [17]

Currently wind energy is not offering grid ancillary services such as voltage or frequency control. These are still offered by fossil power plants. However, as those plants will start to disappear, other technologies have to take over those tasks as well. Technologically, these services could already be provided by wind turbines nowadays. Spain reports great success concerning voltage control via wind power for example. Yet, these technologies will need to be implemented in greater numbers in the future to ensure that the grid can operate without fossil power plants [21].

2.1.3 Solar

As the name suggests solar power uses the energy provided by the sun's radiation to generate electricity. The most common form of solar generation is photovoltaics (PV). The very first PV or solar cell was developed in 1954 in the USA to deliver energy for out-of-space missions. Basically, the PV cells are semiconductors that use the photoelectric effect to convert the energy of the photons into electricity [22]. Most of the cells are made of silicon but other types such as perovskite and cadmium telluride have emerged recently [23, 24]. While the first solar cell only had an efficiency of 5 %, the technology has continuously improved. Laboratories have already reached efficiencies of 27.5 % for silicon cells while commercial cells have an efficiency of around 15 %. A big advantage of the technology is that it can be scaled at will and therefore can be installed on a rooftop with only a few kW of installed capacity up to several hundreds of MW on a field [22].

Besides PV there are concentrated solar power (CSP) technologies to generate electricity. However, they are currently still at early stages with only very few plants operating. In contrast to PV, these technologies cannot be scaled at will and are typically in the MW range. The most developed technologies are parabolic trough collectors (PTCs), shown in Figure 2.5a, and solar towers (STs), in Figure 2.5b [12]. Accordingly to the name, PTCs use parabolic collectors that track the sun and concentrate the sunrays onto a focal point. In the focal point is an absorber pipe that contains a special thermal oil that is heated to around 400 °C [25]. The heat is transmitted to water in a heat exchanger. The water flashes into steam and drives a turbine, which turns a generator to generate electricity. The system is similar to classic fossil power plants, however the source of the heat is renewable. After the water condenses it enters the cycle again, becomes vapor in the heat exchanger and powers the turbine [12]. Although the STs work also with heat their operation is very different. As shown in Figure 2.5b, it consists of a field of heliostats, which are flat mirrors, that track the sun to reflect the sunlight to a so-called solar tower. Inside the solar tower is a steam generator that absorbs the thermal energy and heats up water, which flashes and drives a turbine [25]. Due to the concentration of the sunlight, the absorber can reach temperatures of more than 1,000 °C [12]. The heat transfer medium can be distilled water or, like for the PTCs, special materials, e.g. molten salts [25]. The big advantage of these CSPs is that they can use thermal energy storage systems to continue generating energy when the sun does not shine. These systems contain storage mediums, most commonly sand-rock minerals or salts, to store the thermal energy. When the sun does not shine, the stored heat can be used to continue generating electricity. For example, the solar tower Torresol Gemasolar in Seville has an installed capacity of 19.9 MW and uses molten salt as storage medium. With the storage capacities it is capable of continuing operation for 15 h at full capacity without sunlight, allowing to generate electricity throughout the night [26].

Solar technologies have even greater cost reduction potentials than wind. Currently onshore wind has a global LCOE that is around half in comparison to PV. CSP technologies are even more expensive. However, while onshore wind is expected to reduce its LCOE by -26 % from 2015 to 2025, PV, PTC and ST have potentials of -59 %, -37 % and -43 %, respectively. This means that by 2025 onshore wind and PV will have a similar LCOE of 0.05 and 0.06 $/kWh, respectively. The other technologies are slightly

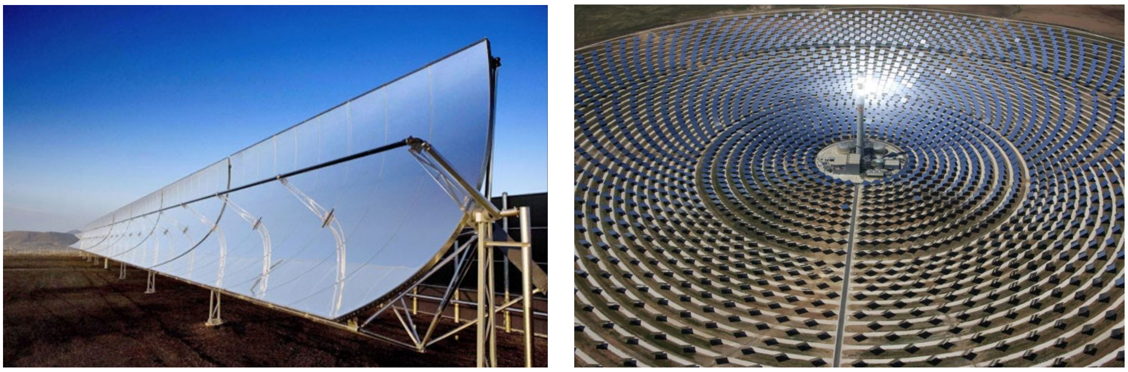

(a) Parabolic trough collector [27] (b) Solar tower [28]

Figure 2.5: Different technologies of CSP

above with 0.09 and 0.08 $/kWh, however, due to the fact that they are more novel and less developed they have higher cost reduction potentials after 2025 [18].

The timescales at which solar technologies are affected by output variations are identical to those of wind, as can be observed in Figure 2.1 [9]. Solar technologies have relatively steady yearly outputs, even steadier than wind, as shown in Figure 2.6 [17]. As mentioned before, they are complementary technologies, which makes their combination very interesting. This is both true on a daily timescale as well as a seasonal. While winds are stronger during the winter and weaker during the summer, it is the other way around for solar resources. Their output is highest during the summer months in Portugal. More critical for solar resources is the variation within hours and minutes. This is especially true for PV as clouds can have significant effects on the output. Due to the aggregational effect these sudden changes can be smoothed, however, they can still be significant, especially on an hourly scale, when the weather changes [9]. Daily variations also have a significant effect as a rainy day produces much less power. For CSP technologies these effects are much less notable as they are usually equipped with thermal storage systems. Therefore these types are mostly not affected on an hour and minute scale. Nevertheless they are still subject to daily, seasonal and yearly influences [26].

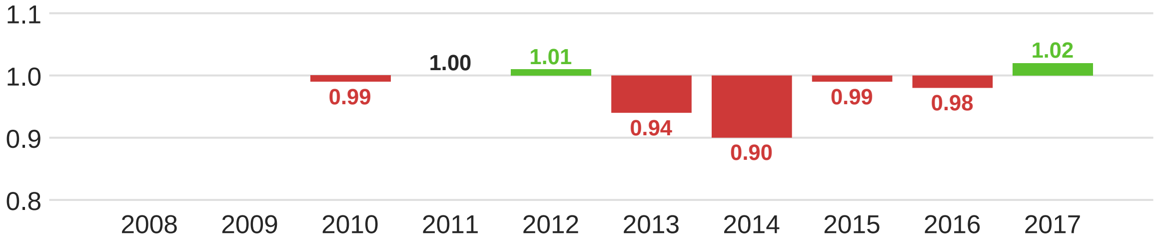
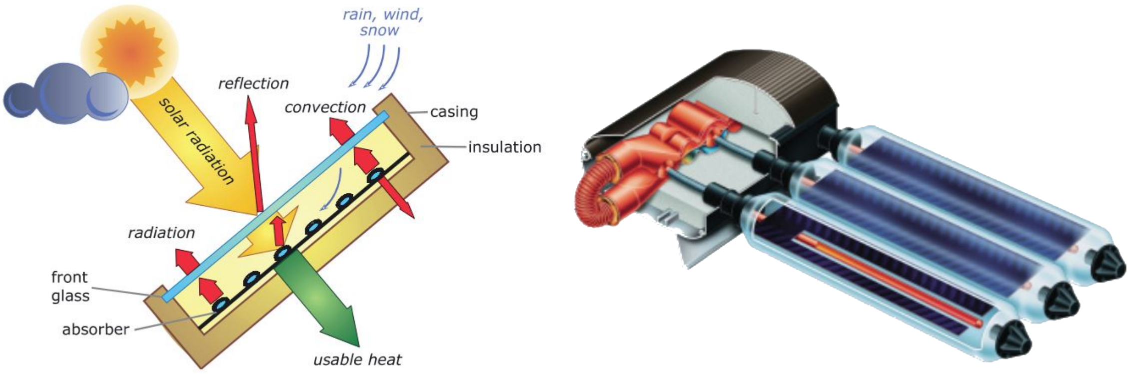


Figure 2.6: CI of solar in the recent years in Portugal [17]

Similar to wind power, solar plants will have to take over grid services in the future once fossil plants are replaced. Potential enhancements contain faster communication within the plants and improved interoperability of different networks. These changes will cause additional costs, however, they are comparatively low for bigger plants with the right market mechanisms. Overall both solar and wind power can already be equipped with the technology to provide grid services such as frequency and voltage control [21].



(a) Processes in a flat-plate collector

(b) Vacuum-tube collector

Figure 2.7: Different solar thermal technologies [12]

CSP technologies use the generated heat to produce electricity. However, the thermal energy can also be used directly for heating. Besides concentrating technologies, which can be used in a district heating system to increase their efficiency further, the more common systems for this application are non-concentrating. Most prominently there are flat-plate and vacuum-tube collectors. Flat-plate collectors, as in Figure 2.7a, consist of a casing and a front glass to protect the actual absorber that transfer the heat to the working medium. The working principle of vacuum-tube collectors, shown in Figure 2.7b, is the same, however, they are more efficient as they are insulated with a vacuum. They are typically used when there is little space for installation. The working medium can be either water that can be directly used or a mixture of water and an anti-freeze. The medium eventually transfers the heat in a heat exchanger to a water that is stored in a tank. This indirect approach is only necessary in regions where temperatures can go below zero, as otherwise the collectors would break when the water turns to ice and expands inside the tubes. As most areas in Portugal do not have negative temperatures, they can use the simpler and therefore more cost-effective method of directly heating the water that will be used [12].

2.1.4 Biomass

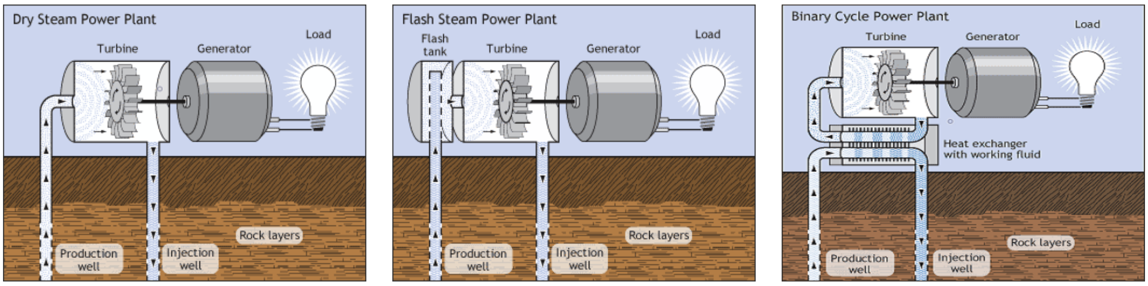
The term biomass refers to organic material. It can stem from plants or animals, which regenerates within a short time-frame. Some sources of biomass are forestry, agriculture, livestock and organic waste. As the sources are diverse, so are its applications. Some uses are firewood or pellets from forest wood for heating, bio oils or biogas from energy crops or livestock residues for electricity generation or transportation. As the energy is stored chemically, it becomes evident that biomass is a very flexible source of energy like fossil oil and gas. The limiting factor for the use of biomass in an energy system is the availability of land. As all biomass ultimately originates from photosynthesis, space is needed, which is limited. Furthermore, other sectors compete for that land. The "food versus fuel" discussion has been ongoing ever since not only waste and by-products were used for biomass but fields were specifically used to grow energy crops to turn them into biofuels. Therefore, it is crucial that the limited resource is used responsibly [12]. This also includes that biomass resources are not overused as they are only renewable if their natural potential is not exceeded [29]. As long as the production is below this potential, the output of biomass is quite constant on a decade and yearly timescale. Variations are more pronounced on a seasonal scale, however due to its ability to be stored or converted, even those variations are rather insignificant [9].

As biomass is highly flexible due to its ability to be stored easily and its high energy density, it will need to play a different role in the future electricity sector. Currently, biomass power plants feed constantly into the grid and are compensated via feed-in-tariffs in most countries. In the future they need to be used differently and they need to take over more responsibilities. They too need to provide grid services. Their biggest advantage is their flexibility and therefore they need to change the way they feed into the grid. Instead of a constant output, biomass power plants need to react flexibly to the output of the non-dispatchable RE resources. Similar to the operation of current gas power plants, they need to respond quickly to variations and produce electricity only when production of the other resources is too low to cover the demand. During periods of high generation from varying RE technologies, they need to store the biomass to build up reserves [30].

2.1.5 Geothermal

Geothermal energy uses the thermal energy that is inside the earth's layers. The temperatures vary depending on the location and depth. High temperature resources can primarily be found along the borders of the tectonic plates where volcanic activity is high. The working principle behind geothermal power plants is always the same, high temperature water is pumped to the surface where it drives a generator and is pumped back down to close the cycle. There are three different types of operation, which are depicted in Figure 2.8. Dry steam power plants, as in Figure 2.8a, use the steam that comes from the production well directly to power the turbine. The condensated water is then pumped back through the injection well. This technology can only be used for resources above 150 ℃ and steam that is 99.995 % dry. The most common type is the flash steam operation, shown in Figure 2.8b. They are very similar to dry steam plants. However, the steam for driving the turbine is obtained differently. The highly pressurized water is directed into a flash tank where it flashes to steam due to a low pressure environment. This steam is used to drive the turbine. The process works best with temperatures above 180 ℃. For low enthalpy resources below 150 ℃, the binary cycle approach is used, which is depicted in Figure 2.8c. The resource fluid is pumped into a heat exchanger where it gives off its thermal energy to a working fluid. The working fluid, e.g. ammonia/water mixtures, has a lower boiling point than water and flashes to drive the turbine [31]. Where the resource's energy is too low to produce electricity it can be used directly for heating purposes, which is done to a small extent in Portugal [32].

All power plants require three conditions to be met to be able to produce electricity. They need to be built in an area with high temperatures close to the surface, the soil needs to be irrigated, e.g. sedimentary rocks, and water needs to be in the fracture network inside the rock. This limits the geographical potential tremendously. In Portugal the potential is limited to the Azores islands, since they are located on the border of the African, North-American and Eurasian plate. However, in the future this potential is expected to be increased using hot dry rock (HDR). Vast amounts of the earth's heat are stored in



(a) Dry steam (b) Flash steam (c) Binary cycle

Figure 2.8: Different power generation technologies [33]

the crystalline basement rocks, which are found almost everywhere. However, these rocks are dry and do not exhibit a fracture network as they are less porous. HDR technology pumps pressurized cold water into the layers to create a fracture network. Once a fracture network is created the operation is similar to traditional geothermal power plants. The only difference is that the water, that will be used as steam to power the turbine, first needs to be pumped into the network. Afterwards it can be extracted normally via production wells and pumped back down via injection wells. So far this technology is still in its developing stage and needs more time to reach full commercial maturity [12]. However, it can be highly interesting as a constant power source since geothermal resources show almost no variations on any timescale as long as the resource is not overused [9].

2.1.6 Marine

The ocean is the potentially biggest untapped RE resource for energy generation. Despite the big potential, not many technologies have passed the stage of demonstration projects and it is still unclear which technologies will come out on top [9]. Therefore, it is expected that these technologies will play a bigger role only medium- to long-term [30].

The first way of harvesting the ocean's energy is using the power that is contained in its waves. The energy can be extracted using different principles such as pressure differentials, floating structures and oscillating columns [34]. An interesting aspect of wave energy is its power density. At 2-3 $\mathrm{kW/m^2}$ it is much higher than that of solar (0.1-0.2 $\mathrm{kW/m^2}$) or wind (0.4-0.6 $\mathrm{kW/m^2}$) [35]. Wave energy is influenced by cyclic fluctuations as most of the green generation technologies. The changes in wave periods and heights are most prominent on a daily and monthly timescale. Seasonal variations are less noticeable in temperate zones like Portugal [9]. The biggest potential in Portugal can be found along the coast north of Lisbon, especially around Nazaré [36].

The second source of marine energy is tidal energy. The tides are attributed to the interacting forces of attraction between earth, moon and sun. Tidal waves follow a semidiurnal pattern in Portugal [37]. Overall tidal energy is subject to several cycles that affect the hourly, daily and seasonal timescale. However, as these cycles are well understood output pattern of tidal plants can be precisely predicted [9]. Most designs use turbines similar to wind turbines, however, there are also other solutions [38].

The third most common strategy is obtaining energy from the ocean current. Just like tidal generation technologies, ocean current technologies use turbines that are similar to those of wind turbines. The difference is that while tidal systems require a dam to direct the flow, these systems do without one. Therefore, they are less intrusive on the environment. The physical characteristics are very similar to those of wind turbines as both work with currents. The main difference is that the much higher density of water allows higher energy yields despite slower current speeds. The major restriction is the geographical limitation of these turbines. They are limited to regions with consistently high current speeds and moderate water depths [12].

2.2 Energy Storage

As grids will have to become more flexible, energy storage becomes a high priority topic. The grids need to be more flexible due to the intermittency of the future power supply. Energy storage systems (ESSs) are not the only way to make grids more flexible but they play a vital role as other flexibility measures cannot sufficiently provide enough. Thus energy storage will need to play a bigger role in the future. As the future energy system will have to be connected across all sectors, as will be explained in subsection 3.2.5, not only electric but also thermal storage will play a bigger role [39]. However, ESS technologies are at different stages of maturity. Figure 2.9 shows at which maturity level the respective technologies are. On the left side in red are the ones that are still in its research stage and will still take some time until they are ready to play a role in the energy system. The ones in the middle in yellow are technologies that are already in the demonstration and deployment stage. This means that prototypes are already trialed and tested and the technologies are on their way to be deployed on a bigger scale. The technologies on the right in green are already commercially available and widely used. It can be seen that pumped storage hydropower (PSH) (also known as PHES) systems are the most mature form of electricity storage [40]. They have been used for decades in the world [41].

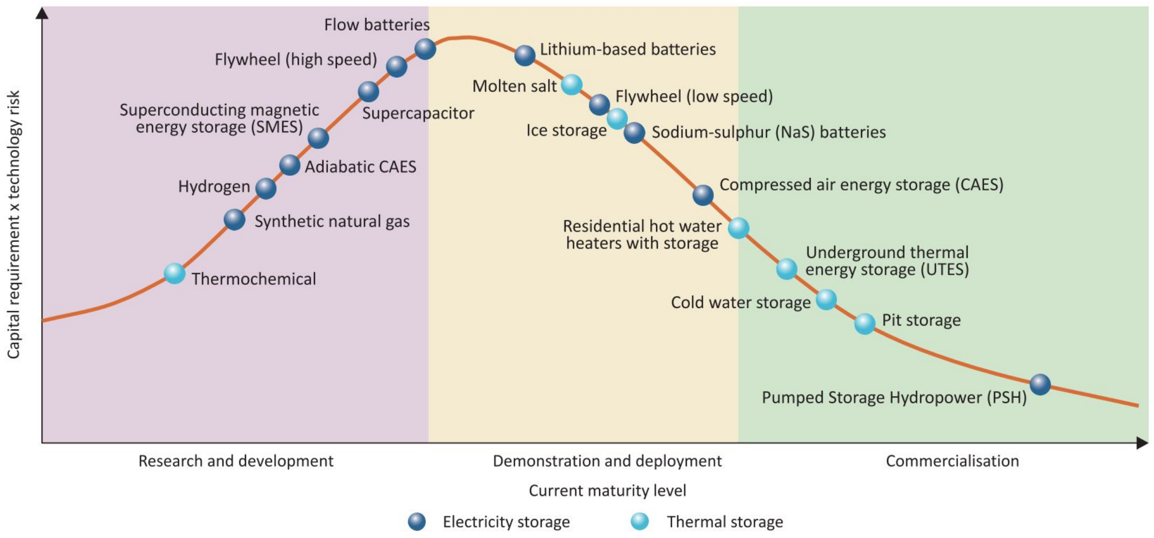


Figure 2.9: Maturity levels for various types of energy storage [40]

The types of storage can be classified into different storage mechanisms. These are mechanical, electrochemical, chemical, electrical and thermal. This section presents the technologies in these groups. However, as there are more and more technologies being developed, not all of them can be covered in this thesis. Therefore, the section focuses primarily on the most mature or influential technologies to date. The future energy system will depend on a mixture of many different technologies as each has its own characteristics [42].

2.2.1 Mechanical Energy Storage

Mechanical energy storage (MES) systems include pumped hydroelectric storage (PHES), compressed air energy storage (CAES) and flywheels. As can be seen in Figure 2.9, these technologies are already at very mature levels and are already being deployed or are on the verge to do so. Other MES technologies exist, like gravity energy storage (GES) and liquid-piston energy storage (LPES), however, due to their immature levels, they are not discussed in this thesis [43].

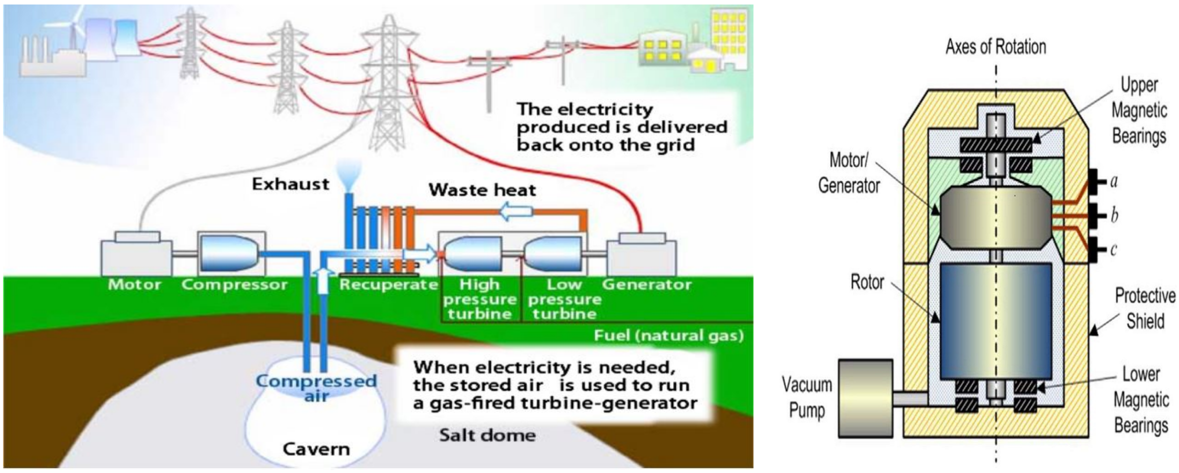
PHES

Pumped hydroelectric storage (PHES) systems are by far the most mature ESS technology. It accounts for 99 % of the world's total storage capacity to date [42]. PHES stores the energy in the form of potential energy. During periods of surplus electricity production water is pumped from a lower to a higher reservoir. During hours of peak demand, the water is sent back through hydro turbines to convert the potential energy back into electricity [44]. The difference to dammed hydropower is that the upper reservoir is not fed by a river but only from the water from the lower reservoir. Thus, it is a pure storage technology unlike dammed power plants. Currently, PHES is the most cost-effective method to store large amounts of electrical energy short- and medium-term [45]. However, they are limited to geographical conditions. The reservoirs cannot be built anywhere since they need a height difference [46].

CAES

Compressed air energy storage (CAES) systems are the second most mature technology for electrical energy storage. The working principle is illustrated in Figure 2.10a and is based on the compression of air [42]. The operation pattern is similar to that of PHES. During off-peak hours, the excess electricity is used to drive a motor to run compressors for injecting air into a storage vessel [39]. The storage vessels are typically aquifers, salt caverns and mechanically formed reservoirs in rock formations [47]. The energy is stored in the form of high pressured air. When power demand is higher the air is released into a set of turbines to feed electricity back to the grid. As the fast expansion of the air causes it to cool dramatically, it is heated up before entering the turbines [39]. CAES is especially interesting for bulk energy storage as the air can be stored at will [45].

The round-trip efficiency of current CAES plants is around 50 %. However, future plants should achieve higher efficiencies using adiabatic CAES. As mentioned before, the air is heated when it expands again to



(a) Working principle of CAES [43]

(b) Setup of a flywheel system [51]

Figure 2.10: Different MES technologies

avoid damage to the turbines. This is currently done using gas. Future systems plan to use the heat that is created initially by the compression of the air instead. The heat is stored in a separate storage system before the air enters the storage vessel. When the air is expanded again it is passed through the heat storage system where it is heated up. Therefore, no additional energy usage is needed. These systems can reach efficiencies of up to 70 % [48]. To date there are only two CAES plants. The plants are in Huntorf, Germany and Alabama, USA with a respective capacity of 290 and 110 MW [42]. CAES and PHES are very similar in their characteristics as they are both large scale storage technologies. However, there are some key differences between the two. Capital costs are very high for PHES while they are significantly lower for CAES [49]. Furthermore, the environmental impact of CAES is very small in comparison to PHES as the storage is underground [50].

Flywheel

Although flywheels also use a mechanical mechanism for energy storage, their field of usage is very different. The setup of a flywheel is shown in Figure 2.10b. It consists of a massive rotating cylinder as main component, which levitates due to magnetic bearings. The rotor is connected to a motor/generator unit. The flywheel stores its electricity as kinetic energy as the mass spins at very high speeds. To increase the efficiency the rotor is kept in a vacuum to decrease resistance [51]. Due to the low friction losses, flywheels have among the highest efficiencies at around 95 %. The flywheels are divided into low-speed and high-speed. Low-speed flywheels rotate with less than 6,000 rpm while high-speed ones spin at around 100,000 rpm [39]. Low-speed flywheels offer shorter periods of storage with higher power capacities. The opposite is true for high-speed systems. However, flywheels are generally only used for short-term storage as their efficiency drastically decreases over longer periods of time. After one day the efficiency already drops to 45 %. Their application is rather to balance out quick changes in energy supply, due to varying generation, and frequency regulation [52]. Their advantages are low maintenance cost, long life cycle, high efficiency, no depth of discharge effects, environmentally friendly, wide operating temperature range and ability to survive in harsh conditions [43].

2.2.2 Electrochemical Energy Storage

Electrochemical energy storage (ECES) systems can be divided into three categories, which are primary batteries, secondary batteries and fuel cells [52]. Fuel cells use energy that is stored from an outside substance like hydrogen or methane and are discussed in subsection 2.2.4. The difference between primary and secondary batteries are that only secondary ones can be recharged [52]. However, they both use chemical reactions to enable the flow of electrons [40]. The secondary batteries are the ones that will be discussed in this subsection. The most prominent types are lead acid, sodium sulfur [47], and lithium-based [53]. The working principle is always similar. They consist of anode and cathode, which are stored in electrolyte. The components are installed in a container that connects the cell to an external DC power source. When the cell is discharged, the anode sends positive ions to the electrolyte. The electrons run through the external circuit, powering the device that is connected to the battery. When the battery is charged, this process is reversed [52].

The lead acid battery is the cheapest and most mature technology to date. Their advantages are low costs of \$300 to \$600/kWh, high reliability and solid efficiency (70-90 %) [47]. Additionally, they offer fast response times and small daily self-discharge rate [39]. However, the technology has downsides as well. It has a low energy density of 50-90 Wh/l, specific energy of 25-50 Wh/kg [39] and specific power of around 150 W/kg [43]. On top of that, with up to around 1,000 cycles, its lifespan is quite short and it performs poorly at low temperatures, which requires a thermal management system [30]. In the future the commercial use of lead acid batteries is limited due to the development of other battery types with higher efficiencies and energy densities [43].

One of these other technologies is the sodium sulfur battery. It has many desirable features such as a higher energy density (150-300 Wh/l) [39], higher efficiencies of more than 85 % and long cycle capability with around 2,500 cycles [43]. Other advantages are the use of inexpensive and non-toxic material, high recyclability (~99 %) and its low maintenance [47]. Its capability to provide prompt and precise response makes it interesting for applications in grid power quality regulation [43]. Nonetheless, the sodium sulfur also has some downsides. First of all, it is a high-temperature battery, meaning it operates at temperatures of around 350 °C, which requires an extra system to ensure operating temperature [39]. This leads to high annual operating costs (\$80/kW/year) and diminishes its potential for residential applications [54]. Despite the inexpensive material, investment costs are still very high (around \$2,000/kW and around \$350/kWh) [47]. Nonetheless, it is considered as one of the most promising technologies for high power bulk energy storage where it has to compete with lithium-based batteries [39].

Lithium batteries are already being deployed in many areas. They are smaller and lighter while more powerful making them especially attractive for portable electronics and cars. Lithium batteries have a specific energy, specific power and energy density from 90 to 200 Wh/kg, 150 to 2,000 W/kg and 1,500–10,000 W/l, respectively [43]. Furthermore, they are characterized by high efficiencies (~97 %), low self-discharge rates of a maximum of 5 % per month, good lifetime of over 1,500 cycles and quick response time. While lithium-based batteries are already employed in the majority of portable devices the scalability to bulk size is facing some issues. Current capital costs (>$600/kWh) are high and the technology is fragile both in terms of temperature and charging. Special protection circuits against overload complicate the system [47]. Despite its high capital costs it is overall the technology with the lowest cost per cycle. Unsurprisingly, these batteries are gaining popularity as 85.6 % of the deployed energy storage system in 2015 were based on lithium. Furthermore, future research and development (R&D) will yield better lithium cells. A new development with nanowire silicon produces already 10 times more than the current technology and prices are expected to drop significantly in the future [43]. A limiting factor, however, is the limited availability of lithium as it is difficult to mine and batteries are difficult to recycle [47].

There are many more battery technologies, such as nickel-based and graphite. Thus the future of battery development is difficult to predict. However, as there is no perfect battery, it always needs to be chosen based on its purpose. One big advantage is the technology's modularity [47]. Although large scale utility battery storage systems are yet rare, there are many fields of application that batteries are already deployed and gaining ground. Due to their scalability they can be used not only in central bulk storage but also for decentralized systems. One of these applications are residential storage systems, especially in combination with solar panels. As residential consumers have very high power costs in Portugal, a correctly sized system, can save up to 87 % of the energy bill [55]. Furthermore, it has beneficial effects on the local grid [56]. Its usage in the transportation sector is also highly promising as a vehicle powered by renewable electricity causes significantly less CO_2 than fossil cars, even when considering the initial emissions during the production of the battery [57].

A different type of battery is the so-called redox-flow battery. Unlike conventional batteries the stored energy is contained in electrolyte that is stored separately and pumped into an electrochemical stack for conversion to electricity. Since electrolyte and stacks can be scaled at will, both energy and power of the system can be tailored to the individual needs, which is one of its biggest advantage over other technologies [58]. Furthermore, depending on the type, they can have quick response times, good cycle life (10,000-16,000) and relatively high efficiencies of around 85 %. However costs are currently very high and need to be significantly reduced in the future for the technology to play a bigger role in the energy sector [39].

2.2.3 Electrical Energy Storage

Electrical energy storage (EES) systems are mainly capacitors. As they do not convert the electrical energy, capacitors are the most direct method to store electricity. They are made of two metal plates separated by a thin insulator. They store energy on the surfaces of the metal plates. They are characterized by low energy densities [51]. However, they have a very high power density allowing them to be charged or discharged much faster than batteries. Due to its limited storage capabilities it is unsuitable for bulk storage but can be used for power quality applications, including high voltage power correction and smoothing the output of power supplies [39].

Supercapacitors are in principal a mixture of both capacitor and battery. This causes them to also have power and energy densities that range between those of capacitors and batteries. The most important features of supercapacitors are their long cycle life with more than 10,000 cycles, their high cycle efficiency (84-97 %) and their high power density [39]. Additionally, they are characterized by a good tolerance for low temperature, very low maintenance, high durability and fast response time. As downsides need to be mentioned the relatively low energy density and high self-discharge of 5-40 % [42]. Additionally their capital costs are high at currently \$6,000/kWh. Overall, due to their characteristics, supercapacitors are suitable for short-term applications but are currently not suited for large-scale energy storage [39].

The least mature EES technology is currently superconducting magnetic energy storage (SMES) [40]. It stores electrical energy in a magnetic field. As the device needs to be cooled below the material's superconducting critical temperature, the method is highly complex. Some of the features are a relatively high power density of up to 4,000 W/l, quick full discharge time (less than 1 min), high cycle efficiency (95-98 %), fast response time in the range of milliseconds and a long lifetime of a up to 30 years. Additionally, SMES systems can be completely discharged for thousands of cycles with little degradation. On the other hand, the capital costs are very high (up to \$10,000/kWh, \$7,200/kW) and they have high daily self-discharge rates between 10 and 15 %. Currently they are suitable for short-term storage in power and energy system applications [39].

2.2.4 Chemical Energy Storage

When it comes to long-term storage, chemical energy storage (CES) is unrivaled. As fossil fuels prove, they can be stored for millions of years and have high energy densities making them ideal for seasonal storage. The most common forms that can be produced from electricity are hydrogen, methane, methanol and hydrocarbons. Hydrogen is the most direct path from electrical to chemical energy. All other forms can be created with the help of a carbon source from hydrogen using the Fischer-Tropsch synthesis. Furthermore, there are compounds like butanol and ethanol that can be made from biomass sources [43].

Hydrogen is produced from electricity through the electrolysis of water [43]. Hydrogen has a very high energy density of 122 kJ/g, which is 2.75 times higher than hydrocarbon fuels. However, it has a very low volumetric energy density. For this reason hydrogen is usually compressed before it is stored [42]. Other methods are liquefaction or the storage in metal hydrides [54]. Typically, after the hydrogen is compressed it is either stored in caverns underground or injected into the gas grid in limited amounts. To convert the hydrogen back into electricity it is possible to use traditional combustion turbines, however, it is normally done via fuel cells, as they are more efficient and quieter [39]. They work like batteries as they are composed of an anode, a cathode, and an electrolyte membrane. Hydrogen is passed through the anode and oxygen through the cathode. The protons go through the membrane while the electrons are forced through an external circuit, producing electricity and water as byproduct [51]. Currently the technology is suffering from two major drawbacks. The first is the cost. At costs of \$500-8,000/kW [44] and \$6-20/kWh, the technology prices need to come down. The other issue is the substantial energy loss during one cycle. The electrolysis has an efficiency of around 60 %, transport and compression cause further losses of 10 % and fuel cells reach currently efficiencies of 50 %. This gives an overall round-trip efficiency of around 30 % [43], which is much lower in comparison to 80 % of PHES [45]. Therefore, cost reduction and efficiency improvement are the main topics for R&D [47]. Nevertheless, hydrogen and fuel cells are expected to become more important in the future [59]. From 2030 on it is expected to be the most economic long-term storage method for energy [45].

When hydrogen is combined with a carbon source other chemical compounds can be created. The technologies are known as power-to-gas (P2G) and power-to-liquid (P2L) depending on which compound is produced. The most popular product is methane, which has the same composition as natural gas [43]. However, when it is produced artificially it is called synthetic gas (SynGas). The very compelling argument is that the existing gas infrastructure could be continued to be used. The gas can simply be injected into the national grid and stored in underground gas storage caverns [60]. However, the additional transformation process leads to even lower efficiencies and higher prices and therefore costs need to be reduced just as for hydrogen [45].

Figure 2.11 sums up the section about electrical storage technologies. It contains the main information about most of the storage systems, namely the energy that is storable by each technology, the power at which it can operate and the discharge duration.

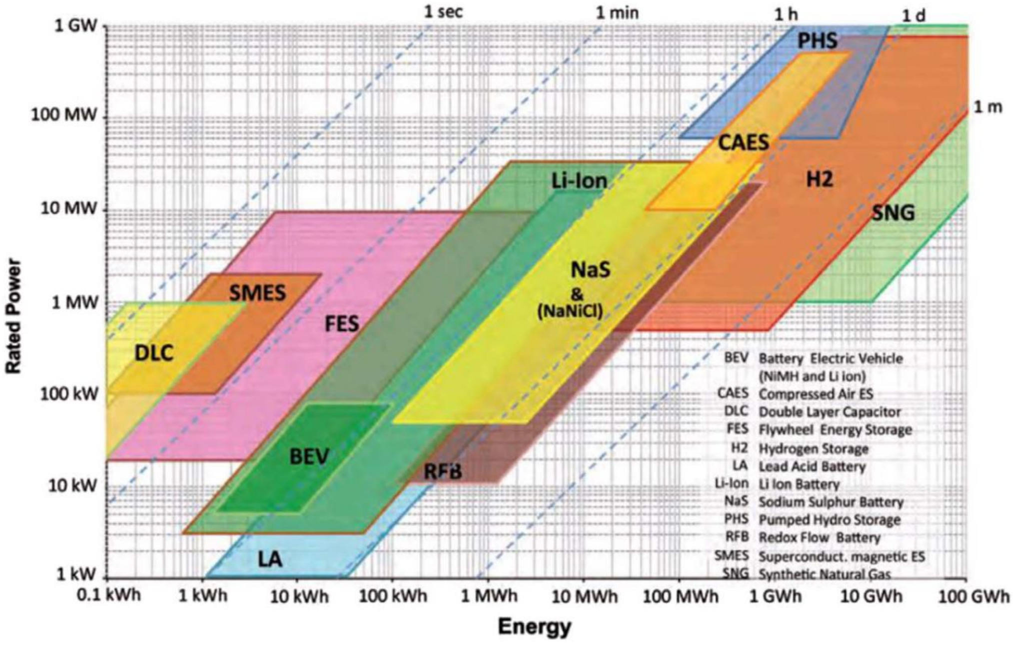


Figure 2.11: Energy content, power rating and typical discharge time for different technologies [51]

2.2.5 Thermal Energy Storage

The last storage type is thermal energy storage (TES). These systems store either heat or cold in a storage medium. They are suited for various industrial and residential purposes. These include process heating and cooling, hot water production, space heating and cooling as well as electricity generation. TES systems are divided into three categories: sensible, latent and thermochemical [51].

Sensible heat systems are the most common. These systems work by changing the temperature of the storage medium. However, the medium does not undergo a phase change and remains either solid or liquid. The performance of this type of system mainly depends on the density and specific heat of the material. The most common storage medium is water. With a high specific heat capacity, low price and wide availability, it is highly suitable for low temperature applications, e.g. space heating [47]. High temperature systems use other materials such as concrete, cast ceramics and molten salts [43]. These materials can reach temperatures hot enough to generate electricity and store energy over longer periods [47]. One application was mentioned in subsection 2.1.3. CSP can store the generated energy during the day to continue operation during hours without sunshine [26]. The systems come, however, with two main disadvantages. The first one is the size that is usually required as the energy density is generally low in comparison to other methods. The second one is the big temperature swings throughout operation, which can cause high stresses on the materials [47].

Latent heat systems are not characterized by a great temperature change. Instead they use the intrinsic energy of the phase change. Therefore, the materials used are called phase change materials (PCMs). The interest is caused by the high amounts of energy that lie in this phase change. For example, melting one kilogram of ice releases 333.5 kJ. To release the same amount of energy in a sensible heat water storage system, it would need a temperature difference of 80 K [61]. Besides the enthalpy at phase transition, material density also plays a major role for these types of systems. On the other hand, PCMs face problems regarding low thermal conductivity and the expansion during the phase change [47].

Thermochemical systems are separated into thermochemical reaction and sorption processes systems. The first type uses the heat to start a reversible endothermic chemical reaction. When the reaction is reversed, the energy can be retrieved again. Sorption involves a sorbate in form of a gas or vapor that is captured by a sorbent that is either solid or liquid. The term sorption includes absorption as well as adsorption. Absorption is when a liquid or gas enters another liquid or solid. Adsorption works by binding a gas on a surface of a solid or porous material. These processes can be reversed allowing to retrieve the injected thermal energy. However, as can be seen from Figure 2.9, the development is still in its early stages and serious efforts need to be undertaken to get thermochemical systems to the commercial state [40].

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Chapter 3

Portugal's Characteristics and Challenges

This chapter discusses the characteristics of Portugal. As every country has a different initial situation, each one of them needs to approach the transformation of its energy sector differently. Thus, the following sections discuss key aspects of Portugal that need to be considered to tailor the solution to its unique characteristics. At first, section 3.1 outlines the current situation in Portugal. It contains information about the electricity, the transport and the heating & cooling sector of Portugal, as they comprise the energy sector. Additionally, the section discusses Portugal's policies regarding energy. Section 3.2 covers the challenges Portugal is facing to convert its energy sector. Each sector is confronted with different issues that are discussed as well as the overall issues. Section 3.3 contains information about Portugal's technical potential for power generation of renewable resources.

3.1 Current Situation

As Figure 3.1 shows, Portugal is highly dependent on fuel imports to supply its energy sector as it has not produce fossil energy since 1994 when it ceased its coal production [62]. It only produces 5.90 Mtons of oil equivalent (toe) of its consumption of 15.51 Mtoe. Oil is the most important source of energy covering 42.7 % of Portugal's primary energy consumption [63].

This section serves to familiarize the reader with the current energy situation in Portugal. At first it explains the electricity sector that comprises a big part of the energy consumption. Afterwards, basic information about the transport sector is given. At last the third pillar of the energy sector – heating & cooling – is described in Portugal. The last subsection discusses the EU's and Portugal's policies that address the future challenges the energy sector is facing.

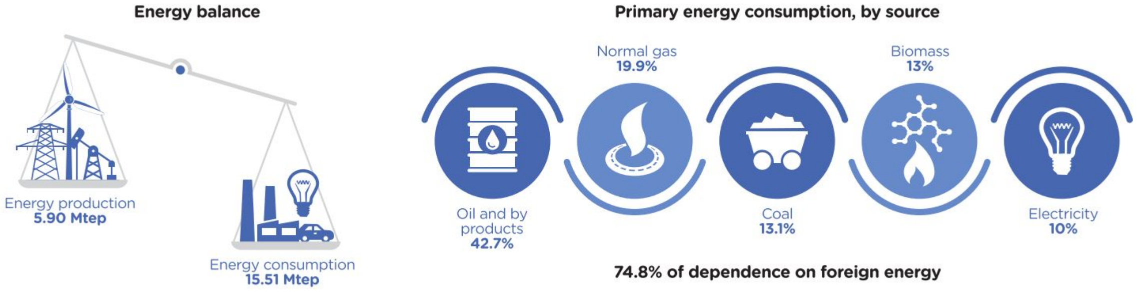


Figure 3.1: Energy production and consumption 2016 in Portugal [63]

3.1.1 Electricity

Since the 1990's the EU focused on making the electricity market more competitive. Thus, it published its first directive in 1996, which stated common rules for the domestic markets in Europe. It had the aim of creating truly competitive electricity markets and was since then extended by two more directives in 2003 and 2007. This meant that all aspects regarding energy – generation, distribution and retail – had to be separated as opposed to the previous monopolistic model [64]. To ensure the liberalization of the Portuguese market several institutions were created. The Energy Services Regulatory Authority (ERSE) is the national regulatory authority (NRA) for the electricity (and gas) sector. Its purpose is overseeing these sectors. Furthermore the Portuguese Competition Authority (AdC) exists to ensure that competition rules are not broken and the market remains liberalized and monopolies or oligarchies do not arise again [62]. As an example, the merger of Energy of Portugal (EDP) and Gas of Portugal (GDP) was prohibited in 2004 [65]. The Portuguese Environmental Agency (APA) proposes, develops and monitors public policies regarding the environment and sustainability. Furthermore, it manages the Portuguese Carbon Fund (FPC), which is a national financial instrument that participates in the carbon market. Through its regulation the meeting of national targets on climate change is ensured [62]. Nowadays, the generation part is open to competition while the retail market is continuously decreasing administrative burdens to increase the amount of participants [66]. Regulated tariffs have ended since 2018 attracting new retail companies. The transmission system operator (TSO) and the distribution system operators (DSOs) have been unbundled and privatized [62]. Since 2001 Portugal and Spain had been in talks to create an Iberian pool for electricity wholesale trade. Interconnections were expanded to reduce the constraints and regulations were harmonized between the two countries. This led to the creation of Iberian Electricity Market (MIBEL) in 2007 [67]. Besides simplifying the trade between Portugal and Spain its purpose is also easing the integration of the Iberian electricity sector into the European market [64].

Generation

Portugal's electrification started with the construction of the coal-fired power plant Central Tejo in 1909 [68]. Until 1950 the evolution of the installed capacity was very slow, as can be observed in Figure 3.2. Afterwards, hydropower became the major source of electricity with its installed capacity rising from 164 MW in 1950 to 1,408 MW in 1960 alone, while thermoelectric power plants continued to

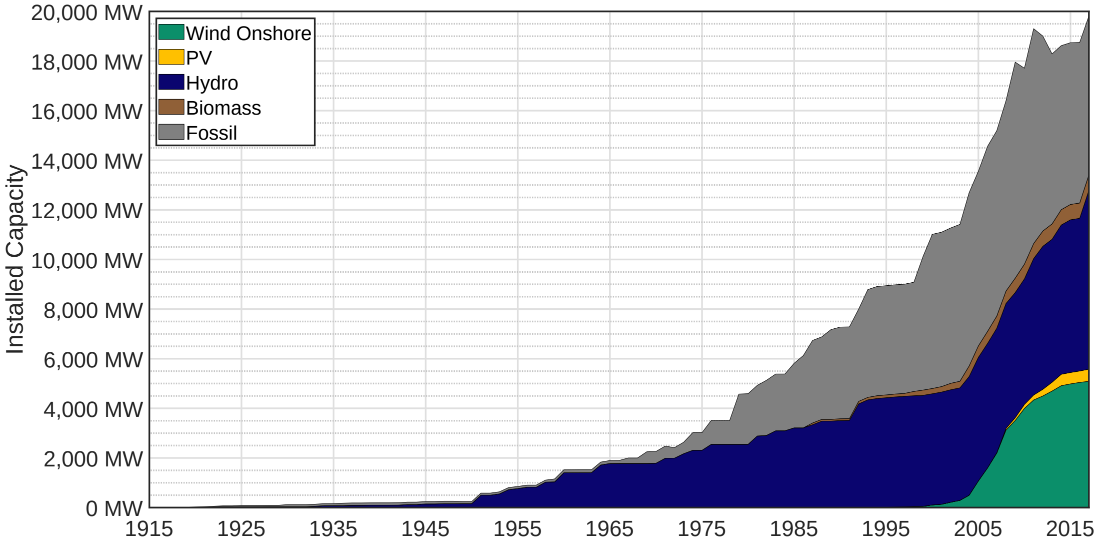


Figure 3.2: Installed capacity in Portugal 1915 – 2017 [17, 69–76]

play only a minor role. In 1966 the share of hydropower reached its peak, making up almost 94 % of the installed capacity. The following decades saw a sharp increase in fossil generation capacity [69]. In the 1990's gas-fired power plants were introduced in Portugal [67]. Nowadays, they have almost completely substituted coal-fired plants constituting for 72 % of the fossil installed capacity [17]. The next change came with the uprising of other forms of RE especially wind power around 2004 [69]. In 2017 all types of RE generation had a share of 68 % of the total installed capacity and 40 % of the generated electricity [17].

Portugal has two mechanisms to compensate producers for their generated electricity. There is the ordinary production regime (PRO) and the special production regime (PRE). The PRO is comprised of traditional fossil power generation and large hydro-plants [77]. Since the implementation of MIBEL 2007 generation in the PRO has been liberalized and plants offer their production on a common Iberian energy platform. Before that the plants were operated centralized by National Power Networks (REN) [78]. The plants that are operated under the PRE need to use either cogeneration or renewable sources to be admitted. As long as a plant under PRE fulfills the technical and security requirements, it can sell all of its energy to the last resource company – in Portugal this is EDP Serviço Universal S.A. – which is obligated to purchase it regardless. This company sells all of the electricity on the Iberian marketplace OMIE. Independently from the obtained price on the market the PRE producers receive a fixed feed-in tariff [77]. The payment period varies for the different technologies from 12 to 25 years [79].

From a macro perspective it can be said that Portugal's ongoing transition towards RE generation outweighs the financial drawbacks. Figure 3.3 compares the costs and benefits of this transition in the period from 2010 to 2017. While the costs for the compensation of electricity production amounted to 6,527 M€ the benefits totaled 13,164 M€. Thus, Portugal's decision to move towards renewable energy created a surplus of 6,637 M€ [80].

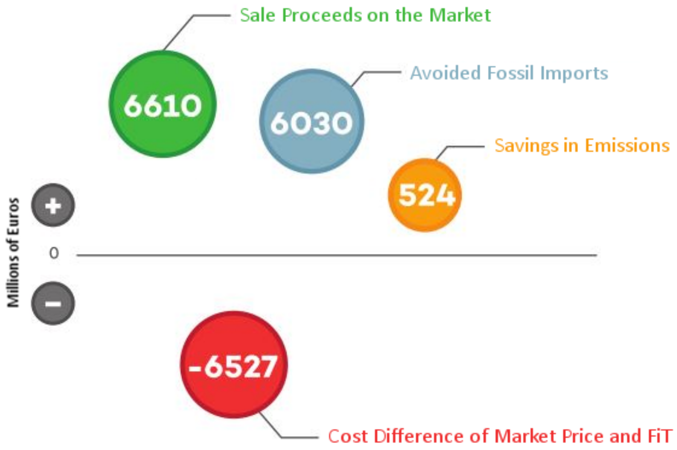


Figure 3.3: Comparison of costs vs benefits of renewable power generation (2010 – 2017) [80]

Transmission & Distribution

The grid is the connection between the power generator and consumer, as shown in Figure 3.4. Historically it was built in a top-down approach with very few big power plants feeding into the grid at high voltage levels. The electricity is transported to the customers, while the voltage is lowered to allow a secure usage of the electricity [81]. The distribution of the electricity is divided into transmission and distribution grid. The transmission grid's purpose is the long-distance transport of electricity and works at high voltage levels between 150 and 400 kV. The distribution grid delivers the electricity to the end user at lower voltage levels. The transmission grid is operated by the TSO that is responsible for the planning, implementation and operation. The concession was granted to REN in 2006. Just like the transmission, the distribution grid is operated by one company. Currently, the concession is held by EDP Distribuição. The operators are compensated via tariffs. The tariffs are mainly allocated by the Portuguese government [62].

The European Commission's goal is the establishment of a single European energy market. To overcome difficulties in the integration process the European Regulators' Group for Electricity and Gas (ERGEG) created regional electricity markets as an interim step. Portugal is part of the South-West Region, which consists of Portugal, Spain and France [64]. Interconnection between those countries is key to facilitate the integration across borders and to guarantee a smooth operation of the MIBEL [82]. Portugal's interconnection with Spain is currently between 2,700 and 3,600 MW. This fluctuation is caused by air temperature and other environmental factors that influence the total capacity [83]. As increasing the interconnections' capacity is seen as the best path to increase overall efficiency for small markets such as the Portuguese [67], it is planned to expand capacities in the future [83].

Consumption

Full legal opening of the market was achieved in 2004 after the process of liberalization was initiated in the 1990's. Since 2006 every electricity consumer can choose their electricity provider. At first, the market was still highly concentrated [84]. However, when the government announced the phasing out

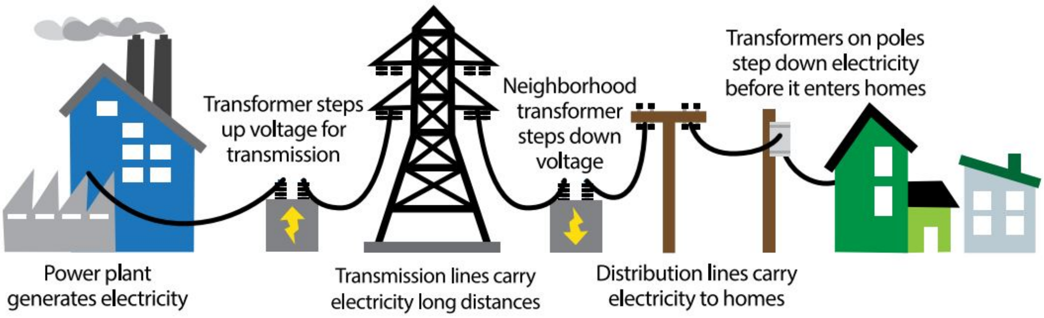


Figure 3.4: The role of the grid in the electricity system [81]

of regulated tariffs for residential customers in 2012, consumers started to switch to the new liberalized suppliers. This led to a higher diversity and by 2013 liberalized suppliers had a market share of 73 % of the total consumption. By the end of 2020 the regulated market will be completely eliminated and prices are solely determined by suppliers and not as previously done by ERSE [85].

Currently, there are 14 suppliers available in the Portuguese market [86]. The biggest retailer, EDP Comercial, arose from the former Portuguese company that was the supplier when the market was still regulated [66]. As many customers did not switch to another liberalized supplier, EDP's market share in the electricity market is over 87 % [87]. In Portugal there are two cost components constituting the electricity bill. The first one is a fixed price for the contracted power per month. The consumer can use not more than the contracted power. However, it is always possible to choose a higher power level. The second is a price that is paid for every consumed kWh of electricity. There exist three different types of tariffs for the consumption of electricity. They are split in a simple, a bi-hourly and a tri-hourly tariff. The simple tariff charges the same price for every hour per day. The other two tariffs make a distinction not only between at which hour the electricity is consumed but also at which day and which season [88]. For the sake of simplicity Figure 3.5 only shows the costs for weekdays in summer. It is observable that both varying tariffs have higher prices during the day when demand is higher, while prices are lower at night. Especially the tri-hourly tariff follows the current demand pattern. The purpose of these tariff types is to lower the peak power demand by incentivising consumers to move their high power and electricity demands to more favorable hours where demand is low and production high [89].

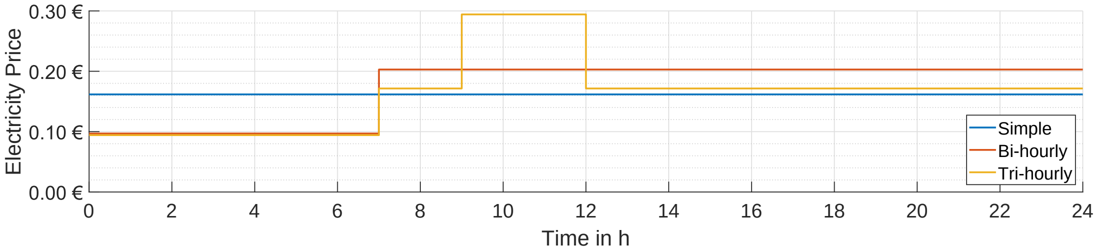


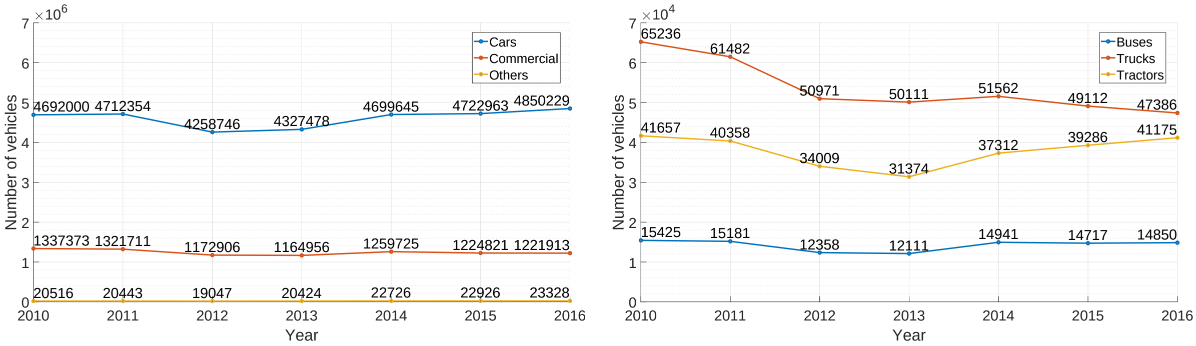
Figure 3.5: Electricity tariffs on a weekday in summer in Portugal by EDP [88, 89]

3.1.2 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 [90]. As Portugal imports 99.8 % of its oil, it exposes the sector to variations of the international fuel prices [91]. 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. Figure 3.6 shows the evolution of the Portuguese vehicle stock since 2010. As can be seen in Figure 3.6a, the market for light-duty vehicles has remained steady. The number of cars shows a dent in the years 2012 and 2013, which can be attributed to the economic crisis. Overall the amount of cars grew by only 3 %, which suggests that the Portuguese market is saturated. For commercial vehicles, the same behavior can be observed. However, the market did not fully recover and numbers have dropped by 9 %. Other types of light-duty vehicles, like motorcycles, play almost no role in Portugal. Despite a growth of 13 % in the 6 years, there were only 23,328 vehicles circulating by 2016. The same dent that can be seen in Figure 3.6a is also visible in Figure 3.6b for the heavy-duty vehicle market. However, the heavy-duty vehicle numbers have not recovered completely yet. Buses and trucks dropped by 4 and 27 %, respectively [92].

The individual transport makes up 89.4 % of passenger transport, while road and railroad transport are only moving 6.4 % and 4.2 % of the passengers in Portugal, respectively. Thus, individual transport is considerably more important than on average in the EU with 83.1 %. Unlike other countries, such as Norway and the Netherlands, the market of electric vehicles (EVs) is still in its early stages. By 2016 only 4.838 EVs and hybrid vehicles had been sold in Portugal [63]. However, the market is starting to grow as in 2017 alone 4.237 electrically powered cars were sold [93]. Currently, there are 521 charging stations available in mainland Portugal and Madeira [94].

Transport of goods is exclusively done via roads and railways, while water ways and airplanes are not used in contrast to other European countries. With 92.2 %, trucks dominate the transportation sector in Portugal and are much more relevant than they are on average in the EU with only 75.8 %. The small rest of the transport sector is conducted via railways, namely 7.8 %, which is lower than the EU average of 17.9 %. This constellation leads to a slightly higher energy intensity, however, the GHG emissions are still lower than the EU average [63].



(a) Light-duty vehicles

(b) Heavy-duty vehicles

Figure 3.6: Number of vehicles in Portugal sorted by type [92]

Table 3.1: Share of different means of transport of the final energy use in 2016 [95]

Means of Transportation	**ktoe**	**TWh**	**Share**
Light-duty vehicles	4.068	47,3	60%
Cars	2.945	34,2	44%
Motorcycles	44	0,5	1%
Commercial	1.078	12,5	16%
Heavy-duty vehicles	1.267	14,7	19%
Bus	182	2,1	3%
Trucks	1.085	12,6	16%
Railway	42	0,5	1%
Air traffic	1.274	14,8	19%
Domestic	135	1,6	2%
International	1.139	13,2	17%
Inland navigation	90	1,0	1%
Sum	**6.740**	**78,4**	**100%**

Given the dominating role of trucks in the transport sector, it is no surprise that they use the second most energy closely followed by commercial light-duty vehicles, as shown in Table 3.1. Please note that due to statistical differences between the sources, the total consumption is slightly different in Table 3.1 and Table 3.2. However, this difference accounts for less than 0.5 % and is therefore negligible. Cars, and thus individual transport, still make the biggest share at 44 %. Combined, light-duty and heavy-duty vehicles alone are responsible for 79 % of the total and 95 % of the domestic final energy consumption in the transport sector. Of the remaining sectors only the international air traffic has a significant impact with 17 %. The remaining means of transportation, motorcycles, buses, railway, domestic air traffic and inland navigation share a mere 8 %.

As can be seen in Table 3.2, only 4 % of the final energy consumption are covered by renewable sources. These sources are mainly biogenic fuels. Additionally, 57 % of the electricity that was also produced in 2016 in Portugal was renewable. This share has not been added to the renewables. However, since the overall share of electricity in the transport sector is below 0.5 %, the impact is negligible. The main sources are still fossil fuels with a share of 95 %. Diesel is the main source of energy with 59 % percent. This is due to the fact that vehicles for long distance like trucks and buses almost exclusively use diesel. Additionally, 54 % of Portuguese cars are diesel powered. Other sources like liquefied petroleum gas (LPG) account for only 1 %. In total Portugal's transport sector used more than 78 TWh in 2016 [96].

Table 3.2: Share of different energy sources of the final energy consumption in the transport sector in 2016 [96, 97]

Energy source	**ktoe**	**TWh**	**Share**
Fossil fuels	6.377	74,2	95%
Gasoline	1.140	13,3	17%
Diesel	3.964	46,1	59%
Jet fuel	1.273	14,8	19%
Renewable fuels	274	3,2	4%
Electricity	33	0,4	0%
Others	89,2	1,0	1%
Sum	**6.773**	**78,8**	**100%**

3.1.3 Heating & Cooling

Due to its favorable geographical position, Portugal has had traditionally low demands for heating and cooling [98, 99]. However, due to the low demands, housing insulation was long neglected in the building sector [100]. This results in low energy efficiencies in Portugal's housing sector. Despite the fact that central heating has grown from 5 % [101] to slightly above 10 % between the years 2001 and 2011, it remains at a very low level. The majority instead is heated with individual heaters that are mainly powered by electricity and wood. As can be seen in Figure 3.7, 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 % [102]. Cooling is done exclusively via electricity. However, it plays a marginal role so far in the Portuguese energy system [103].

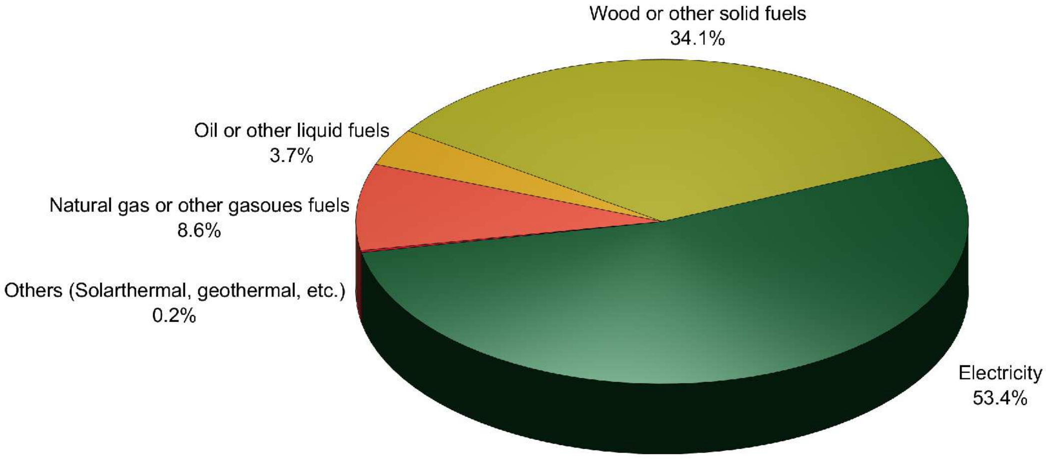


Figure 3.7: Types of heating systems in Portugal 2011 [102]

Portugal has introduced an energy performance certificate (EPC) system, which is supervised by Energy Agency (ADENE). So far almost 1.5 million of the Portuguese real estate properties have been certificated by energy experts [104]. The EPC records among others equipment, lighting, window and insulation efficiency, green heating and energy management systems. Therefore, it has a holistic view of the energy consumption of buildings and is not limited to heating and cooling. Additionally, it contains recommendations for energy savings and the according payback periods [105]. All certificates are uploaded to the platform casA+ to allow access to the findings for stakeholders. Based on the results, ADENE evaluates which measures are the most effective to increase the energy efficiency in Portuguese homes [106].

Figure 3.8 shows the results of the EPC system regarding energy efficiency of Portuguese buildings. For the existing building stock, it can be observed that the majority is energy inefficient. 82.5 % have a rating of C or worse. On average existing buildings in Portugal have a low C grade. New buildings show much better values. In contrast, only 17.8 % of the existing buildings have a grade of B- or higher. For new buildings all of them are a B- or better. This is due to the fact that new buildings are simply not allowed to be less efficient than a B-. Existing buildings have to have a rating of at least C when they undergo major renovations [107].

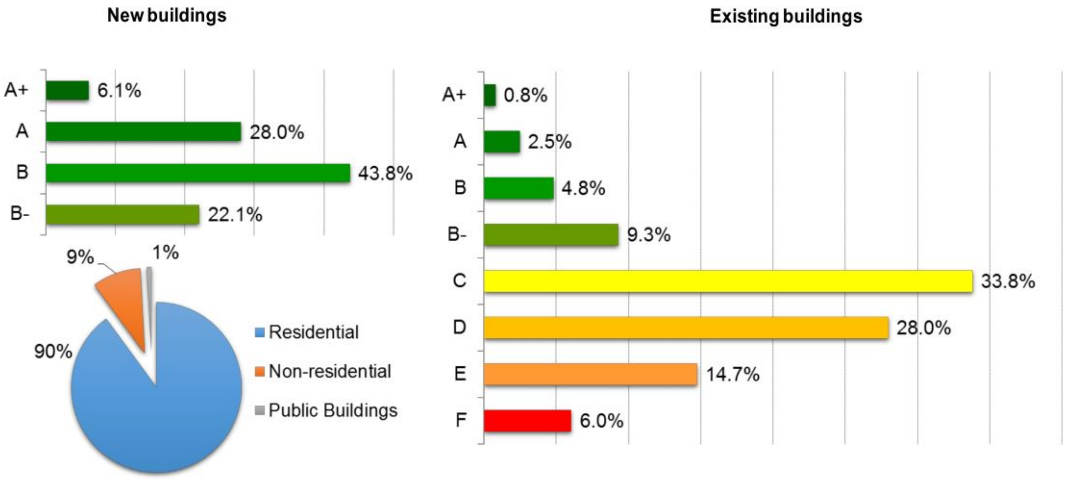


Figure 3.8: Current situation of the dwelling stock and new buildings [107]

3.1.4 Policies

The need to decarbonize the energy industry has been recognized in the EU and ever since the Paris climate agreement in 2015 also worldwide. The measurements to achieve a greener Portuguese society are bundled under the Renewable Energy Directive, which established an overall policy [108]. The cornerstones of the European energy strategy are the reduction of GHG emissions, the increase of RE generation, the improvement of energy efficiency and the construction of interconnections. The achievement of these goals is measured in milestones, which are shown in Figure 3.9. The European Commission (EC) has released intermediate targets that need to be achieved on a European level in 2020, 2030 and 2040, respectively, to achieve the final goals for 2050 [109]. For GHG emissions the aim is to reduce the emissions by 80 to 95 % by 2050 in comparison to their levels in 1990 [110]. This is to be achieved by increasing the share of RE production throughout this time and other measures such as lower emissions of cars and other types of vehicles [111]. So far the latest point in time where a minimum share of RE is defined is 2030. In 2018 the goal for the share of renewable energy was increased from 27 % to 32 % [112]. Portugal has an even higher goal of 40 %. Targets for energy efficiency and interconnection capacity were also defined. In October 2014, the European Council agreed on a target of improving overall energy efficiency by at least 27 % by 2030 [113]. On 30 November 2016, the revised Renewable Energy Directive increased this goal to 30 % [114]. Several directives were passed to facilitate this efficiency increase. The Energy Performance of Buildings Directive regulates the energy efficiency in buildings. It specifies that member states need to state minimum energy performance requirements for existing and new buildings. Furthermore, they need to ensure that by 2021 all new buildings have to be nearly zero energy buildings (nZEBs). The Ecodesign Directive sets minimum energy efficiency requirements for products and appliances. The Energy Labelling Directive ensures that consumers can clearly evaluate the efficiency of energy-related products [115].

The ultimate goal of the EU is to establish an energy union. This would mean a fully connected European energy market, which improves energy efficiency and security [118]. Besides decreasing legislative hurdles between the countries, it is highly important to establish the physical interconnections of electricity. In

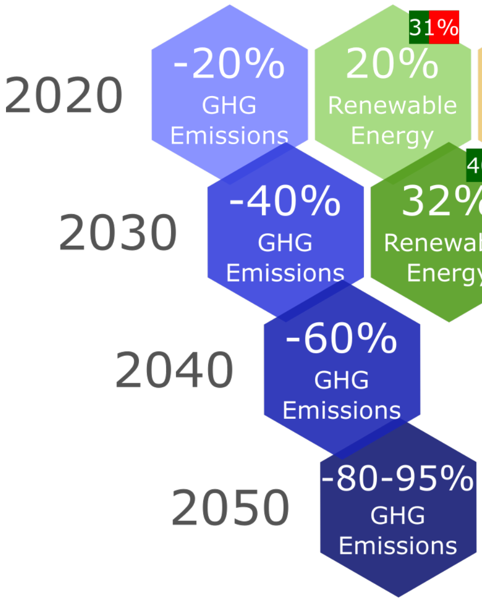


Figure 3.9: European (hexagons) and Portuguese (rectangles) milestones for 2020, 2030, 2040 and 2050 [109, 110, 112, 116, 117]

the past these interconnections were of low importance as countries tried to rely very little on neighboring countries. In light of the integration of the European countries into a united system, this is not the case anymore. Thus, the goal for 2030 is to build interconnection lines that can transfer 15 % of a country's generation capacity to neighboring countries [119].

As every EU country has different available resources, the obligations of the Renewable Energy Directive need to be adapted to the individual situation. To do so, Portugal introduced its own national action plans that explain how it wants to achieve their goals. After initially bundling all actions under the National Energy Strategy 2020 (NES2020), it was repealed and replaced by two action plans in 2013 [62]. The National Renewable Energy Action Plan (NREAP) and the National Energy Efficiency Action Plan (NEEAP) split the responsibilities in the areas of RE generation and efficiency. The NREAP contains several measures to promote different renewable technologies. Besides wind and solar power projects it also contains plans for the creation of a pilot zone for wave technologies. Portugal went beyond Europe's requirement of 20 % of RE by 2020 and aims at 31 % instead, as shown in Figure 3.9 [116]. Portugal's plan to achieve this share is by reaching 10 % of renewable energy in the transport sector, 30.6 % in heating & cooling and 60 % in the electricity sector [62]. The backbone of this RE electricity increase is the construction of new hydro power capacity under the National Program of Dams with High Hydroelectric Potential (PNBEH), which plans an installed capacity of 8940 MW [120] and the installation of 5,300 MW of wind capacity [116]. The NEEAP prompted the review of the national energy efficiency program and made it a policy priority. This led to several new laws for the efficiency of buildings, transport and the industry [107]. Once again Portugal established a more ambitious goal and instead of reducing its primary energy consumption to 20 % by 2020, it wants to reduce it by 25 % [117].

Portugal has already achieved its goal of 10 % of interconnection capacity of its generation capacity. By 2017 around 3,000 MW were installed for export of electricity to Spain [62]. With the currently installed generation capacity of 19,800 MW in 2017 [17], this represents 15.2 % and would therefore be sufficient for 2030's goal as well [109]. However, as the capacity increases in the future, interconnection capacities have to be increased as well to ensure that it remains above the 15 % requirement.

Traditionally, Portugal has been a technology "follower", meaning it adopts developed technologies from other countries instead of researching itself [121]. Currently, the expenditure for R&D as a ratio of the GDP is the lowest among the countries that are members of the International Energy Agency (IEA). In an effort to change that, the NES2020 contains commitments to create energy research in Portugal. Its aim is to spend 2.7 % of its GDP on R&D [122]. Some of the main projects are the development of a floating platform for offshore wind turbines and Mobi.E, which is Portugal's national electric mobility network promoting e-mobility [62].

3.2 Challenges

Portugal is in 5th position when it comes to the RE share in the EU. However, at 28.5 % in 2016 this means that even the best of Europe's green countries have many challenges ahead until a 100 % renewable energy sector is achieved [63]. Fortunately, the public has a positive attitude towards renewable energy and does not need convincing [123]. Nonetheless, there are many issues that are still in the way. This section discusses the main challenges that countries, which want to transform their energy sector in general and Portugal specifically, are facing.

3.2.1 Integration of Renewable Electricity

In the current system most of the energy that is used, is stored chemically in oil, gas and coal. However, besides biomass, which is another chemical form of storage, all forms of renewable energy generation are electric. The disadvantage of electricity is that it is difficult to store. As Portugal's potential for biomass is too low to cover the country's energy demand, it is essential to deploy other forms of RE generation to cover the demand in a sustainable way [124]. This will lead to high penetrations of variable renewable technologies, in particular solar and wind, which makes the balancing of the grid more demanding. Therefore, it is crucial to find ways to deal with the issue of intermittency [125, 126].

To tackle the issue of increasing RE penetration, there are several measures that can influence the transition from a fossil to a sustainable energy system. As described in section 3.1.1 the grid has historically been very inflexible as the electricity was provided in a top-down approach with a few big fossil power stations feeding into the grid at high voltage levels and consumers using the electricity at lower voltage levels [81]. With the emergence of renewable technologies, this is changing. While large hydropower stations are still feeding into the grid at high voltage levels, the situation is different for wind and solar power. Wind parks and big solar parks usually feed into the grid at medium voltage levels. However, as consumers start installing solar panels at home, they are not only consuming but also producing energy, which is fed into the grid at consumer voltage levels, i.e. in Portugal 400 V [127]. This means that not only the point-of-entry changes but also the amount of generation sites. Thus the situation has become increasingly complicated with the introduction of RE generation [128]. This requires a grid that caters to the different characteristics of RE generation and is far more flexible – the so-called smart grid [129].

Despite its complexity, the current grid is built very simply given the size of its task. Distributors know very little about the consumption and their main goal is to secure a stable power production that covers the demand. As very little instrumentation is installed below the level of the substations, it is highly difficult to asses the state of the network for the operators. It was standard that power outages were usually only determined by customer calls. Due to the uni-directional power flow and the *n+1* rule, which meant that the networked was over-provisioned at twice the capacity of peak demand, this level of knowledge used to be sufficient. However, this approach is highly inefficient [127]. The smart grid builds on the old grid but uses digital technology to bring it into the digital age. To do so it uses interconnected components, e.g. smart meters, that allow the communication between all participants of the energy sector. Thus creating a two-way communication opposed to the previous uni-directional [81]. Due to this increase in knowledge it is now possible to monitor the grid and thus optimize its operation [130] as well as enable the large scale integration of distributed power generation [131].

A big novelty in this system is the possibility of demand-side management (DSM). Before the smart grid, electricity suppliers were only able to ensure grid stability by adjusting the power generation. With DSM they are also able to adjust the demand when an increase in supply is not possible. Figure 3.10 shows how powerful DSM can be in the future to increase grid efficiency and lower peak demand. The methods can be categorized into three different approaches: reducing, increasing and rescheduling [42].

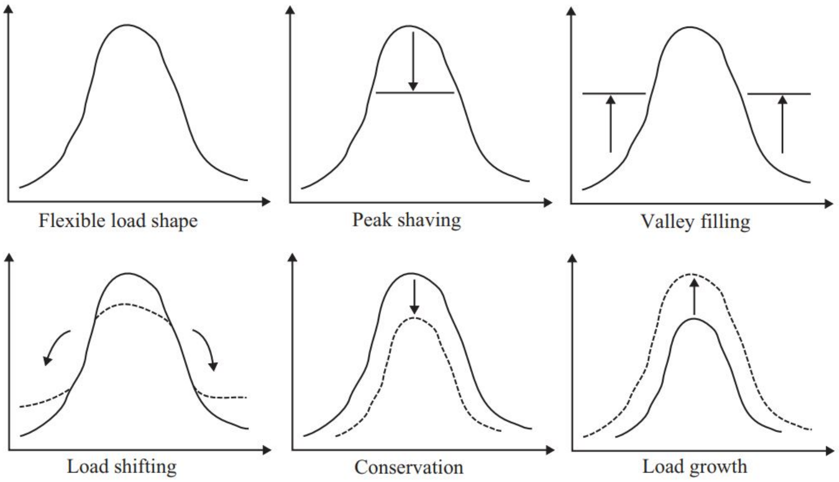
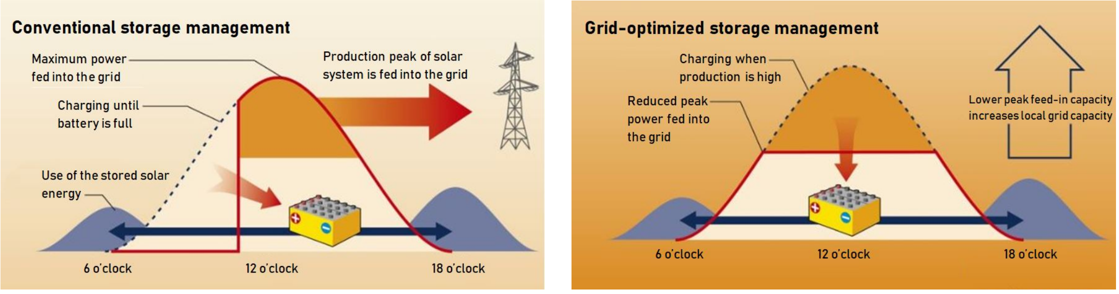


Figure 3.10: Types of demand-side management [42]

Peak-shaving and conservation are reduction approaches. Peak shaving allows to lower the peak demand and therefore lower the need of maximum installed capacity of the grid [42]. An example of this can also be found on the generation side in the residential sector when PV systems and battery storage are combined. On a sunny day, when the generation of the PV panels surpasses the demand, the battery can be charged in two ways, shown in Figure 3.11. The outdated approach is to simply charge the battery until it is full. However, this might become a problem, if the battery is already full before maximum



(a) Conventional storage management (b) Grid-optimized storage management

Figure 3.11: Mechanism of peak-shaving for PV generation [134]

power generation is reached. If the battery is full before noon and the electricity demand is still low, the PV system will feed electricity at very high power levels into the grid, as shown in Figure 3.11a. If many systems do this in the same area, the power lines can be out of capacity. However, there is a second "intelligent" approach, as depicted in Figure 3.11b. Instead of charging the battery as soon as excess electricity is generated, the charging time can be moved to times when the output power is at higher levels thus lowering the fed in maximum power into the grid. This would allow to install more PV systems in a grid at the same capacity [132]. Governments have already tapped into this resource. The Reconstruction Loan Corporation (KfW) is a government-owned development bank in Germany. It offers low interest-rate loans for storage systems as long as the PV system never feeds more power into the grid than half of the installed peak power [133]. Thus, twice the solar power can be installed with the same grid capacity. The battery storage can be twice beneficial because it can not only lower PV production peaks but also demand peaks, by supplying power when demand is very high and therefore once again, lowering the grid capacity demand. Conservation, on the other hand, is the overall decrease of the energy demand when the supply is rather low, e.g. because wind and solar resources are currently low. At this point flexible loads come into play. Flexible loads are systems that do not always need to run and can react to the current supply. An example would be cold-storage warehouses that can work within a temperature range. When the supply is low they can turn the cooling system off, thus lowering the load on the grid [42].

Load growth and valley filling fall into the category "increasing". Load growth is used when the production of variable renewable energy is very high but the demand is rather low. If the load is not increased, the electricity would need to be curtailed, creating losses. What is done instead, is to use the aforementioned flexible loads. However, this time they are activated. In the example of the cold-storage warehouse this means that the cooling system is turned back on, possibly at even higher power demand levels. Valley filling is the method of creating a more consistent load curve, which makes balancing easier. Taking the example of the warehouse, this would mean that the cooling system stays on, although it would normally be turned off, lowering the temperature further [42].

The last method is load shifting, which makes up the category "rescheduling". Once again flexible loads are employed. Throughout the day there are demand peaks and valleys. However, this causes a strain on the system as rapid demand changes need to be addressed. The loads that are not crucial to be working during peak hours, can be scheduled during off-peak hours [42]. It becomes obvious that DSM can benefit the system tremendously as it reacts to changes on both the generation as well as the consumption side. However, this also shows how a smart grid with communication devices on both ends, such as smart meters, are essential to control not only supply but also demand [127].

Another way of easing the impact of variable production on the electricity system and increasing the value of renewable power generation, is by improving the forecast of its output [135]. This is especially necessary for smaller electricity grids, where only a few variable plants comprise the system, such as Portugal's islands [136]. For grids with many plants, this is a smaller issue due to the aggregational effect, which smoothens the output curves [9]. The forecast algorithms are constantly improved to correctly predict varying power generation upfront [137]. Nowadays, especially day-ahead solar forecasting is quite accurate but there is still more research necessary, specifically for wind forecasts [138].

Besides improving the national grid, it is also of high importance to strengthen Portugal's interconnection with Spain. The advantage is that the system becomes more efficient, which reduces the costs to meet national electricity demands as less generation capacity needs to be installed. Instead, during a day of low variable generation, the electricity can be imported from other European countries and vice versa on a productive day [119]. By 2050 Portugal needs an interconnection capacity between 4 [139] and 6 GW [140], as seen by experts. However, due to its geographical position, Portugal does not only depend on its own interconnections but also on the interconnections of other countries as it lies at the outskirts of Europe. Currently, Portugal and Spain are well connected, while the connection from Spain to France is insufficient at only 1.70 to 3.05 GW [141]. With less than 3 % of Spain's generation capacity [142], this means that the Iberian peninsula is practically shut off from the rest of the European electricity market [82]. Although plans are already in course to add 2 GW, thus increasing its capacity to 5 GW [143], it is still very low in comparison to the size of the electricity markets of the two respective countries [82]. The minimum capacity demanded by the EU by 2020 is 10 GW [144] and experts assess the needed capacity for 2050 to be between 17 [139] and 30 GW [140]. Thus Portugal has highly vested interests in ensuring the increase of the interconnection capacity between France and Spain [82].

Energy storage can help significantly to facilitate the integration of large amounts of non-dispatchable RE generation capacities. As they can be seen as flexible loads but also generation, they can provide many of the previously described DSM services and more [145]. Portugal has traditionally high capabilities in hydropower storage due to its many dammed power plants. However, it is not certain, if it is able to fulfill all the requirements that will be asked from energy storage in the future. Portugal will need to find other ways of low-cost storage solutions. On top of that, not only the capacity but also its efficient integration into the energy system plays a crucial role [4]. This starts at the residential levels with people combining their PV system with a battery storage that saves the energy generated during the day to give it off in the evening when dwellers are home again. If many Portuguese homes installed both PV panels and a storage systems, large amounts of flexible capacity would be created that enable a more agile grid while lowering the need for grid capacity expansions [56]. Ultimately, the integration into an overall smart energy system, which is described in more detail in subsection 3.2.5, is crucial. Such a grid combines all sectors to ensure that energy storage is used efficiently since it is a costly factor [4]. Therefore, research is also conducted in the direction of curtailment vs. storage, meaning that instead of installing more storage, more generation capacity is installed and the surplus electricity is not used at all but instead simply curtailed [146].

As the RE generation technologies will change the way electricity is produced, the electricity market will have to change with it. One issue is caused by the fact that renewable generation sources such as wind and solar have almost no operating costs. This will drive electricity prices down on the wholesale spot market, known as the merit-order effect. Since the investment costs are high for these technologies, other forms of compensation need to be found to ensure their economic operation, especially if feed-in tariffs are to be faded out. Additionally, price volatility is likely to increase creating a bigger need for balancing services. This is especially a problem for countries that have very inflexible generation matrices, such as Germany where slow nuclear, lignite and coal power plants prevail instead of gas power plants. Furthermore, intra-day trading will play a more significant role, especially when forecasting of RE is imprecise [42]. Overall short term markets will increase in importance to the electricity system and will need to become even more flexible. Another issue is that national markets are still thinking in their old pattern of having a closed of grid, putting their interests first, without thinking about the influence that decisions have on neighboring countries. This will become a bigger issue when the interconnections are expanded and needs to be addressed to achieve the ultimate goal of creating an energy union across Europe [147].

Changes are not only to be made to the wholesale but also the retail market. System flexibility is often perceived as a technical issue, however, it also highly depends on the market design. For example, flexible energy tariffs, such as Portugal's bi- and tri-hourly tariffs, are already a start into the direction of having different prices for different times of demand. New tariffs can not only be time but also location dependent to alleviate congestion in specific points in the grid [42]. On top of that many consumers will become so-called prosumers with solar panels on their roofs. Prosumers not only consume electricity but also produce electricity, which they feed into the grid. This allows for new retail methods to incorporate their own generation systems into the market [147]. First projects have already emerged in Portugal, such as *Shar-Q*. *Shar-Q* is a project that investigates how peer-to-peer (P2P) electricity sharing can be achieved. This changes the energy suppliers duties, as shown in Figure 3.12. Instead of providing the energy that it has bought on the electricity market, it distributes the energy created in its own district like an intermediary and only buys energy when there is too little generated [148]. Versions of this concept do already exist in other countries such as Germany where *buzzn* operates since 2010 [149]. It becomes obvious that there are many challenges to come to create a market design that is prepared for the introduction of RE generation capacities on a large-scale that are also efficiently integrated into the system [150].

All these measures will help to increase the amount of renewable energy in the electricity mix. However, this can only happen if the basics are covered. This means that as a technology follower country, Portugal needs to adapt and implement new technologies quickly [152]. A good example that Portugal is capable

Figure 3.12: The future role of an energy provider in the concept of Shar-Q [151]

of doing so, is the wind sector, where Portugal reached maturity within only seven years. This is only about half the time that it took Denmark, which is one of the countries driving wind research [153]. However, other factors besides a quick introduction of new technologies to the Portuguese market also play a vital role. Construction concessions of new wind and solar parks, need to be processed quickly and afterwards connected to the grid. This is an issue that Portugal is lacking behind, especially in the solar sector with more than 8,000 MVA waiting to be approved [154].

3.2.2 Transportation Transformation

With a final energy consumption of 78.8 TWh in 2016 the transport sector even surpasses the electricity sector, which had a national consumption of 49.3 TWh, by 60 % [155]. This figure shows the great effort that the transport sector is facing to turn itself green. Currently, the main supply stems from fossil sources, mainly diesel and petroleum [156]. To replace these two sources of energy alone with biofuels grown in Portugal, the necessary land required would be 49 % of Portugal's land mass [157]. Presently, the agriculturally used land occupies more than 3.6 million hectares, which represents only 39 % of Portugal's land [158]. Assuming that one hectare produces 1,500 l of oil [157] and all land could be converted to grow fuel crops, the entire agricultural land could only produce enough to satisfy the consumption of road traffic, which lies at 62 TWh [96]. Apart from the tremendous effort to change the whole agricultural sector and the fact that not all farm land is suitable to grow fuel crops, this would bring the entire Portuguese food industry to a halt and Portugal would entirely rely on imports to feed its population. This example shows that organically produced fuels are not suitable to be used to a large extent to cover the need for fuel in the future in Portugal. Instead they will only play a minor part.

The fuel for the transport sector will have to come mainly from electricity in the future. Several technologies are available. The first one would be to produce liquid or gaseous fuels via P2L or P2G that is then used in conventional internal combustion engines (ICEs). More innovative technologies are hydrogen vehicles and battery electric vehicles (BEVs). Hydrogen vehicles also use a gas, namely hydrogen that is produced via P2G, to power themselves. However, it is not burnt in a conventional ICE but in a fuel cell. BEVs on the other hand use the electricity directly, which is stored in batteries that are typically positioned at the bottom of the car. When looking at the efficiencies, which are shown in Figure 3.13,

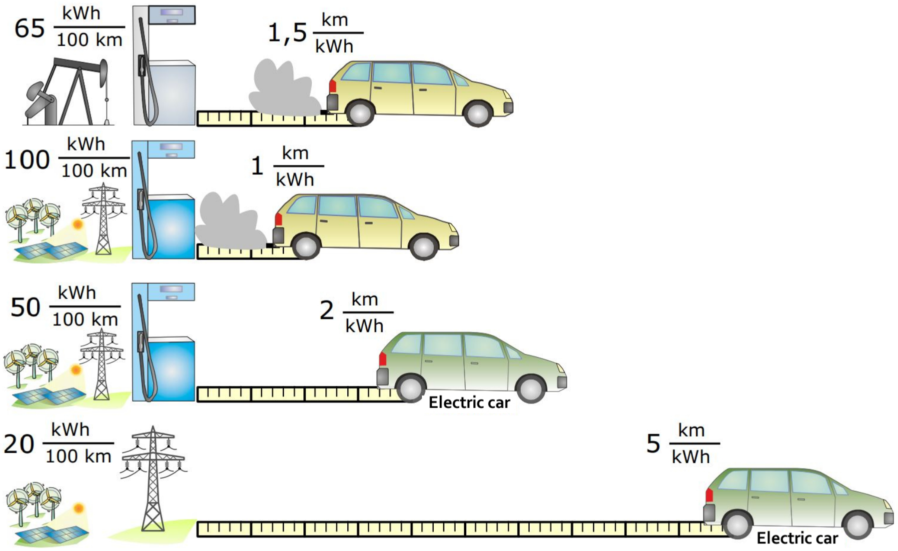


Figure 3.13: Comparison of the efficiency of a fossil fuel powered car with those of cars using P2L/P2G and an ICE, P2G and a fuel cell, and batteries [157]

it becomes evident that ICEs will be outdated in the future. To substitute all of the fossil fuels in road transport alone, it would require 93 TWh of electricity, around twice as much as Portugal consumed in 2016 in total. This shows that ICEs are obsolete and cannot play a major role in the future energy system. Instead fuel cells and battery-powered vehicles will be needed on a grand scale. As shown in Figure 3.13, especially BEVs are far more efficient in their energy use requiring less than a third of the energy of an ICE to drive the same distance, making them especially competitive for the future [157].

As light-duty vehicles will mainly need to be BEVs in the future and they make up 98 % of the domestic car pool [92], this will have a great effect on the charging infrastructure in the transport sector. The charging process is very different from that of petroleum or hydrogen powered vehicles. However, the most important aspect is that it takes longer in comparison to traditional cars. Even if BEVs could be charged at comparable speeds, it would require a lot of power. For example, to charge a BEV with a 100 kWh battery in 5 minutes it would require an average of 3,000 kW of power. This would require a much more powerful distribution grid to facilitate such type of recharging, let alone the strain that is exerted on the battery. Even current fast chargers only reach around 100 kW [159]. Although chargers will be more powerful in the future, the projections are that charging cars will be different in the future. The charging stations of the future will provide lower power levels but the vehicle is not charged when the tank is empty. Instead, the car will be charged whenever it is parked, which is most of the time. Thus, it is crucial for the Portuguese government to develop new charging concepts that adapt to the new infrastructure demands. Especially in the transitional period it is necessary to position the charging stations strategically well to cover the most area with the least charging stations, while still ensuring that BEVs find a charging spot [160]. This can also lead to new concepts such as parking lots that use solar panels for shading and charging simultaneously [161]. Additionally, this infrastructure needs to be built up within little time as the CO_2 emission thresholds for light-duty vehicles shrink quickly until 2030 in Europe [162].

These changes to the charging infrastructure need to be accompanied with a clear plan on the charging scheduling. Even if charging stations operate at low power levels, it would create a big burden on the electricity grid, if too many BEV were demanding power at the same time. At low BEV penetration levels this topic is still of low concern but it will become an important part of the energy system soon and therefore should be planned early on to be prepared [163]. However, there are also vast advantages of having a fleet of BEVs connected to the grid. The traditional approach is to charge the vehicles making the system a unidirectional grid-to-vehicle (G2V) approach. However, with the right hardware and software setup, this connection can work bidirectional. Vehicle-to-grid (V2G) means that the vehicle can also feed electricity back into the grid when it does not need it [164]. Smart G2V systems can already offer grid services like peak-shaving and valley-filling by charging during off-peak hours [165] or they can charge when there is an excess of power [166]. Vehicles capable of V2G can, however, also be used as a distributed energy storage system [167]. On top of that, V2G offers many grid services, such as active and reactive power support and more. Further benefits are among others that it reduces power grid losses and the possibility to integrate it into the DSM system described in subsection 3.2.1. However, to achieve this high level of sophistication, a complex hardware and software infrastructure needs yet to be built. Furthermore, the degradation of the batteries due to the additional use needs to be managed. A non-technical issue is that the social behavior needs to be adjusted to the new type of transportation system [168]. Nonetheless, overall BEVs and hydrogen cars are inevitable. As a result of their use the levels of air pollution can be strongly reduced. A topic that is especially significant in densely populated cities [169].

So far the section has mainly discussed light-duty vehicles. However, heavy-duty vehicles, trains, airplanes and ships also need to be powered by renewable sources. These underlie different characteristics that forbid it to apply the same concept that is used for light-duty vehicles [157]. While trucks and buses are also powered by an ICE, they have to cover bigger distances. This is currently still one of the biggest weaknesses of BEVs. As the energy density of batteries is low, they cannot drive as far as a fossil vehicles on one tank. As it is unclear how the technologies will evolve, it is likely that they require another source of energy besides batteries. An electric roadside solution can be one answer to this problem while still keeping efficiency high. The power can be transferred for example via catenary with overhead lines, similar to trains. Demonstration projects for different types of power transfer have already been conducted successfully. However, international standardization is key in this process [170]. While the transition for trucks and buses is still relatively simple, it is much more difficult to turn airplanes and ships green. One main difference is the product life cycle. While road vehicles have a lifetime of around 10 to 15 years, it is very different for airplanes and ships. Additionally, they cannot be easily powered by overhead lines or anything similar. Thus both, the transition speed as well as the technology to achieve this transition, are difficult factors. Portugal will need to find ways to replace the fossil fuels in both sectors. Ships for domestic use that use electric energy either via batteries or other means, like fuel cells, are already in use. Portugal needs to stimulate the replacement of fossil powered ships by these new technologies. Until then the fuel needs to be provided renewably, e.g. P2L and P2G can be used both for domestic and international navigation [171]. For airplanes it is similar, however, the technology is not as far as it is for ships. Battery powered planes are limited to light aircrafts. The difficulty lies in the fact that while ships can be heavy, aircrafts need to be as light as possible, making them the most difficult for battery use. Thus, it is most likely for airplanes to use fuel cells in the future. However, it will take more time for commercial airplanes to use hydrogen. Until then Portugal needs to create the infrastructure to produce enough renewable fuels, either from biomass or P2L [170]. In contrast, the transition for trains is very easy. Railways are almost completely electrified in Portugal nowadays and the goal simply needs to be to electrify the remaining ones, which is already happening [90].

Besides changing the way how different types of transport are powered, it is also necessary to shift the means of transports that are used. This means for freight transport to try to move goods that are constantly transported via trucks to trains or ships that are more efficient at transporting goods [172]. Portugal's Strategic Plan for Transport and Infrastructure (PETI3+) is working in that direction to use more environmentally friendly means of transport. For example, it aims to increase cargo by train by 40%. It is important that the country continues to pursue such goals. The same applies to passenger transportation. Alternatives to individual transport, especially in urban areas, are crucial in the future of the transport sector. Greater use of public transport and car-sharing, as well as better-functioning transport networks are essential [90]. It is clear that the transition in the transport sector will be difficult and have a fundamental impact on the energy sector. Portugal needs to tackle this issue proactively and soon to reach the first milestone of 10 % of renewable energy in this sector by 2020 [156].

3.2.3 Renewable Heating & Cooling

As discussed in subsection 3.1.3, Portugal is already mainly using renewable (biomass) or potentially renewable (electricity) energy sources for heating and cooling. Thus, the effort to transform the rest of the sector is rather small in comparison to most other European countries that mainly rely on fossil fuels to cover their heat demand. For example, district heating systems can relatively easily be changed to renewable systems as only the generation unit has to be changed. The pipeline network for the heat distribution remains the same. As cooling only relies on electricity, the transition is already done, as long as only renewable electricity is used [102]. Therefore, the crucial point in Portugal is not the transformation of the generation system but the increase in energy efficiency and consequently the decrease in the overall energy demand of the sector [107]. This becomes especially relevant as fuel poverty is still highly relevant in Portugal. On average 22 % of the inhabitants are fuel poor regarding space heating and 29 % regarding space cooling [173]. On top of that Portuguese households show a heating gap of 95 %, meaning they only use on average 5 % of the energy that is actually required to keep the house at the minimum temperature of 20 ℃. As a result, an increased energy efficiency is not only beneficial in decreasing the energy demand but also in increasing the life standard for the Portuguese population [100]. The following subsection 3.2.4 contains further challenges to the heating sector as it discusses the improvement of the thermal performance through an improved building infrastructure to increase the aforementioned energy efficiency.

3.2.4 Energy Efficiency

Energy efficiency is fundamental in the energy transition. Germany, for example, would see an increase in final electrical energy demand from around 600 TWh to over 3,100 TWh without efficiency measures. With moderate efficiency improvements the demand only rises to 1,300 TWh [157]. Many of the measures described in the previous sections already increase energy efficiency as a side-effect. For example, BEVs have a much higher efficiency than vehicles with an internal combustion engine. However, there are also direct measures that improve energy efficiency.

The most relevant factor is the improvement of the thermal performance of Portugal's dwellings. Despite the mild climate are the country's heating needs in absolute values still similar to those of countries with more severe winters [100]. As a result, the NEEAP includes thermal retrofitting as a cornerstone [107]. Portugal has set regulations for air-conditioning, heating and insulation for nZEBs. These regulations are mandatory for new buildings after 2020 [174]. Additionally, Portugal has launched a long-term national strategy to promote building renovation. Currently, the renovation rate is very low in the country. As new constructions have dropped significantly, it is key to increase the renovation rate [175] and ensure high thermal standards by increasing the requirements [176]. These regulations need to have in mind the changes that the Portuguese climate is facing to ensure adequate results, as current requirements of the building thermal code are not sufficient to prevent overheating. Consequently, they need to be revised and adjusted as this issue will grow in the future [177]. Many papers have been published that review this issue for different areas in Portugal [178–186]. Additionally, oversight measures need to be improved as they are currently not working well yet [106].

Besides that Portugal needs to ensure that the European directives, the Energy Efficiency Directive, the Ecodesign Directive and the Energy Labelling Directive are well implemented. These directives ensure that appliances become more efficient, thus, decreasing the energy demand. The Energy Labelling Directive ensures that the public is well informed about how efficient devices are to make responsible purchase decisions [115]. Currently Portugal's NEEAP lacks details in these areas. Therefore, Portugal needs to set clear and ambitious goals in the indirect and direct increase of energy efficiency in the public, residential, appliances, industrial and transport sector [187].

3.2.5 Smart Energy Systems

The transition of the energy sector needs to lead towards the creation of a so-called smart energy system. A smart energy system goes beyond a smart grid. A smart grid uses digital technologies, e.g. smart meters, to monitor and manage the distribution of electricity [62]. In contrast, a smart energy system takes a more holistic approach. It combines and includes the electricity sector with the heating & cooling, industry, buildings and transportation sector. Based on the smart grid, the smart energy system coordinates the utilization of RE for electricity as well as the conversion to other types such as heat and fuel. Additionally, it regulates other previously described measures, e.g. energy conservation and efficiency improvements [188]. This makes the whole system more efficient by using synergy effects instead

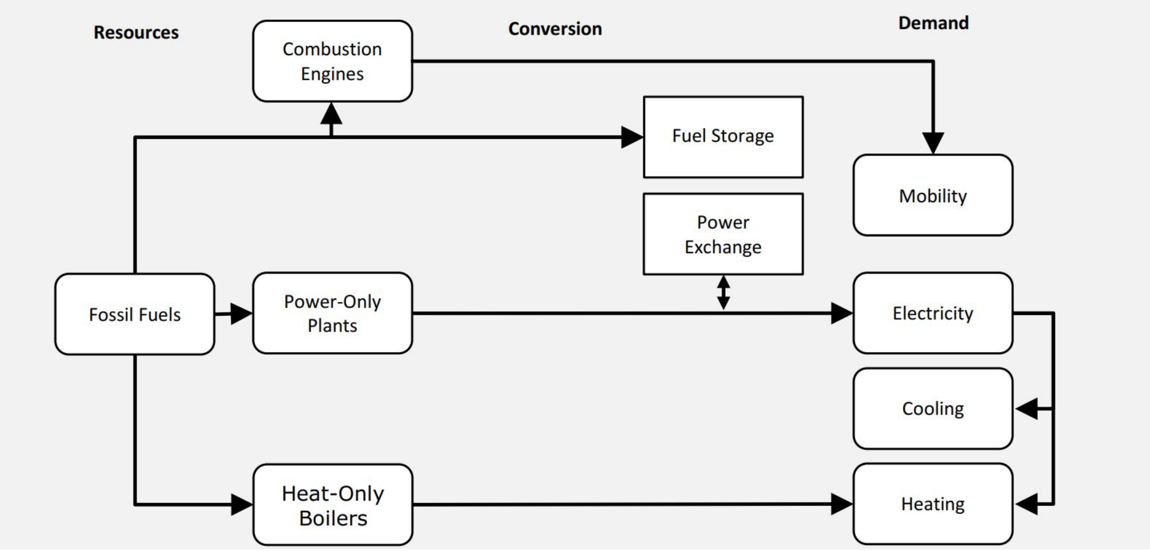


Figure 3.14: Interaction between sectors in the old fossil-based energy system [191]

of looking at each sector separately [189]. Some examples of these synergies are that electricity for heating & cooling can be used for balancing power demands or that electricity for vehicles is used to replace fuels and provide grid services [190]. An additional benefit is that the need for electricity storage, which is a high cost component in the future energy system, is reduced by replacing it with fuels that are made with excess electricity during time periods with surplus production [4].

However, creating a smart energy system means that the system becomes more complex. This becomes apparent when comparing the fossil-based energy system, that is the current state of the energy system, in Figure 3.14 and the future smart energy system, that the energy system is currently evolving into, in Figure 3.15. In the traditional system the interaction between the sectors is very limited. All of them rely on chemically-stored energy, such as oil and gas. These are then burnt for the conversion into either mechanical energy for transportation, electrical energy for the electricity sector or thermal energy for heating & cooling. The main interaction is that electricity could be used for heating & cooling as well. This ensured a simple yet inefficient and CO_2-intensive energy system [191].

The future energy system in Figure 3.15 is much more complex than that. The sectors are closely linked with each other while fossil fuel has completely disappeared as resource. Instead, it is replaced by biofuels, RE generation and renewable heat generation technologies. All of these technologies are carbon-neutral and therefore guarantee a sustainable energy sector. However, their downside is that most of them have varying outputs and thus are non-dispatchable generation technologies. As wind and sun cannot be adjusted to consumption needs, consumption needs to react more to the current production. This creates the need for technological changes in the overall system, of which the key changes are highlighted in blue in Figure 3.15. Besides the aforementioned generation part, it is mainly the conversion infrastructure that needs to become more flexible to incorporate high shares of variable generation systems. As can be clearly seen this complicates the system a lot, while also creating many synergy situations, with electricity becoming the main form of energy in the system [191].

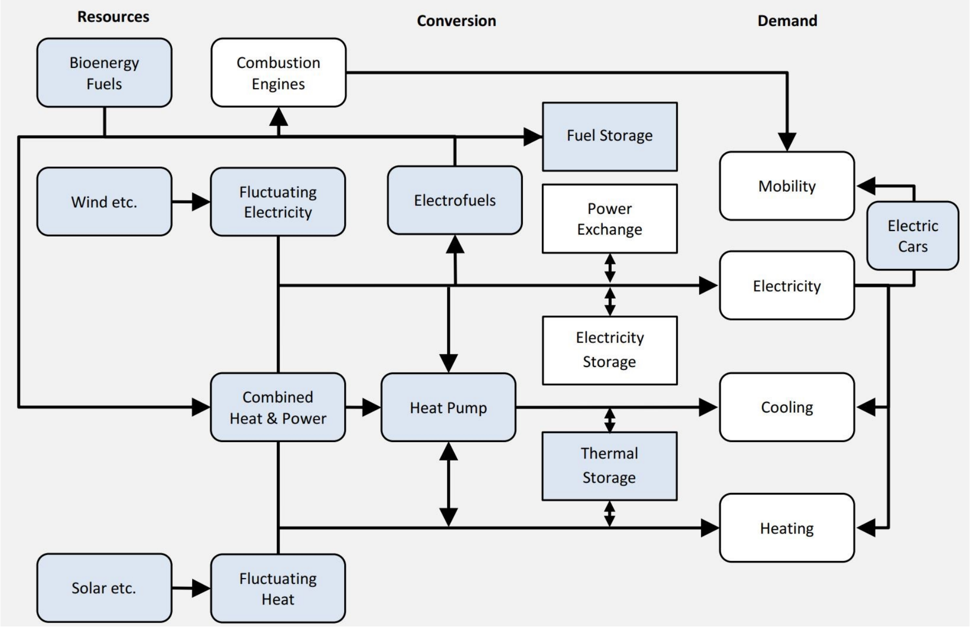


Figure 3.15: Interaction between sectors in smart energy system [191]

3.2.6 Policies

All these changes need the right legislative framework to accommodate the changes and motivate stakeholders to make the right decisions towards a future smart energy system [192]. This starts with an energy market that is designed to integrate large amounts of renewable energy in the future as the current market design is suboptimal [62]. Furthermore, Portugal needs to adjust their current compensation system for RE for the future.

The current feed-in tariff (FiT) system is working very well in the current situation and Portugal has among the lowest prices due to its clear and effective pricing structure [193]. However, in the future RE systems will make up the entire generation side. Therefore, new compensation models need to be created to adapt to the new market and make RE generators bear more responsibilities, such as grid stability, while still incentivizing new investments [194].

Another mechanism that ensures future investments is a carbon tax, which Portugal introduced in 2015 [195]. Carbon taxes have a very high potential in creating a favorable environment to decrease GHG emissions [196]. However, the current Portuguese system needs to be restructured to work correctly. Suggestions on how to restructure the system already exist and need to be implemented soon to ensure lower carbon emissions, higher employment and an increased GDP [195].

Another area that needs to be revised are the efficiency regulations as the current version is unlikely to achieve Portugal's set targets [197]. A long-term strategy is barely mentioned in the NEEAP and needs to built. While the structure of energy agencies exists at all governmental levels, the monitoring of efficiency measures needs to be clearly structured. Policies regarding the public sector are well designed and set clear goals for the future, but this is not quite the case for the residential, industry and tertiary, and transport sector. For example, the industrial sector needs to have obligations for the future to increase energy efficiency. Additionally, special importance lies on incentives in the renovation of buildings in Portugal as the energetic renovation rate is especially low and shows no signs of improvement [187]. As mentioned before, this requires a well-designed thermal building code [62]. Other countries have implemented highly effective energy efficiency policies, such as the Slovak Energy Efficiency and Renewable Energy Finance Facility (SlovSEFF), which creates a good financial environment for energy saving projects [115].

On top of all that, the European aspect cannot be left disregarded. As a European common retail market for electricity is the ultimate goal, all countries, including Portugal, need to work on harmonizing legislation and overcoming technical issues. Only then can a common market be actually implemented throughout Europe [152].

3.3 Potential for Renewable Power

Portugal is blessed with advantageous climatic and geographical conditions. This circumstance provides it with high potentials for renewable power generation [198]. As Figure 3.16 shows, Portugal has ample options to increase its share of renewable energy and is almost not constrained by natural limitations. The only potential that is not high is biomass due to Portugal's high population density and shortage of usable land [199]. This section has a closer look at Portugal's technical potential for different types of renewable power generation and storage.

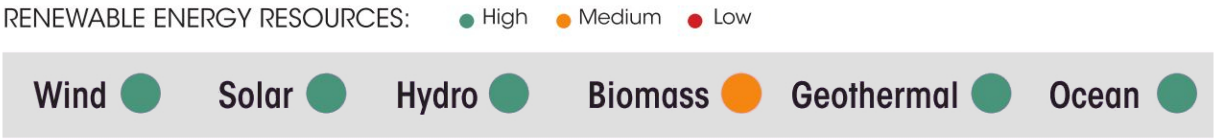
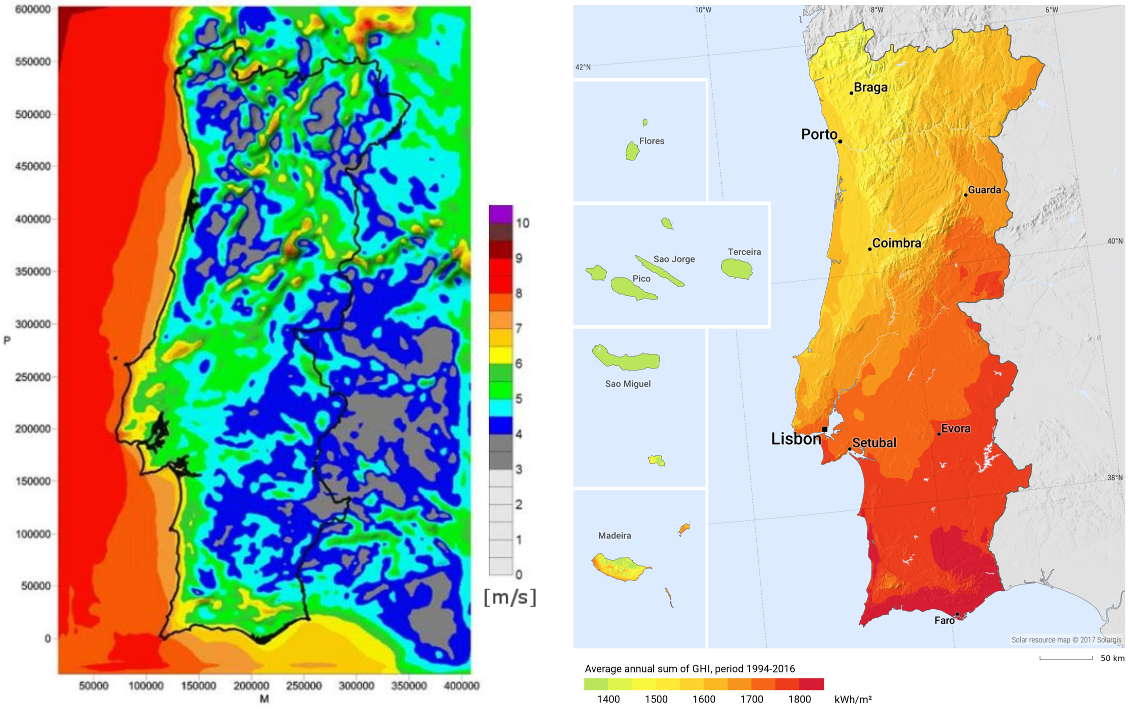


Figure 3.16: Summary of Portugal's potential for renewable power generation [199]

3.3.1 Wind

Portugal is highly invested in the wind power generation with an installed capacity of 5,090 MW by 2017 [17]. By 2020, Portugal aims at an installed capacity of 5,300 MW, of which 27 MW will be offshore [62]. Figure 3.17a shows the average wind speeds in Portugal at a height of 80 m. It can be observed that the highest wind speeds can be found in the mountainous regions in the North of Portugal, as well as in the Lisbon area, in the South and along the coast [200]. This distribution is in accordance with the locations of current windparks, which are mainly found in the North and the Lisbon area [201]. Earliest studies assessed the potential of onshore wind power in Portugal to be around 4,500 MW [202]. However, with modern developments these projections were strongly increased as the current capacity already exceeds these projections. Current assessments estimate a potential of 7,500 MW [203]. So far Portugal has not yet tapped into its offshore wind potential as no commercially used offshore wind turbine has been installed. However, Portugal's coast is rich in high wind speeds. Especially Sagres's cape and the Lisbon area have high wind potential at sea [204]. The limiting factor for Portugal's offshore wind industry is the fact that the sea depth increases quickly off the coast. Therefore, the offshore wind potential for fixed turbines is estimated only up to 3.5 GW. However, the potential for floating turbines is rated much higher at 40 GW [205]. While climate change should have no effect on the potential of wind power, data of past years suggests that the distribution of power production will be changed to a small extent. While the production should slightly decline in winter and spring, it is expected to increase in summer and fall [206].



(a) Average wind speeds at a height of 80 m in Portugal [200]

(b) Photovoltaic power potential in Portugal in kWh/kW$_p$ [207]

Figure 3.17: Wind and PV resources in Portugal

3.3.2 Solar

While Portugal is already rich in wind resources, it is even richer regarding solar resources. The irradiation shown in Figure 3.17b is far above average for European standards, allowing the generation of much solar electricity at low costs. Especially the regions east and south of Lisbon feature high yields per kW$_p$. The Azores islands are not as favorable while Madeira has good conditions along its southern and western coast. In the most southern areas of mainland Portugal, gains of over 1,700 kWh/kW$_p$ can be expected. To put this into perspective, the best location of the most dedicated PV-installer in Europe, Germany, has a maximum of only 1,257 kWh/kW$_p$. Even the Azores islands achieve higher outputs. Nonetheless, Germany is still able to run PV plants economically with potential for an even higher solar penetration [208]. In contrast, Portugal had only 490 MW of installed capacity by 2017 [17], despite having among the most favorable conditions for PV in Europe [209]. The NREAP states that the capacity is supposed to more than double by 2020, reaching 1,000 MW [116]. The General Administration of Energy and Geology (DGEG) expects an even higher installed capacity for that year of 1.434 MW for

Figure 3.18: Dual usage of agricultural land with PV [214]

big plants and 339 MW of microgeneration [210]. The geographical potential for PV is much higher and estimated to be between 9 [203] and 13 GW [211].

In the future this potential could increase due to dual usage of agricultural land [212]. PV panels are installed above the soil at a height that allows the normal processing of crops via regular farming equipment, as shown in Figure 3.18. The advantages are that the land is used more efficiently as it produces both food and electricity. Additional advantages are that the panels provide shading and prevent water evaporation. Two topics that are highly relevant in Portugal, especially in light of the climate change. Nonetheless, as this approach is still rather new, it still needs to be investigated to see, if it proves a competitive technology and how it can be used in Portugal [213].

Other solar technologies such as CSP are still in their development phase and have not made a big breakthrough yet. However, due to its high solar irradiation, Portugal has been a country of interest since the early stages of the technologies' development [215]. Initially the aim was an installed capacity of 500 MW by 2020 [116]. However, to date there is no capacity installed and the goal was decreased to 50 MW to showcase the economic viability [62]. Since the technologies have not been commercially introduced on a wide scale, the evaluation for the potential is difficult. Current estimates consider a potential of 12 GW [211].

3.3.3 Geothermal

Currently, the use of geothermal energy is not too significant in Portugal. On the Portuguese mainland geothermal energy is not used for electricity production at all. The only installed capacity can be found in Azores with 23 MW [216]. The potential in the Azores is very high due to their unique location. They are situated at the junction of the Eurasian, African and North American tectonic plates. This leads to high seismic and volcanic activities [217, 218]. The Azores have a potential of around 230 MW, which can highly contribute to their transition towards a renewable energy system [211]. By 2020, the NREAP plans to increase the capacity to 75 MW [219]. To date, the potential on the mainland is restricted to direct uses, e.g. in spas or for heating uses [220]. However, with the emerging HDR technology new sources could be tapped. The estimated potential on the mainland is around 750 MW [211].

3.3.4 Marine

Wave, tidal and ocean current power generation is still the biggest unknown factor in the future energy generation since the theoretical potential for them is significant. There are still many different concepts being developed and it is unclear which technologies will become commercially available and what their future costs will be [35]. However, Portugal has great potential for marine technologies due to its long coast [36]. The Portuguese government estimates that 25 % of the electricity demand could be covered by these technologies. Given the potential job creation, Portugal is heavily invested in driving marine power forward. By 2022 first demonstration projects are expected to be developed and commercial maturity should be reached by 2030 [205]. For wave power the potential is estimated between 3 [205] and 7.7 GW [211] by 2050. Regarding tidal and ocean current power there have no studies been conducted yet to assess the future potential. Therefore, it is recommended to do so in the near future.

3.3.5 Biomass

Just like geothermal power, biomass can be used not only for electricity but also heat generation, which is already used extensively in Portugal. On top of that it can be converted into biofuels. Figure 3.19 shows that the main part of Portuguese land is covered by bushes or forests, which has potential for biomass use. Biomass resources are diverse in Portugal, ranging from animal manure, over forest and agricultural residues, as well as solid waste to wastewater. Apart from that traditional energy crops can be used [124]. The total biomass that can be used ranges between 22.9 [203] and 42.5 TWh [124]. The expected amount of biomass that is available for energy production according to [203] is shown in Table 3.3.

For electricity production the current installed capacity is 624 MW [17]. Eight new forest biomass power plants are being constructed, which add 167 MW [221]. According to the NREAP, the installed capacity is supposed to reach 952 MW by 2020. 560 MW of this capacity are combined heat and power (CHP) plants [116].

Overall, Portugal's biomass potential is still quite untapped and biomass can be used more in the future. In the heating sector it already presents a more economical and environmentally friendly solution [222]. However, it is always crucial to assess the sustainability of its usage to ensure that resources are not overused [29]. In Portugal this is currently the case for forest biomass, which needs to be looked at more closely to make sure that enough material can grow back [124].

Table 3.3: Amount of available biomass according to [203]

Type	**Amount [TWh]**
Solid Waste	2.90
Biogas	1.64
Forest Biomass	8.58
Other Biomass	1.65
Bioethanol	5.42
Biodiesel	2.78
Total	**22.97**

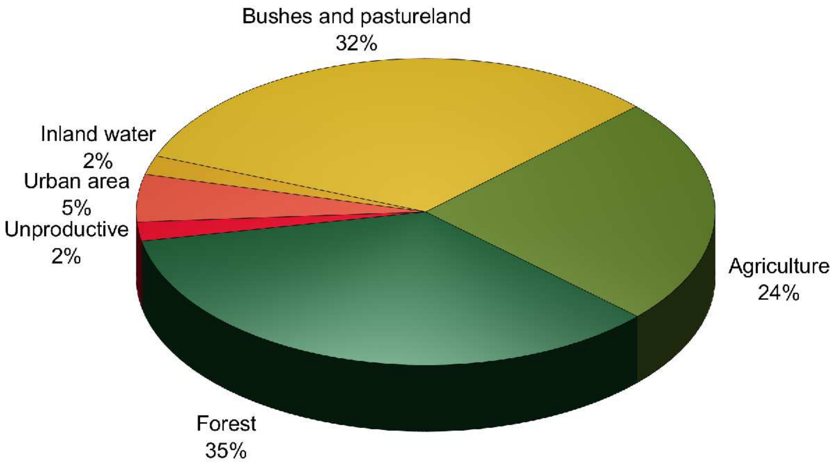


Figure 3.19: Landuse in mainland Portugal in 2010 [223]

3.3.6 Hydropower

Portugal has great hydropower resources, which it has used from the very beginning. As mentioned before, Portugal relied mainly on hydropower for its electricity generation until the 1970's [69]. By the end of 2017, the installed capacity was 7,193 MW, thus exceeding the installed capacity of 6,403 MW of fossil power plants [17]. Hydropower also plays an important role in the future of Portugal's electricity generation. While in the past run-of-the-river plants were built, the focus has shifted towards reversible capacity in form of storage hydropower in the past years. The benefit is that it creates high storage capacities for variable RE with high efficiencies [62]. The National Program of Dams with High Hydroelectric Potential (PNBEH) coordinates the future expansion targets [120]. By 2020 the installed capacity was expected to be 8,940 MW [62]. However due to delays and projects that weren't conducted, the future capacity that will be certainly installed is 8,398 MW by 2023. As many of these power plants have reversible capabilities, the storage capacity will increase alongside. In 2016 the reversible storage capacity was 3,188 GWh with a pump-back capacity of 2,437 MW [76]. By 2050 the potential for hydropower is 9,830 MW [120], with 3,441 MW coming from run-of-the-river plants [211]. The unknown factor is the climate change. According to studies hydropower plants could be affected due to a dryer climate than currently [224].

3.3.7 CAES & Gas Storage

Another type of storage that depends on the geographical circumstances besides dammed hydropower are the gas-based storage systems. These are CAES and P2G products such as hydrogen and methane. Despite the need for detailed studies about the potential of these storage methods, not many have been conducted so far. Ding assessed the storage potential for methane in Portugal in 2010. It was concluded that, as depleted reservoirs and aquifers were not available, only salt caverns would be potential storage locations. After excluding the majority due to different criteria, suitable caverns were found in the regions of Nazaré, Caldas da Rainha and Peniche. Depending on the criteria, Portugal has a potential of additional 450 to 1,650 Mm^3 [60]. This would be a significant improvement over the current capacity of 333 Mm^3 [76], which was only able to store enough gas for 21 days in 2017 [17]. Carneiro et al. published a study that exapnded the evaluation to hydrogen and pressurized air. The study found 46 potential storage sites in Portugal, however, as the study was intended as a first screening of the potential it did not quantify the available capacity. Instead, it is meant to give information on which sites to study in greater detail. Like Ding it concluded that salt caverns are the most promising geological formation. As all of these technologies rely on underground storage, the technologies rival for some of the locations. Which locations are suitable for which gases has to be found out by future in-detail studies of the identified locations.

Chapter 4

EnergyPLAN Model Creation and Optimization

This chapter serves as preparation for the optimization part. First of all, it explains what modeling actually is. To do so, it discusses the methodology behind it, different tools that can be used and why the particular program, EnergyPLAN (Version 13.2), was chosen for this thesis. Furthermore, it lists other papers that have conducted research in this area for Portugal, other countries and even continents. Afterwards, EnergyPLAN is explained in greater detail to help the reader understand how it works and what advantages as well as limitations it has. Last but not least, the section contains information about the second tool, MATLAB (Version 9.4), that is used in the design process. As EnergyPLAN can only evaluate a given energy system, a second tool was needed to optimize the energy system.

The section 4.2 discusses the reference model to which the optimized model is compared to. The reference model is based on past information to verify its validity. In this case the model recreates Portugal's energy sector in the year 2016. The goal of the optimized model is to create a reliable energy system that is not only more sustainable but also more cost-efficient in comparison to the old one.

The core of this chapter is the optimization model, which is presented in section 4.3. Optimizing an energy system for the future is always based on various assumptions. This is especially true when the time frame is very large, as it is in this case. The energy system is likely to change profoundly and creating models for every different scenario would not only be unfeasible in terms of computation time, it would also create an almost infinite number of scenarios. Therefore, it is crucial for the optimization to only create models that are probable and desirable in the future. The section 4.3 explains the assumptions that were made as well as explaining the reasoning behind these choices to create a realistic model for Portugal. Additionally, it discusses the decision parameters that were optimized. Limiting these parameters is decisive for creating a model that can be computed within reasonable time.

4.1 Modeling and Optimization

Modeling has many meanings but in this case it is defined as "the representation [...] of a process, concept, or operation of a system, often implemented by a computer program" [226]. In the field of energy, the main aim of modeling is to represent the real-world energy system to be able to analyze and improve it. This can be an entire energy system or simply a specific aspect, e.g. demand response in Corvo in the Azores [227]. A good model requires a good methodology that allows a structured approach. Different methodologies are shown in this section alongside with computer-based tools that implement these methodologies to serve different purposes in the energy system.

4.1.1 Methodology

The methodology defines what type of analysis and optimization is conducted. The models are divided into two different types: macro- and micro-models. Macro-models cover large areas with the goal to analyze the long-term energy supply and demand of the inspected area. Therefore, their temporal resolution is rather low to keep computation time at reasonable levels. Their drawback is that usually they are not able to understand the dynamics of production, transmission and distribution [228].

Micro-models, on the other hand, are generally simulation tools based on a bottom-up approach. Their aim is to reconstruct the load curves of the inspected system, e.g. the Portuguese energy system. They are highly suitable to see the behavior of an energy system when new technologies are introduced [229]. The temporal resolution of these tools is typically one hour as it is sufficiently precise to model variations of variable energy sources. The reason behind that is that the aggregational effect smoothens the abrupt variations over larger areas [230]. Nonetheless, the amount of input information needed is considerable and micro-models limit their temporal horizon to typically one year. EnergyPLAN falls into the second category [229].

In general the work flow is comprised of four steps [228]:

1. Define reference energy demands: To start creating a model of an energy system it is crucial to know how much energy and what type of energy needs to be supplied.
2. Define a reference energy supply system: The new models need to be compared to a baseline. Therefore, the current supply system is modeled to see how the new system influences the current one.
3. Define the regulation of the energy supply system: Models can be optimized with different parameters giving priorities to different technologies or regulation strategies.
4. Define alternatives: Due to the uncertainty of the future, the creation of several scenarios is necessary. Otherwise the model would diminish its usability when the technology development goes in another direction than anticipated. When different models are created the interaction of the technologies and their influence on the overall system are better understood and this problem can be avoided.

4.1.2 Tools

There are several tools to model energy systems. They serve different purposes for the evaluation of energy systems as they use different methodologies. Table 4.1 lists the majority of the tools currently available. The table evaluates the tools by seven categories. A simulation tool models the operation an energy system with the given input. Scenario tools generally combine several years to obtain a long-term scenario. Therefore, their time-step is larger than simulation tools to offer an outlook around 20 to 50 years into the future. Equilibrium tools investigate the correlation of supply, demand and prices in a whole economy or some part of it. Top-down tools are macroeconomic tools that use macroeconomic data to determine the evolution of energy demands and prices. Their counterpart are bottom-up tools. They identify investment options by evaluating various energy technologies. Optimization tools can be

Table 4.1: Selection of tools to create energy system models [231]

Tool	Simulation	Scenario	Equilibrium	Top-down	Bottom-up	Optimization	
						Operation	Investment
AEOLIUS	✓	–	–	–	✓	–	–
BALMOREL	✓	✓	Partial	–	✓	✓	✓
BCHP	✓	–	–	–	✓	✓	–
COMPOSE	–	–	–	–	✓	✓	✓
E4cast	–	✓	✓	–	✓	–	✓
EMCAS	✓	✓	–	–	✓	–	✓
EMINENT	–	✓	–	–	✓	–	–
EMPS	–	–	–	–	–	✓	–
EnergyPLAN	✓	✓	–	–	✓	✓	✓
energyPRO	✓	✓	–	–	–	✓	✓
ENPEP	—	✓	✓	✓	–	–	–
GTMax	✓	–	–	–	–	–	–
H2RES	✓	✓	–	–	✓	✓	–
HOMER	✓	–	–	–	✓	✓	✓
HYDROGEMS	–	✓	–	–	–	–	–
IKARUS	–	✓	–	–	✓	–	✓
INFORSE	–	✓	–	–	–	–	–
Invert	✓	✓	–	–	✓	–	✓
LEAP	✓	✓	–	✓	✓	–	–
MARKAL	–	✓	✓	Partly	✓	–	✓
Mesap PlaNet	–	✓	–	–	✓	–	–
MESSAGE	–	✓	Partial	–	✓	✓	✓
MiniCAM	✓	✓	Partial	✓	✓	–	–
NEMS	–	✓	✓	–	–	–	–
ORCED	✓	✓	✓	—	✓	✓	✓
PERSEUS	–	✓	✓	–	✓	–	✓
PRIMES	–	–	✓	–	–	–	–
ProdRisk	✓	–	–	–	–	✓	✓
RAMSES	✓	–	–	–	✓	✓	–
RETScreen	–	✓	–	–	✓	–	✓
SimREN	–	–	–	–	–	–	–
SIVAEL	–	–	–	–	–	–	–
STREAM	✓	–	–	–	–	–	–
TRNSYS16	✓	✓	–	–	✓	✓	✓
UniSyD3.0	–	✓	✓	–	✓	–	–
WASP	✓	–	–	–	–	–	✓
WILMAR	✓	–	–	–	–	✓	–

programmed to either optimize the system from a technical or economical perspective. Technically, they optimize the operation of the given system. Economically, they optimize the investments that need to be done regarding new energy stations and technologies. Both types are typically simulation tools [231]. An in-detail evaluation of the various tools would exceed the scope of this thesis. For further information, see [228, 231, 232].

4.1.3 EnergyPLAN

EnergyPLAN has been under development since 1999 at Aalborg University [231]. The program is a deterministic input/output simulation model [232]. Its main use is the assistance in the design process of national or regional energy systems by simulating the entire system [231]. The program has also been used at lower levels but 80 % of the published studies analyzed national or state energy systems [233]. EnergyPLAN includes transport, heating, electricity, gas, and industry in its energy system analysis and can thus be seen as a holistic model [234]. It simulates an entire year using an hourly time step [227]. This short time step allows a realistic inclusion of fluctuating renewable energy as wind and solar, as well as means to balance them out with storage systems [234]. Although these sources have variations at even smaller timescales, as explained in section 2.1, these become insignificant on a national level [230]. Outputs are energy balances containing numerous information, e.g. annual electricity production, CO_2 emissions, fuel consumption and import/export [232]. Figure 4.1 shows the overall schematic of EnergyPLAN. It can clearly be noticed that the program does not separate the energy sectors but allows the simulation of an intertwined smart energy system [235]. This sectour coupling makes the system highly complex. However, as EnergyPLAN is highly optimized, it only takes a few seconds for the simulation of an entire energy system [232]. This is crucial for using optimization algorithms, as they require to run hundreds to thousands of different configurations to find the ideal system (see subsection 4.1.5). The greatest disadvantage of the program is the currently limited implementation of storage technologies. It allows the simulation of dammed hydropower storage as well as PHES, which can be adjusted to model other storage types, e.g. batteries or CAES. Therefore, it was decided to use as second storage technology CAES due to its comparatively high maturity.

4.1.4 State of the Art

Many studies have already been conducted to find a more sustainable energy system in different regions using EnergyPLAN. This ranges from creating a new system for a specific region to entire continents and the world. On a smaller scale studies were conducted for the municipality of Aalborg [236] and Frederikshavn [237] in Denmark and South Tyrol [238] in Italy. The number of studies for countries are far greater. Studies exist for Brazil [239], Croatia [240], Denmark [241–243], Finland [244], France [245], Germany [246], Iran [247], Ireland [248–250], Mexico [251], Nigeria [252] and Pakistan [253]. Some studies even discuss the transformation of the entire EU based on renewable sources [191, 254]. This is only an incomplete list. More studies can be found in [233, 255].

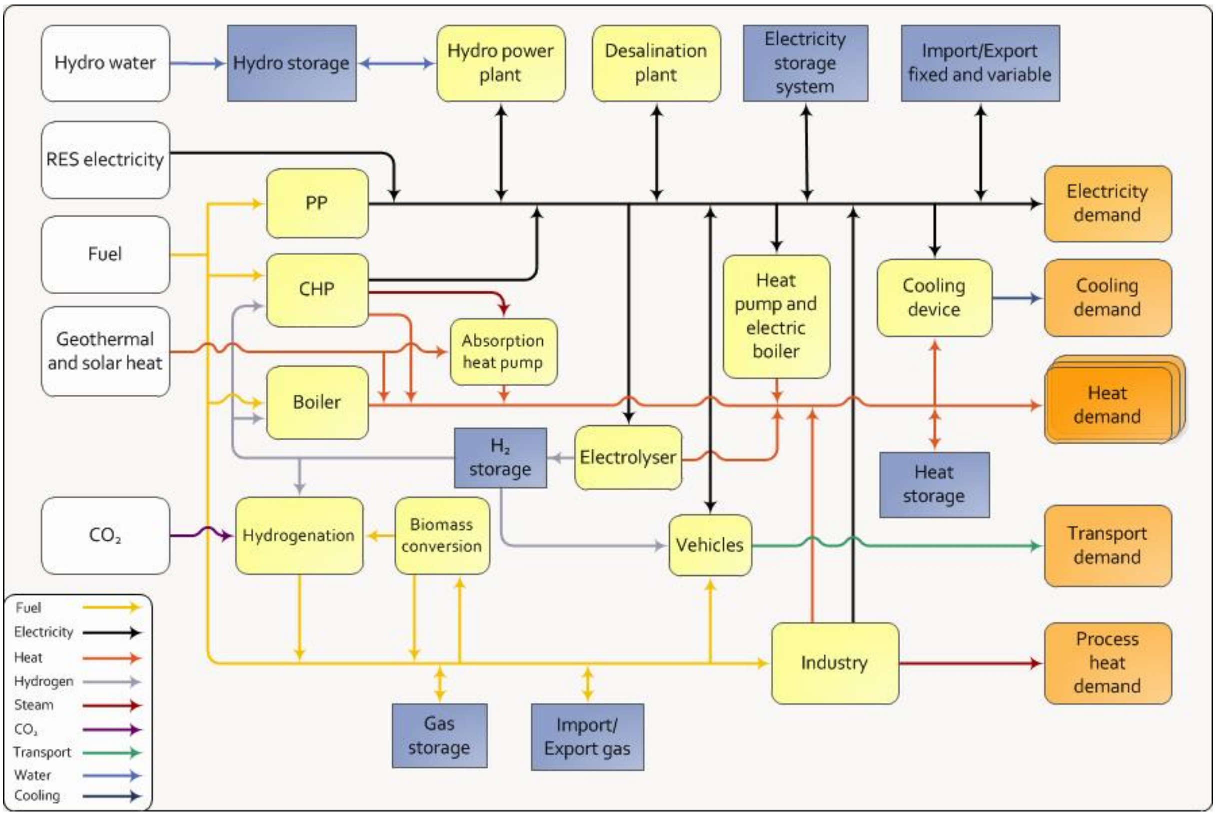


Figure 4.1: Overall schematic of EnergyPLAN [235]

Most of these studies use EnergyPLAN to model an entirely renewable energy system. An example is the analysis of Denmark's energy system by Lund et al. [243]. However, as EnergyPLAN can analyze different aspects of an energy system, it can also be used for different purposes. Like many others, Krakowski et al. did not only create a 100 % renewable energy system but investigated a range of 40 to 100 % [245]. Zakeri et al. investigated the maximum amount of renewable energy that could already be integrated into Finland's current energy system [244]. Sadri et al. used EnergyPLAN to develop a general procedure for long-term environmental planning in the transport sector in developing countries, since these face a very different situation. Unlike developed countries, the amount of vehicles is still rising sharply and it is difficult to predict how the shift from fossil to electric vehicles will affect this development. This is of high significance to correctly plan future energy systems. Akuru et al. tried to improve the resilience of Nigeria's energy system using renewable energy sources. During their research they found out that Nigeria could easily transform their energy system into a renewable and robust one. An additional finding of their study was that for individuals it is much easier to drive this transition using the country's abundant resources [252].

Several scientific papers [229, 256–259], reports [260, 261] and theses [262–265] have been published that investigate different aspects of Portugal's energy system. EnergyPLAN was used by [229, 256, 263], while [257] used MARKAL, [264] used RENPASS, and [259, 262] used H2RES, which was developed by the Instituto Superior Técnico in Lisbon and the Faculty of Mechanical Engineering and Naval Architecture at the University of Zagreb [231].

Krajačić et al. tried to answer the question how to achieve a 100 % renewable electricity supply in Portugal by 2020 using H_2RES. The simulation was carried out as a closed system, thus ignoring synergy effects of transmission capacities. Furthermore, sector coupling was not considered due to the close proximity of 2020 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, as cost data was not used the authors suggested to refine the model in the future to also verify the economic feasibility [259].

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. The transmission capacity is kept at 3 GW and does not adjust to the European goal of increasing transmission capacity to 10 % or 15 % of the entire generation capacity. Storage systems besides hydro storage are not considered, which explains the high amounts of exported electricity and critical excess energy production (CEEP). The results show that an entirely renewable electricity sector would have higher costs than systems with lower shares of renewable energy. The study does not use an optimization algorithm to improve the generation mix [256].

Soares created different scenarios for a ten-year period and looked at the share of renewable energy they would allow. The values ranged from 37 to 86 % for the final year 2023. According to the model, higher shares of RE were not feasible given the constraints. However, 86 % of RE resulted in costs that were more than 150 % higher than the 37 % scenario. In return, CO2 emissions were decreased by 98 %. A smart energy system was not considered, given the relatively short time period that was observed. The author suggested improved cooperation with Spain to reach a completely renewable system [265].

The next study was by de Almeida Garret Rodrigues Pena and created two scenarios for the Portuguese energy system in 2030. One scenario was business-as-usual, which increased energy demand by 46 % and CO_2 emissions by 43 % in comparison to 2010. The second scenario aimed at increasing the energy security by decreasing Portugal's dependence on imports. Thus, the share of renewable energy was increased. However, CO_2 emissions still increased by 19 %. The thesis did not contain a scenario that aimed at reaching a specific share of renewable energy or GHG emissions [262]. Both scenarios fail to reach Portugal's goal to decrease its GHG emissions by 40 % by 2030 in comparison to 1990.

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. Their results show an increase of the share of RE from 15 % in 2005 to 56-59 % by 2050. This resulted in a decrease of GHG between 49 and 74 %. RE was found to be cost-effective, even when no GHG cap was imposed. Unlike many others, the study also integrated the transport and heating sector into their analysis. However, they did not consider how these sectors would need to change to meet the European goals for GHG emission reduction by 2050. According to their results Portugal would fail to meet the goal of 80-95 %. The study further shows that a minimum generation of fossil cannot be tolerated in future energy systems to meet European emission goals [258].

The 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 most ideal scenario, the buildings, refinery, agriculture and waste would already produce enough GHG to use up the available maximum amount. Including the estimated emissions from the industry, transport and energy sector, Portugal would exceed the allowed emissions by around 150 % [260].

Penisga's thesis analyzed the potential of electric vehicles in Portugal until 2050. It focused its attention on the electricity and transport sector, specifically light-duty vehicles. The heating sector was excluded from this study. The authors created a plan for the change in the generation capacities as well as the amount of electric, hybrid and fossil cars. Hydrogen cars were not considered in this study. The generation mix for electricity was dominated by renewable energy by 2050, however, over 13 TWh of natural gas were still used and the capacities were not optimized. By 2050 the study expected a share of 38.6 % of ICE, 27.6 % of hybrid and 33.7 % of electric cars. Overall the amount of cars was expected to decrease from 4.7 in the reference year 2014 to 4.2 million. The obtained system led to a decrease in CO_2 emissions to 6.11 Mt of CO_2 [263].

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 of 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 results obtained allowed a decrease by 70 % in comparison to 2005 while almost achieving 90 % of RE generation [229].

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 (i.e. 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 [257], as was already suggested by Soares [265].

Fernandes developed a renewable electricity sector for the Iberian peninsula for the year 2050. Five scenarios were developed in the thesis using solar, wind and run-of-river as resources. Other resources were not considered and only solar and wind capacities were changed to create the scenarios. The first three aimed at reducing the yearly residual load to zero. The fourth one made a trade-off between higher installed solar and wind capacities and lower transmission costs. The last scenario used even higher capacities to further reduce transmission costs. As only the yearly residual load was reduced, the hourly variation was very high for both countries. As both countries had similar variation patterns, they would not be able to balance out the variations to obtain a stable Iberian electricity system. To balance out the variations, the thesis looked briefly at ways to store the electricity in electric cars but obtained infeasible results of 9,000 cars needed per inhabitant in Portugal. Other means of storage were not considered. The study only considered the electricity consumption of the reference year 2013 and did not account for electricity demand changes due to electrification of the transport and heating sector [264].

The most recent study was conducted by the Renewable Energy Association (APREN) and published in May 2018. The report looks at GHG emissions from all parts of the energy system and furthermore addresses the changes that will occur in the future in the Portuguese energy system, e.g. electric mobility, smart grids and the digitalization. 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 a reduction of 60 and 75 %, respectively. The higher reduction is achieved by an improved sector coupling. To balance out variations in the renewable energy production, natural gas with carbon capture and 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 more than 20 %. The report also investigates the job creation opportunities due to increased RE use. The 75 % scenario creates around 30,000 jobs in the energy sector in contrast to around 10,000 in the conservative scenario [261].

4.1.5 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 according to specific parameters. In the current version 13.2, EnergyPLAN is only able to run a limited amount of scenarios and only changes one variable at a time. Furthermore, the change of the variable has to be implemented manually [235]. Therefore, the implemented tool only suffices for refining a system but does not suit for the optimization. The main issue is that the variables are interdependent and optimizing one for a specific scenario does not mean that its value is still ideal when changing another variable. Furthermore, the amount of time that would be spent on optimizing the system manually would be unfeasibly long.

Thus, the optimization has to be conducted externally. Optimization algorithms are divided into local and global algorithms [266]. In this case a global algorithm is necessary as the goal of the optimization is to find the absolute minimum and not a local one. Local algorithms, as the name suggest, would converge on any of these local minima and are therefore not suitable. The most prominent optimization algorithms are genetic algorithm (GA) and particle swarm optimization (PSO) [267]. They and their adaptations have already been deployed in the optimization of various aspects of the energy system [238, 268–271].

Choosing an optimization algorithm for a specific problem is difficult as there is no perfect algorithm [272]. For the optimization in this thesis the gray wolf optimization (GWO) algorithm was chosen, which is based on the hunting behavior of gray wolves [273]. Due to its pack hunting it is somewhat similar to the PSO. The main principles of the algorithm are the social hierarchy of the pack and its characteristic hunting behavior by gradually encircling the prey, i.e. the best solution of a problem. The algorithm allows a single- [274] as well as multi-objective approach [275]. In this case, the single-objective algorithm was applied as the main goal was to minimize the costs of a carbon-free energy system.

There are several reasons for choosing the GWO algorithm for this optimization problem. The first one is its highly competitive results compared to other heuristics. Furthermore, the algorithm has a high exploration ability, meaning that it covers the search space to a great extent. Additionally, it avoids the convergence in local optima very well, which is very important for a search space that has many of them. Another reason is its high convergence, making sure that a viable solution is found as long as reasonable parameters are entered [274]. On top of that, it has already proven its reliability in numerous studies [276–279]. Lastly, the author of the program was already familiar with the algorithm, which allowed a fast implementation and adaptation for the problem at hand. An in-detail explanation of optimization algorithms in general and the GWO algorithm specifically would exceed the scope of this thesis as the main task is the design of a carbon-free energy system for Portugal. For further information on the GWO, please see [273–275].

The software that was used for the optimization is MATrix LABoratory (MATLAB). As the name suggests, it is primarily designed for the computation with matrizes [280], of which there are many in the optimization process. There were three reasons for choosing MATLAB. Firstly, EnergyPLAN already offers a toolbox, developed by Pedro Santana from the University of Las Palmas de Gran Canaria, for the coupling of EnergyPLAN and MATLAB, which can be downloaded on the website of EnergyPLAN [281]. The toolbox allows to change the input of EnergyPLAN within MATLAB, run the simulation in EnergyPLAN and obtain the results in MATLAB for further analysis. The second reason was the profound knowledge of the author in MATLAB, which was necessary to extend the toolbox's capabilities to not only run EnergyPLAN through MATLAB but also to optimize the energy system of Portugal using the GWO algorithm. Lastly, another advantage of MATLAB is that it can be run in parallel, which allows to simulate several energy system configurations in EnergyPLAN at the same time [282]. This is essential in this case as thousands of configurations are tested before a final result is reached.

The scheme of the optimization process is shown in Figure 4.2. After the initial population is generated, each configuration of the energy system, also known as agents, is handed over to EnergyPLAN to be evaluated. The results are sent back to MATLAB. The agents are ranked to extract the best results. Afterwards, the positions of each agent are updated to create a new wolf pack, i.e. agent pool. The new agents are sent back to EnergyPLAN to be evaluated again. This process is repeated until a stopping criterion is met or the optimization canceled. The detailed explanation of the code, which was used for the optimization of the energy system, would exceed the scope of this thesis as the code is a mean to achieve the main goal of finding the ideal energy system. For further information about MATLAB and its parallel computing toolbox, please see [280, 282]. The code can be found in Appendix A for the proficient MATLAB user.

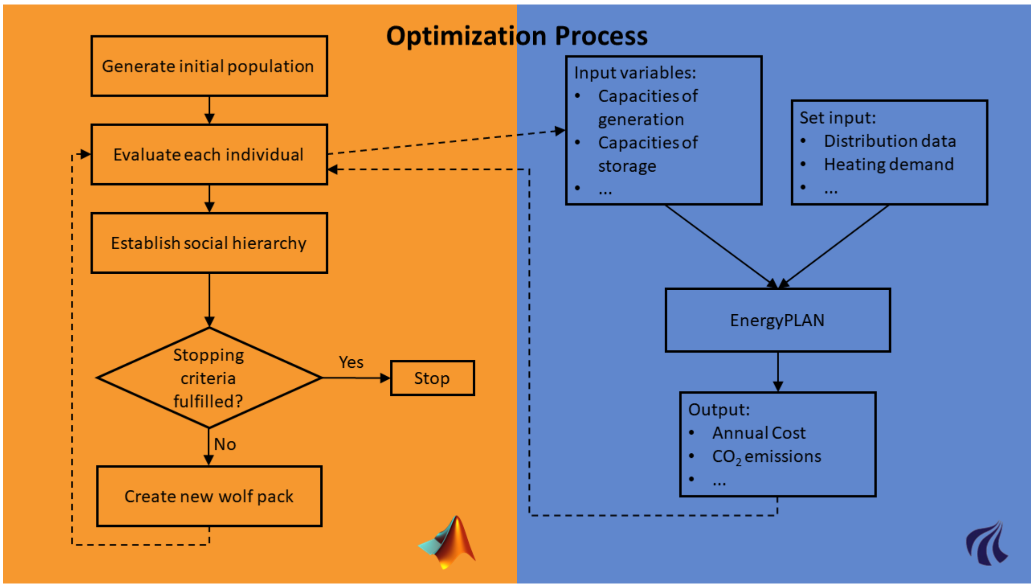


Figure 4.2: Diagram of the optimization process and the interaction between MATLAB (left) and EnergyPLAN (right)

4.2 Reference Model

As explained in subsection 4.1.1, every model requires a reference model to make the obtained result comparable. It is most favorable to create a reference model that is as close to the present as possible. However, it takes some time until all necessary data to create the model is made available. Depending on the country, this means that reference models have to model information that is already a few years old. At the time of this thesis the preliminary results for 2016 had already been published and thus 2016 was used for the reference model. The main sources for the model creation were [16, 60, 76, 97, 283, 284]. These sources allowed to establish Portugal's national energy consumption in total as well as split up into electricity generation, transport, industry and households. The results are shown in Table 4.2. It is clear 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 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 perfectly adequate and the energy system is correctly modeled in EnergyPLAN. According to EnergyPLAN, the energy sector was responsible for 49 Mt $CO_{2\text{equivalent}}$ in 2016, which matches official results that state around 50 Mt [261].

To ensure that the results are consistent across the four sectors that are modeled by EnergyPLAN, a comparison with the official values was made for all sectors, namely energy generation, transport, industry and household. The comparison is shown in Table 4.3. Please note that it neglects hydro, wind and solar as these are exclusively used for electricity generation. It can be observed that some fuel types are primarily used in one specific sector. Coal is almost exclusively used in power plants for electricity generation. Oil plays a huge role in the transport sector and also somewhat in the industry. Those two sectors alone attribute for around 93 % of the total consumption. Overall, the reality and the simulation

Table 4.2: Comparison of total national primary energy demand split by energy source between the official values and the simulation results [76, 97, 284]

Energy Source	**Official [TWh]**	**EnergyPLAN [TWh]**	**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 %**

match very well. The deviations never go above 2 %. Therefore, it is certain that the reference model is sufficiently precise to serve as comparison to the new energy models. However, it needs to be noted that the future energy system will significantly differ from today's due to several factors that are explained in chapter 3. This should be kept in mind when comparing the two energy systems in chapter 5.

Table 4.3: Comparison of total national energy demand split by fuel type between the official values and the EnergyPLAN (EP) simulation results for each sector [97, 284]

	Electricity Generation			**Transport**		
Fuel	**Official [TWh]**	**EP [TWh]**	**Error**	**Official [TWh]**	**EP [TWh]**	**Error**
Coal	32.94	33.62	2 %	0.00	0.00	0 %
Oil	2.14	2.19	2 %	64.51	63.01	-2 %
NGas	14.32	14.61	2 %	0.69	0.69	-1 %
Biomass	3.31	3.38	2 %	0.03	0.03	0 %
Sum	**52.71**	**53.80**	**2 %**	**65.24**	**63.73**	**-2 %**

	Industry			**Household**		
Fuel	**Official [TWh]**	**EP [TWh]**	**Error**	**Official [TWh]**	**EP [TWh]**	**Error**
Coal	0.15	0.15	1 %	0.00	0.00	0 %
Oil	39.33	38.76	-1 %	4.97	4.97	0 %
NGas	30.45	30.68	1 %	2.94	2.94	0 %
Biomass	16.67	16.67	0 %	8.89	8.89	0 %
Sum	**86.60**	**86.26**	**0 %**	**16.80**	**16.80**	**0 %**

4.3 Optimization Model

Creating realistic input is crucial to obtain a reliable scenario. There are many factors to consider, such as the future electricity demand or heating infrastructure. The problem is that many sources that are needed to create a model do not consider all these factors themselves, increasing the difficulty to find reliable sources for each variable. An example is the development of the electricity demand in Portugal until 2050. Many sources, such as [110, 261, 285, 286], of which some were discussed in subsection 4.1.4, do not consider the obligation to reduce GHG emissions as stated in the Paris agreement or other goals set by the EU and Portugal [109, 110, 112, 116, 117]. Therefore, they do not take into account the increasing demand in electricity caused by sector coupling. Furthermore, since the model was created for a very distant future, many forecasts had to be made to create a realistic model. The following subsections discuss the changes for each part of the energy system and how they were implemented in EnergyPLAN.

4.3.1 Electricity Generation and Storage

In the future most traditional sources of energy disqualify themselves due to their GHG emissions. Therefore, 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 different types of generation and storage technologies. The generation technologies considered for the model are shown in Table 4.4. The table contains the minimum and maximum values that the optimization has to stay in. The minimum values are based on the installed capacities in 2017. The only cases where this does not apply are *River Hydro* and *Dammed Hydro*. This is owed to their way of capacity expansion and their lifetime. Since each new plant adds significantly more capacity than a wind turbine or a PV plant and they have a longer life-time, hydro power plants, that are currently being built, were also considered in the allocation of the minimum installed capacity. The maximum capacities are based on the geographical limitations of Portugal, as discussed in section 3.3.

However, there are some exceptions. One of them is tidal power. Currently there are no assessments of Portugal's potential for this technology. Therefore, a low estimate of 1,000 MW was considered to see, if the technology would be of interest in Portugal. The minimum installed capacity of thermal plants is the expected installed capacity of biomass [221] and gas plants by 2030 [210]. The reason why those two types of power plants are combined is owed to the implementation in EnergyPLAN. The program does not distinguish between the two but combines them under *Thermal Plants*. This is a simplification by EnergyPLAN. To establish the amount of energy used by each energy source, it also requires the user to input the ratio between the different fuel types, i.e. for the future scenarios SynGas and biomass. The maximum value for thermal plants was set to around 250 % of the value of maximum load in 2016 [76]. As the results in chapter 5 show, more capacity was not needed.

Regarding combined heat and power (CHP), there was no optimization done. However, some adjustments regarding the fuel usage and the installed capacity were made. The capacity was increased to the predicted value for CHP by 2020, which is 560 MW (see subsection 3.3.5 for further information). The fuel usage needed to be adjusted as well since currently more than half of the primary energy comes from non-renewable resources. As 14 TWh of biomass were already used in 2016 the share of fossil fuels could not be replaced by an increased use of biomass [97]. Otherwise the maximum available amount of 42.5 TWh [124] would already be largely exhausted. Instead the electricity and heat production was decreased accordingly to take into account the reduced fuel usage. This decrease of electricity and heat, which would need to be covered with other sources, is discussed in the subsections 4.3.4 and 4.3.5.

Table 4.4 also contains estimates of the future capacity factors. The capacity factor is the ratio between the actual produced power and the theoretical maximum of produced power. Due to technological improvement, all of the technologies are likely to improve, especially those that are very recent. For wind power the capacity factor can be increased by using, for example, larger blades. For hydro power and thermal plants, the capacity factor is not listed in this table as they depend heavily on the variation in input. For example, in a dryer year the capacity factor of hydro power will be lower due to less

Table 4.4: Setup of the available capacities in EnergyPLAN

Technology	**Min [MW]**	**Max [MW]**	**Capacity Factor**	**Sources**
Wind Onshore	5,090	7,500	0.35	[76, 203, 287]
Wind Offshore	0	10,000	0.39	[203, 287]
PV	490	13,000	0.27	[76, 211, 287]
CSP	0	12,000	0.30	[211, 287]
River Hydro	3,189	3,441	—	[17, 62, 120, 211, 287]
Dammed Hydro	5,210	6,400	—	[17, 62, 120, 287]
Tidal Power	0	1,000	0.42	[287]
Wave Power	0	7,700	0.08	[211, 287]
Geothermal	0	980	0.85	[203]
Thermal Power	3,123	20,000	—	[17, 210, 221, 287]
Industrial CHP	560	560	—	[16, 116]

precipitation while the capacity factor of thermal plants will be higher that year as they have to balance out the lack of hydro power. The capacity factors are largely based on [287], which combined the findings of several studies for capacity factors in the US. Since these factors differ in Portugal, they were slightly adjusted depending on the characteristics of Portugal.

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 implementation of another technology. Primarily, it is designed for pumped hydroelectric storage (PHES) but it can also be adapted for compressed air energy storage (CAES) or battery energy storage (BES). As Portugal does not have a potential for PHES, it was decided to model the inclusion of CAES for Portugal. The reason behind this is that CAES is the most mature technology to date, as discussed in section 2.2.1, and the development of the technology is more predictable than for batteries. Regarding the storage of dammed hydro power, a linear increase was used, e.g. an increase of 20 % in dammed hydro power capacity also resulted in a 20 % increase in storage size and pump-back capacity. As explained in subsection 3.3.7, Portugal has a maximum capacity of 1,983 Mm^3 for the storage of gases. As CAES, hydrogen and gas storage use the same available storage, an interdependency between these variables was created in the optimization. This ensured that no capacity was shared, as this is physically not possible.

Other topics regarding the electricity system are the interconnection capacity with Spain and the grid stability. Concerning the interconnection capacity the European goal of 15 % was used for the calculations. This means that for each configuration of the energy system the installed capacities were summed and multiplied by 15 % to obtain the transmission capacity for the given system. As discussed in subsection 3.2.1, RE generation systems will need to take over the grid services in the future. Since promising results are already seen today (see section 2.1), this is assumed to not pose a problem in the future.

Modeling always means that simplifications need to be made. For example the effect of the climate change on offshore wind capabilities [288] as well as hydro [224] in Portugal was omitted. Residential electricity storage could also not be considered due to the simplified implementation of storage technologies in EnergyPLAN [56]. However, this does not decrease the validity of the model as it is still accurate [230].

4.3.2 Heating & Cooling

Portugal's heating and cooling behavior will greatly change in the future, primarily due to the change to electricity as primary source, new building standards and the climate change. Many studies have shown how district heating systems have great benefits for the creation of a smart energy system as they are highly flexible and efficient when CHP plants are used [4, 189, 190, 289, 290]. However, to use district heating the houses would require to have central heating which is often not the case in Portugal. It is unlikely that this will change in the near future as renovation rates are very low in Portugal [107]. Therefore, only the existing infrastructure for district heating is considered. The only change to the current district heating that is made, is that the fossil sources are replaced by biomass. Given the low renovation rate in Portugal [107] and the extremely high heating gap of 95 %, great reductions in the heating demand are not considered. Instead, any improvements of the housing insulation is expected to be used to decrease the heating gap [100]. Thus, the total heating demand in 2015 and 2050 are almost identical, as seen in Table 4.5. Please note that the heating demand information is currently only available for 2015. However, due to the low total heating demand and the consistency for each year, these values are sufficiently precise, as shown in section 4.2. Adding Portugal's district heating demand to the total values in Table 4.5, both years show a heating demand of around 21.5 TWh. However, the fuel demand is much lower in the future.

Table 4.5: 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

The biggest change in the heating sector is how heat is produced. Currently, the reliance is already high on (potentially) renewable sources (see subsection 3.1.3). This share as well as the efficiency will have to be increased. A first step is to get rid of all fossil boilers. Thus, all oil and gas boilers will have to be replaced by either biomass or electricity. Since there is a limited amount of biomass available, the heat demand to be covered was overall reduced to 3.20 TWh, as can be seen in Table 4.5. Thus, the main source for heat will have to be electricity. This should pose no problem to the Portuguese population as it is already highly familiar with electric heating. The difference between the current system and the future is that, while nowadays most of the heating is done with electric heaters that have an electric efficiency of almost 100 %, individual heat pumps will take their place. A/C units that are already common in Portugal are designed to keep a specific temperature and can either heat or cool depending on the temperature difference. Since those units have a higher efficiency than simple electric heaters, they will cover the majority of the electric heating demand. Out of the total 15 TWh, 2 TWh will be covered by electric heating and 13 TWh by heat pumps that have an electric efficiency of 300 %. Higher efficiencies are possible but this would require more complex systems that rely on central heating [157].

All these systems are supplemented by solar thermal systems. Due to the mild winters, the technology can be very simple and no prevention measures to keep the water from freezing need to be taken. Thus, it is assumed that solar thermal contributes greatly to Portugal's heat demand in the future as it is very cost-efficient in most regions. In theory, solar systems are capable of providing most of the heat demand and should always be considered for renovations [182]. However, it is highly unlikely that Portugal will change completely towards solar heating. In (4.1) it is shown how the solar input is calculated for each type of heating. To compute the annual input $Q_{\mathrm{in}_{\mathrm{tech}}}$ for each technology several factors play a role. The first of them is the number of households that use solar thermal. Given the short amount of time to change the Portuguese heating system the Pareto principal is applied, which yields $n_{\mathrm{HH}} = 3.26$ million systems [291]. The reason behind this nonetheless high share is the cost-efficiency in Portugal and the strong political support. New incentive mechanisms were put in place that offer grants that cover up to 60 % of the costs of solar thermal systems in residential buildings [292]. G_{avg} is estimated at $2,000\,{}^{\mathrm{kWh}}/_{\mathrm{m}^2}$ [293]. The efficiency η_{sol} is set to 80 % and every system has on average a solar area of $2.5\,\mathrm{m}^2$ [14]. The share for each technology, i.e. biomass, heat pumps and electric heating, are 18, 71 and 11 % respectively. The results were used by EnergyPLAN to compute the available solar heat energy using other parameters such as the storage capacity. The results are shown in Table 4.5. This solar heat replaces other heat sources, which explains how, for example, the fuel input for biomass is lower than the heat demand.

$$Q_{\mathrm{in,tech}} = n_{\mathrm{HH}} \times G_{\mathrm{avg}} \times \eta_{\mathrm{sol}} \times A_{\mathrm{sol}} \times s_{\mathrm{tech}} \tag{4.1}$$

given

$Q_{\mathrm{in,tech}}$ = total annual irradiation on the solar thermal systems

n_{HH} = number of households with a system = $4,080,200 \times 80\,\%$

G_{avg} = average annual irradiation at optimum angle = 2,000 $\quad [G_{\mathrm{avg}}] = \frac{\mathrm{kWh}}{\mathrm{m}^2}$

η_{sol} = average solar thermal efficiency = 80 %

A_{sol} = average size solar system = 2.5 $\quad [A_{\mathrm{sol}}] = \mathrm{m}^2$

s_{tech} = share of technology in total heat demand

In the future, heating and cooling needs will change due to climate change. Winters will become milder and summers hotter [294]. Therefore, heating needs could simply be decreased and cooling increased accordingly to accommodate the new system. However, as explained before, improved heating systems are likely to first aim at decreasing the heating gap. Thus, the heating demand is kept steady. The cooling demand is likely to increase though. According to Oliveira Panão the current cooling needs lie between 16 and $32\,{}^{\mathrm{kWh}}/_{\mathrm{m}^2}$ in Portugal. This range is projected to increase to $26 - 41.2\,{}^{\mathrm{kWh}}/_{\mathrm{m}^2}$ [295]. On average this makes a 40 % increase in cooling, raising the need from 9.18 to $12.86\,{}^{\mathrm{TWh}}/_{\mathrm{a}}$. This value was assumed for 2050 as the renovation rate also affects the cooling needs. Since the rate is low it is unlikely for the thermal insulation of buildings to cover the increased cooling needs alone. Therefore, more electric cooling needs to be deployed since an unchanged cooling demand would result in a greater cooling gap.

4.3.3 Transport

As described in subsection 3.2.2, the transport sector will need to undergo fundamental changes in the upcoming decades. Biofuels are not capable of replacing the entire fossil fuel demand and especially road-based transport will have to transform towards electrically powered vehicles. This prevents an uneconomical increase in electricity demand as shown by Quaschning [157]. Based on the findings of this study, most of the individual transport will be conducted with BEVs. Trucks and buses will also need to be electric. Due to the long distances they have to cover, a larger share will need to be powered via P2G. Since the product life cycles of planes and ships are much greater than that of road vehicles, it is expected that they will still rely on conventional fuels. However, they stem from sustainable resources. Since Portugal has enough biomass to produce enough biofuels for both their national aviation and maritime sector (see subsection 3.3.5), both fuels are produced using biomass for the entire demand. If the demand increases above the available capacity, electrofuels can be produced, however, in the given model this is not regarded as necessary. Table 4.6 shows the demand split into the sectors and types of fuel. A reduction in the demand is not considered. Forecasting the transformation of the transport sector is highly complex due to new technologies and mobility concepts being introduced, such as car sharing or the promotion of increased bike use [169]. Due to the uncertainty a conservative assumption was chosen for this thesis by keeping the total amount of kilometers of each technology unchanged. This was done to ensure feasible results that do not depend too much on a changed mobility concept. Instead, any improvements in efficiency of the technologies are expected to be eaten up by an increased wish to travel.

Table 4.6: Fuel demand by each sector and type in 2050

Means of Transportation		**Share**	**Efficiency Factor**	**Demand**
Light-duty vehicles	**47.3 TWh**			
BEVs		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

EnergyPLAN is also capable of differentiating between dump and smart charging. Smart charging is part of demand-side management (DSM) and adapts the load on the grid depending on the power that is currently available. When variable sources have low outputs, the charging process can be delayed as the car is parked for longer than the charging process would require [164, 166]. This load balancing via EVs can help reduce the demand of flexible power plant capacity for grid stabilization [296]. For the model 6 TWh are available for smart charging, while the other 66 % are considered as inflexible dump charge.

4.3.4 Industry

The industry has not yet been discussed previously but is responsible for a large share of the GHG emissions in Portugal, namely 11 % [156]. These emissions are mainly caused by fossil fuels being primarily used for high temperature processes. Process heat is also used in the service and residential sector, e.g. for cooking, however, their influence is much lower. The industrial processes usually require high temperatures. This makes heat pumps useless, as they are most efficient with a low temperature difference. Therefore, electricity needs to be used directly to cover these demands [157]. Nonetheless, the energy demand can be lowered through efficiency measures. Studies estimate savings between 34 % [297] and 50 % [298]. For this study energy savings of 30 % were considered in accordance with Quaschning [157]. Some of the industrial electric and heating energy demand is covered by CHP by the industry sector itself. Since around 50 % of this energy stems from fossil sources, the electricity produced via CHP was reduced accordingly. The reduced amount of electric and heat energy produced by CHP needs to be replaced and was added to the total electricity demand. Overall, the additional electricity demand of the industry to replace fossil fuels is 24.39 TWh.

4.3.5 Energy Demand

All these measures will change the amount and the share of each energy source. First of all, all fossil sources need to be replaced. As described before, sector coupling and the smart energy system are mainly based on electricity from which almost all other energy forms are created. Therefore, the electricity demand will increase significantly in the future, which politicians need to consider when creating new legislation. The other source that is available is biomass. In this case the main concern is that the energy source is used sustainably within its natural limits.

Table 4.7: 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**

Table 4.7 contains the information about the current electricity demand and for 2050. Overall, it can be clearly noted that the demand will increase. The new demand is 83 % higher due to other sectors relying more strongly on electricity. Regarding the consumption that already existed before the sector coupling, a constant demand is considered. There are many factors that influence this type of demand, e.g. the number of residents in Portugal and efficiency measurements. Projecting the development of the Portuguese population is highly important, however, also highly difficult. Sources either estimate a decrease in the population [299] or an increase [203]. Also the effect of efficiency measurements is difficult to estimate. According to Fuinhas et al., Portugal's growth is directly coupled to its energy

consumption [300], however, Mathiesen et al. have shown that Denmark was able to decouple the two. This proves that, despite the historic correlation, economies can still grow while decreasing their energy demand [242]. Given the complexity of the estimation, the electricity demand was kept at 38.71 TWh. The difference is that a share of the electricity was considered as flexible demand to take into account DSM in the future energy system. This demand was estimated to be 22 % of the uncoupled and industry demand, using a conservative adaptation of Kwon et al. [301]. As described in subsection 4.3.2, the heating demand will remain unchanged but the electricity demand will decrease due to the increased use of heat pumps. The cooling demand will increase by 40 % though. The industry's energy demand for process heat and other processes as well as the decreased energy output from industrial CHP plants will have to be replaced, resulting in a sharp increase of 24.39 TWh. The transport sector will rely mainly on electricity and hydrogen. The electricity demand is 17.49 TWh and that of hydrogen 5.21 TWh.

4.3.6 Costs

There are countless sources for cost predictions. Some evaluate future fuel prices [211, 302], some generation technologies [18, 303–305], storage technologies [306–308] or give a holistic prediction [309]. The complexity to predict future prices is shown by Lund et al. that concluded that a historic evaluation of prior predictions showed that all of them were wrong [310]. Given that external electricity prices will change as well, the issue becomes even more complex. Therefore, the cost predictions are less important as it seems initially as no prediction will be able to reach precise values. The cost database for 2050 used in this thesis is that provided by EnergyPLAN [311]. It contains scientifically well researched values and is therefore suitable for the purposes of this thesis. The only changes that were made were those regarding compressed air energy storage (CAES). As described in subsection 4.3.1, EnergyPLAN allows to model one more storage technology besides hydrogen and gas storage. By default it is modeled for PHES and therefore the cost assumptions need to be changed. For the investment costs [307] was used while [306] was used for the life time of the respective components. The resulting database was used for both the reference and the future models. The reason behind this is that it allows a better comparison of the costs of each system. The complete list of the costs can be found in Appendix B.

Chapter 5

Results & Recommendations

This chapter contains the results of each scenario that was simulated. Each scenario was simulated four times to make sure that the optimization algorithm did not get trapped in a local optimum. The best result was chosen for evaluation in each scenario. Three different scenarios were created. The parameter that was changed for each scenario is the capability index (CI) of the hydro resources. As explained in subsection 4.1.3, EnergyPLAN is only able to simulate one year. However, due to the high reliability of Portugal on hydro power this poses a problem. The reason is that electricity generated by hydro power varies heavily on a yearly timescale (see subsection 2.1.1). For example, in 2016 28 % of the electricity in Portugal was generated by hydropower, making it the most important source of power. In 2017, however, only 10 % came from hydro resources despite an almost identical yearly electricity demand and an increased installed capacity. These variations cannot be balanced out by wind and solar but have to be compensated by dispatchable resources. As natural gas and coal are not available in the future, this challenge will have to be managed by gas plants powered by biogas and synthetic gas (SynGas), and biomass plants, large energy storage systems and a better interconnected European electricity market. Therefore, it is important to check the behavior of the system at different hydro CIs. The results can be combined to create a more realistic scenario for Portugal. After an initial look at how each system's power generation is composed both in capacity and share of produced energy, a deeper analysis is conducted to further study and compare the scenarios. Other aspects, besides the installed capacity and the energy demand and production, were the storage demand of the different storage types that were modeled in EnergyPLAN and the costs. The costs were not only compared between the scenarios but also to the costs of the reference model to check if not only the technical but also economical viability is guaranteed.

Based on these results, an overall system is created that allows Portugal to generate enough energy not only in one scenario but across all of them. Furthermore, recommendations on future steps are given to facilitate this change and create a schedule to ensure a smooth transition from the old to the new energy system.

5.1 Variation of the Hydro Capability Index

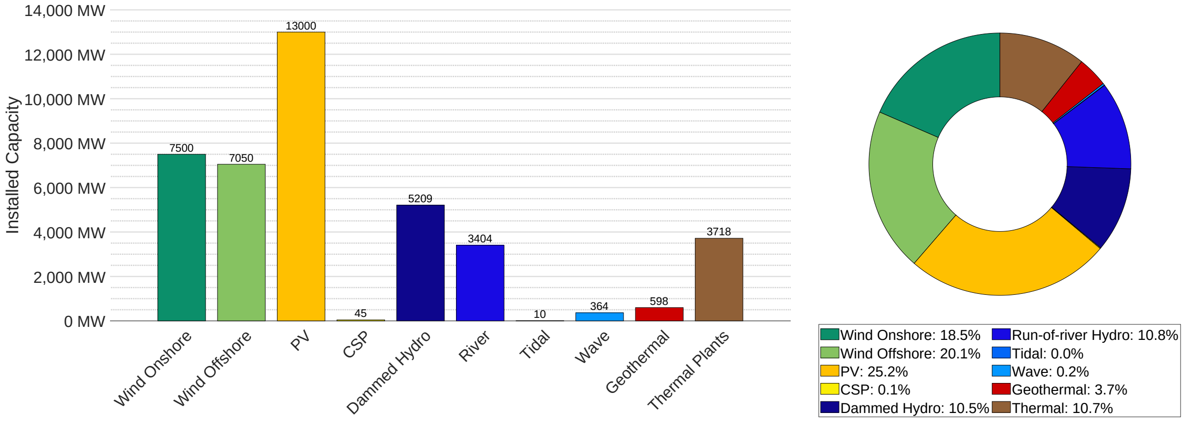
Three different years were chosen to model different scenarios, a wet, a dry and an average year. For the wet year 2016 was chosen as it had the highest CI in the last ten years at 1.33. Furthermore, it is the reference year for the system. Therefore, it is interesting to compare how economical a completely renewable system in comparison to the current system is. For the dry year 2017 was chosen, as it had the lowest CI in the last ten years at 0.47. However, the same relative power generation distributions as for 2016 were used to keep the scenarios comparable. This scenario is expected to have higher capacities overall as other generation technologies need to replace the share of hydropower. An average year with a CI of 1.00 was also used to see what the demand would be when leveled out over the years.

5.1.1 High Hydro Capability Index (Wet Year)

Figure 5.1 shows the results for both capacity and produced electricity in 2050. Figure 5.1a shows the ideal installed capacity for each technology. Figure 5.1b contains the corresponding share that each technology produced. According to the figures, the future system will rely greatly on wind and solar as Portugal's source of electricity. Regarding wind, onshore and offshore have a combined installed capacity of 14,550 MW. Thus, 83 % of their technical potential of 17,500 MW was used. This translates to a respective share of 18.5 for onshore and 20.1 % for offshore wind of the overall electricity production. Combined they hold a share of 38.6 %. The reason why the capacity of onshore was maxed out while the one of offshore was not is likely to be due to the costs. Offshore turbines are still somewhat more expensive. Nonetheless, both technologies are highly cost-efficient and their output is somewhat consistent throughout the year, thus decreasing the need for long-term storage. The second point is especially true for offshore wind power as its output is more consistent than that of onshore.

The second biggest source after wind is solar. The result recommends to install 13,000 MW of PV, maxing out Portugal's available technical potential. This translates to a share of more than a quarter at 25.2 %. In contrast, concentrated solar power (CSP) is seen as not competitive given its capacity of almost zero. It is most likely that its cost is simply too high to compete with the other technologies. Since its source is the same as for PV, the distribution of its generation is the same. Thus the more cost-efficient PV is chosen over CSP. In total wind and solar will provide around two thirds of Portugal's electricity demand and consequently build the backbone of the country's energy system.

Hydropower has traditionally played a big role in Portugal's power matrix. By 2050 it will still be important but to a lesser extent. The traditional hydropower plants, dammed and run-of-river, have an installed capacity of 5,209 and 3,404 MW, respectively. This means that the geographical potential for run-of-river plants is used almost completely, while the capacity for dammed hydropower is kept at the minimum. Thus run-of-river plants are the more economical option in comparison to hydropower with storage dams as they are more costly to build. This also shows that the storage capabilities of this type of power generation will not need to be increased in the future and the plants currently under construction will suffice. In contrast, it is recommended to expand the installed capacity of run-of-river plants to



(a) Capacity of each generation technology

(b) Share of produced electricity

Figure 5.1: Future generation mix by 2050 for a high capability index

the maximum availability. Their share of the electricity production is 10.5 % and 10.8 %, respectively. Overall, this draws the conclusion that a further expansion of hydropower is not as cost-efficient as other options. Besides the cost, another reason could be the distribution of production of hydropower over the year. Figure 5.2 shows the monthly capacity factor of both run-of-river and dammed hydropower as well as wind and solar power. It can be seen that both hydropower types decrease their average output over the year. The variations are quite strong as, for example, dammed hydropower has a capacity factor of around 60 % between January and May but between July and December it only lies at around 20 %. Therefore other technologies need to provide electricity during those months. Figure 5.2 also shows that the distribution profile of wind is very similar to that of hydropower as it decreases during the summer months. Thus, these two types typically produce electricity around the same time. However, wind power increases again in fall. Overall, it can be seen that it is more evenly distributed. As costs of wind turbines are expected to decrease more strongly than those of hydropower, the current cost benefit of hydro will disappear. At similar costs, wind power is more favorable than hydropower due to its smoother distribution curve. In contrast, PV has a very different power generation pattern and therefore does not compete with the other technologies as it produces at different times, mainly during summer when output of the others is low. Instead wind and solar power complement each other and create not only a very smooth power output on a yearly basis as mentioned in subsection 2.1.2 but also on a monthly basis.

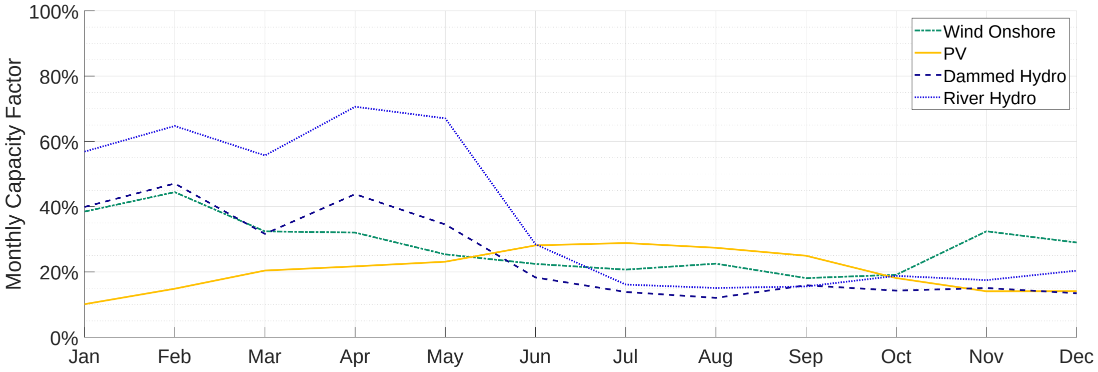


Figure 5.2: Distributions of wind onshore, dammed hydro and run-of-river hydro in 2016 [16]

Marine generation technologies are of little interest at the expected development maturity by 2050. At an installed capacity of 10 MW, tidal power can be neglected. This can be mainly attributed to the still comparatively high costs. Other technologies, such as wind and solar power, simply have much lower LCOEs. For tidal power to become interesting, it would need to have a faster development curve. The same applies to wave power. Its installed capacity of 364 MW translates to a 0.2 % share of the electricity production. Although it is expected to be less expensive than tidal, it cannot yet compete with other generation technologies. Therefore, both technologies lack considerable installed capacities. Just like CSP, they are replaceable in this scenario.

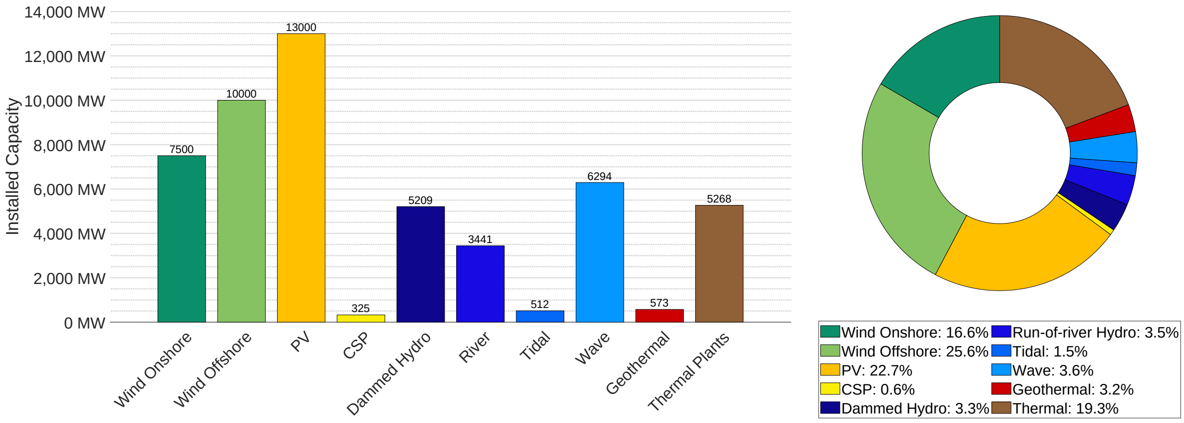
The case is somewhat different for geothermal power. At an installed capacity of 598 MW and a respective share of 3.7 %, it contributes noticeably to the energy system. The issue is that Portugal's mainland has very limited resources for its application. Furthermore, results from other runs for this scenario contained almost no geothermal power at similar costs. Nonetheless, if the costs decrease accordingly, it could play a minor part in the future of the power matrix.

The last technology are thermal plants. As EnergyPLAN does not distinguish between the different types, this category includes both gas and biomass power plants. The industrial CHP plants are not included as their capacity is fixed. However, their energy production of 3.26 TWh is included under the thermal share as they are also thermal power plants. Contrary to the current energy system, the gas power plants do not burn natural gas but biogas and synthetic gas (SynGas), which is produced through electrolysis and CO_2 hydrogenation. SynGas is not imported like natural gas but produced nationally, thus making Portugal self-sufficient. The installed capacity of 3,718 MW lies considerably above the minimum capacity of 3,123 MW. This suggests that even for years with a high hydro CI, the planned installed capacity for 2030 is not capable of balancing out the grid in times of low output of varying generation technologies. The primary energy usage for gas and biomass for a wet year is 9.85 and 2.68 TWh, respectively. Portugal's gas production is 10.7 TWh, thus making it self-sufficient and creating a small surplus of almost 1 TWh.

5.1.2 Low Hydro Capability Index (Dry Year)

The second scenario models the energy system when the CI of hydro is low. This means that other generation technologies will have to step in to make up for the lack of electricity coming from hydropower. Figure 5.3 shows the results for such a situation. Figure 5.3a shows the recommended installed capacities and Figure 5.3b the corresponding share of the energy production in the low hydro capability scenario.

Once again, wind power is seen as one of the most important technologies. In the previous scenario wind power already played a prominent role, yet it grows of importance even more now. This time both potentials are used to their maximum. The expansion also increases their total share of produced electricity from 38.6 to 42.2 % in comparison with the previous scenario. However, the individual shares differ greatly. While offshore wind has increased from 20.1 to 25.6 %, onshore wind has fallen from 18.5 % to 16.6 % despite the same capacity. This decrease can be attributed to an overall greater electricity demand of the system, which is further discussed later on.



(a) Capacity of each generation technology (b) Share of produced electricity

Figure 5.3: Future generation mix by 2050 for a low capability index

The situation for PV is similar to the previous scenario. The technical potential is used entirely resulting in an installed capacity of 13,000 MW. Due to the increased total energy demand the share of PV decreases to 22.7 % as it is not possible to install more PV. The main difference to the previous scenario regarding solar technologies is that CSP plays a minor role this time. The recommended installed capacity is not very big at 325 MW but it shows that in the given situation CSP can contribute to cover the energy demand. Nonetheless, the share is rather small at 0.6 % and could be substituted by other technologies. For CSP to play a bigger role, it would need to decrease its costs even further.

Interestingly, the installed capacities of hydropower are similar to those of the previous scenario. Dammed hydropower is still kept at its minimum, which is not surprising as in a dry year its LCOE is even higher than in a wet one. However, run-of-river plants are still attractive and their capacity is used entirely. Due to the much lower energy output, their shares differ greatly to the high CI scenario. Dammed and run-of river hydro plants only make up 3.3 and 3.5 %, respectively, of the entire electricity generation, in contrast to 10.5 and 10.8 % in the previous scenario.

Maritime technologies show the biggest change in comparison to a year with a high hydro CI. Both technologies, tidal and wave power, show high installed capacities at 512 MW and 6,294 MW, respectively. Due to the lack of energy from hydro power these technologies are needed to substitute parts of it. In this scenario they become financially viable and show significant shares of 1.5 % and 3.6 %, respectively. In this extreme scenario wave power is more relevant than both hydropower technologies dammed and run-of-river.

Geothermal power, on the other hand, has not increased but remained steady at 573 MW. Its share, however, has decreased due to the increase of the total energy demand to 3.2 %. Geothermal power can be very useful, nonetheless, in energy systems that are lacking energy in general. As the demand in a dry year is much higher, this is the case for Portugal. All capacities are increased to cover the added demand. The advantage of geothermal power in such a scenario is that it provides electricity at a very continuous level. In contrast, other technologies vary heavily throughout the year, which needs to be accounted for in the system.

The last mean of energy generation is thermal plants. As shown in Figure 5.3a, like almost all technologies, the installed capacity has increased. However, the new capacity of 5,268 MW does not have to result in a higher share of energy generation, as thermal plants are the only type of plants where installed capacity and produced energy are uncoupled. In this case though, the increase in capacity is followed by an increase in produced electricity. For the given scenario, 19.3 % of the total electricity production stem from thermal plants. The primary energy use increases accordingly to 25.95 TWh of gas and 4.79 TWh of biomass. This is in accordance with the previous statement that the overall demand for electricity increases for years with a low hydro CI. The additional energy is mainly used for the conversion of electricity to gas that is then used in thermal plants at moments of low electricity output of other generation technologies, especially hydropower. An interesting aspect is that the usage of gas increases much more than that of biomass. This is owed to the limit of biomass usage that is set in the optimization to ensure that the optimization does not exceed the available domestic amount of biomass resources.

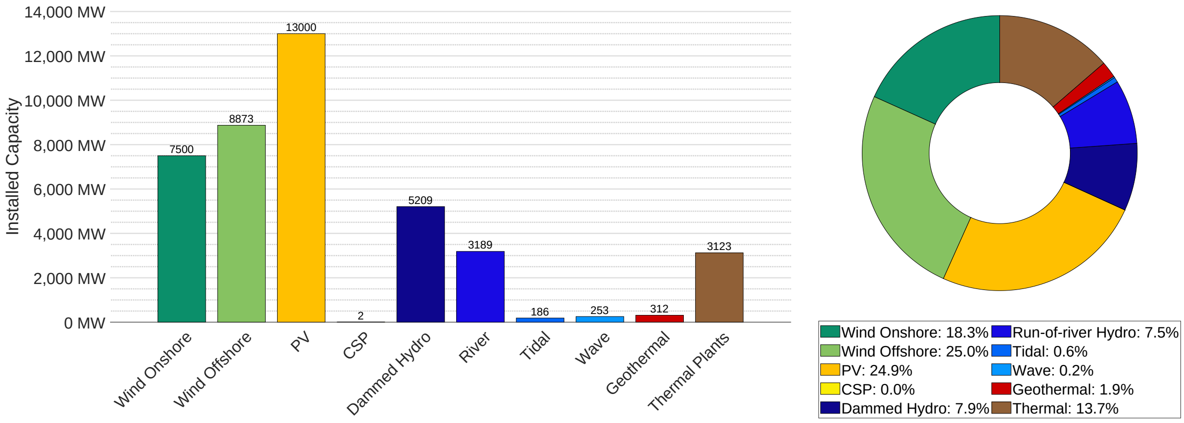
The low hydro CI scenario represents an extreme scenario that models a highly unfavorable availability of natural resources for the given year. It has shown that installed capacities increase strongly to cover the grown electricity demand.

5.1.3 Average Hydro Capability Index (Average Year)

The previous two scenarios presented extreme scenarios that were either very favorable or unfavorable. Although both scenarios contain highly relevant results, they do not represent the average behavior. Therefore, a third scenario was created that assesses how the system should look like for a year with an average hydro CI. The results are shown in Figure 5.4. Figure 5.4a shows the results for the recommended installed capacities and Figure 5.4b holds information about the shares of electricity production for the respective technologies.

Once again, wind power is the backbone of the energy system. As in every scenario, onshore wind is used to its maximum technical potential of 7,500 MW. Offshore wind has an installed capacity that lies between the two extreme scenarios at 8,873 MW. Despite that decrease in comparison to the dry year with a low CI, offshore wind is able to sustain its share because of the lower total electricity consumption. Onshore wind increases its share accordingly to the changed electricity demand. In conclusion, in all three scenarios the energy system relies heavily on wind power with combined shares always around 40 %. Thus, it becomes evident that Portugal needs to invest heavily into wind power in the future as it is a reliable and cost-efficient technology.

Just like onshore wind power, PV reaches its full potential at 13,000 MW. This translates to a similar share in comparison to the other scenarios of 25.0 %. For the case of CSP, the situation is more differentiated. In the given scenario the installed capacity is 2 MW, which is even lower than it was for the wet year. Therefore, it seems that the projected costs of CSP are simply yet too high to compete with other technologies. This will only change, if costs come down even further. Otherwise CSP is not viable, even in a country with high solar irradiance like Portugal.



(a) Capacity of each generation technology (b) Share of produced electricity

Figure 5.4: Future generation mix by 2050 for an average capability index

The results for hydropower are different to those of the two scenarios. Dammed hydropower is still kept at the minimum of 5,209 MW. However, run-of-river plants are also at their minimum capacity of 3,189 MW. This somewhat contradicts the previous two results, where its capacity was maxed out. To understand this result, a more in-depth analysis of the respective optimization result is needed. The explanation is found when looking at the second best result of this optimization run, which recommends an installed capacity of 3,441 MW and therefore the maximum once again. The reason behind it is that a change of 252 MW of capacity affects the overall result only minimally and thus its importance is rather marginal. Optimization algorithms do not always find the absolute optimum but a very close result. The change of the run-of-river capacity affects the cost by less than 1 % and therefore the algorithm sees the system as optimized already. The results for the shares in electricity production are in accordance with the expectations. Dammed hydropower is responsible for 7.9 % of the produced energy and run-of-river plants for 7.5 %.

The results for both maritime technologies are rather low. With 186 MW the installed capacity of tidal power is higher than that of wet year. In contrast, the capacity of wave power is lower at 253 MW. As the scenario does not require as much electricity as that of the low hydro CI, both tidal and wave power become less interesting for the future energy system again. Accordingly, their installed capacity and their shares of the electricity production are decreased. Both technologies play an almost marginal part in the average scenario, although tidal power is more important with a share of 0.6 % in comparison to that of wave power at 0.1 %.

Interestingly, the installed capacity of geothermal power is lower than in the other two scenarios. The results for capacity and generation share are 312 MW and 2.0 %, respectively. The variation in the capacity shows that all currently less mature technologies, namely tidal, wave and geothermal, are within close proximity to each other in terms of viability in Portugal. This also applies to a lesser extent to CSP. Thus, the development of these technologies needs to be closely followed to see how each technology can play its role or if some technologies are clearly more beneficial for the Portuguese energy system and should be valued over others.

Another technology that delivers somewhat unexpected results are the thermal plants. Like geothermal power, their installed capacity falls below that in the other scenarios and is kept at the minimum of 3,123 MW. However, the share in the energy production of 13.7 % is higher than in the wet scenario, proving that capacity and production are uncoupled for thermal power plants. It can be concluded that the capacity is lower as the system is better balanced and more power is not needed from thermal power plants. Nonetheless, the system requires overall more energy to balance out the decrease of hydro energy. Thus, it is only logical that also the total electricity demand falls in between the two other scenarios.

5.2 Comparison of Scenarios and Further Analysis

So far only the installed capacities and their share in the electricity production has been evaluated in each scenario. However, it is also necessary to draw conclusions from the comparison of the scenarios. This is necessary due to the limitation of EnergyPLAN to simulate only one year at a time. The analysis would be incomplete, if every scenario would be looked at separately. 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 reliable under any circumstances. Furthermore, the issue of storage is investigated. So far attention has only been given to the generation side. However, as storage becomes more important, it also needs to be analyzed to give a good estimate about how the future energy system should look like. Lastly, the costs of each of the developed scenarios are compared not only to each other but also to the reference model to see, if the scenarios are not only technically but also economically feasible.

5.2.1 Installed Capacities

Figure 5.5 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. Therefore, it strongly suggests that Portugal should use all its available potential to make use of this cost-efficient resource. Offshore wind power does not have a constant value but increases as the hydro CI decreases. In a year where a lot of electricity stems from the hydropower plants, it is simply not necessary to produce more electricity via offshore wind. Nevertheless, even for a wet year, the installed capacity is above 7 GW, which shows that regardless of the hydro CI, the technology has to play a major role in the future Portuguese energy system.

Regarding PV, the case is identical with that of onshore wind power. The installed capacity is kept at the maximum of 13,000 MW across all scenarios. Therefore, Portugal needs to strongly increase its current capacity of 490 MW. It is likely that both onshore wind and PV could even provide more electricity than in this study, if the technical potential turned out to be even higher than currently estimated. The results of CSP suggest the complete opposite. Based on current cost predictions, the technology is simply not cost-effective and other technologies are more favorable in the case of Portugal.

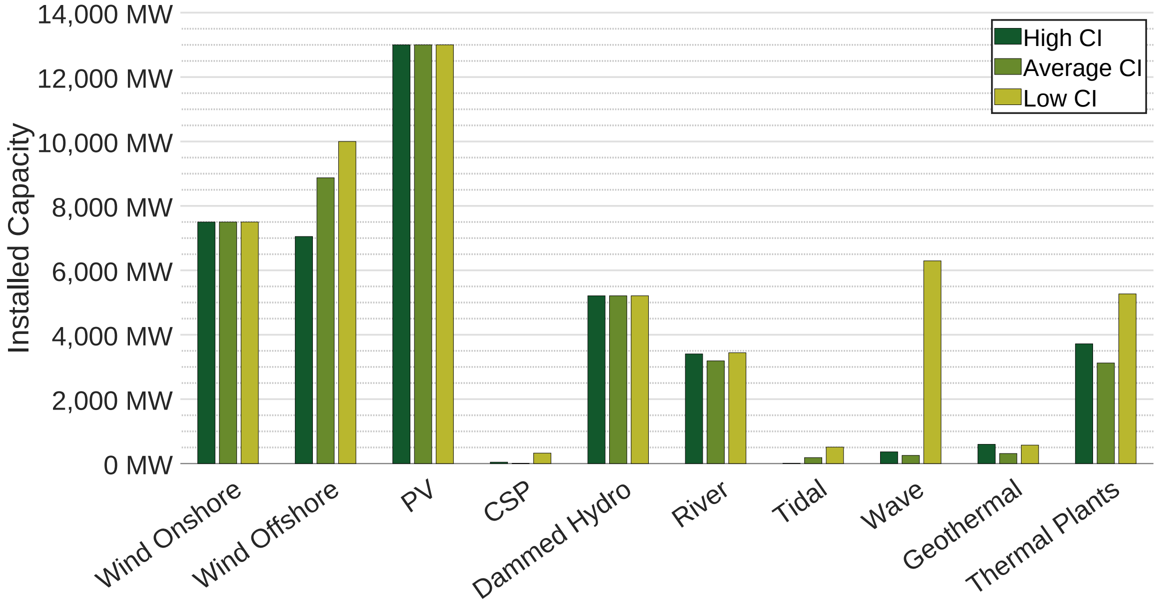


Figure 5.5: Comparison of the installed capacities of each scenario

Dammed hydropower is another technology that does not change across the scenarios. However, this time it is always kept at the minimum. This suggests that the current expansion plans are sufficient as long as the assumption that the increase in installed capacity translates to a linear increase in pump-back and storage capacity. Regrading run-of-river plants, two scenarios are kept at the maximum, while the average scenario recommends to not further build this type of plant. This unusual result is explained in subsection 5.1.3 and is caused by the optimization algorithm. Therefore, it is advisable to use Portugal's technical potential for run-of-river plants to its fullest, although there is very little left.

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. Nonetheless, the results show that Portugal could make use of tidal power, although only to a small extent. The sharp increase for wave power is understood when considering the capacity factor from Table 4.4. While all other technologies have a capacity factor of at least 0.27, wave power has 0.08. This means that much greater capacities need to be installed to produce the same amount of power. In the wet and average year less energy is needed and therefore the role of wave power is negligible. Only in the dry-year scenario, the additional energy of wave power is needed. Therefore, almost 7 GW are installed, which is comparable to the 7.5 GW of onshore wind. However, wind onshore accounts for 16.6 % of the electricity production, while wave power only contributes 3.6 %. All in all, wave power is a technology that should be considered in Portugal, especially since the country is also invested in the R&D of the technology.

The capacities of geothermal power vary but every scenario has at least a share of 2 %. Therefore, geothermal can play a minor role in the energy system of Portugal's mainland as long as the cost predictions for the hot dry rock (HDR) technology are correct. 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, if the system is further improved. 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. This would increase the reliance on other countries and their ability to provide power in those moments of low production. Therefore, it needs to be decided politically, if this dependence is acceptable or not.

The reason, why this possibility of importing more electricity was not considered in the optimization process, is that a limitation on the imported electricity was imposed to ensure Portugal's energy independence. 6.74 TWh would have exceeded this objective as the limit was set to 5 % of the net electricity demand that was forecasted to be 90.23 TWh, as explained in subsection 4.3.5.

5.2.2 Electricity Demand

In the previous sections it was said that the energy demand is increased as the hydro CI sinks. This is supported by Figure 5.6, which shows the total energy demand for each scenario. The category *electricity demand* is the sum of the uncoupled and the industrial demand from Table 4.7. The values of heating, cooling and transport are also obtained from this table. It can be observed that the demand is higher than the total stated in Table 4.7. This is due to the fact that Table 4.7 discusses the electricity demand imposed by the industry, the households and the transport sector. It is the amount of energy that is requested by the end-user. However, it does not consider the electricity the energy industry itself requires to provide this amount of electricity. As explained in subsection 4.3.1, in the future thermal power plants cannot rely on natural gas anymore. Instead the gas needs to be produced in a CO_2-neutral manner. This process, as well as the hydrogen production for the transport sector, requires electricity, which is accounted for as P2G in Figure 5.6. It shows that all other demands remain constant, while only the demand for P2G increases. This increase is not linear across the scenarios. The difference between the dry and the average year is much greater than that between the average year and the wet one. This shows that during a dry year other generation technologies are clearly struggling to provide enough energy as the share of hydropower diminishes. Thermal power plants as well as the improved European interconnection need to make up for the lack of energy. In contrast to the electricity consumption has the primary energy demand clearly fallen. In the reference model it lies at 256 TWh in comparison to 146 – 151 TWh.

5.2.3 Electricity Production

The other part of the energy demand is the energy production. Previously, the production was looked at separately for each scenario, however, a comparison is needed to better understand the behavior of the overall system. Figure 5.7 gives information about the share of each technology in the electricity production for every scenario. The inner ring corresponds to a wet year, while the middle and outer ring correspond to an average and dry year, respectively. Overall, the scenarios show very similar behavior.

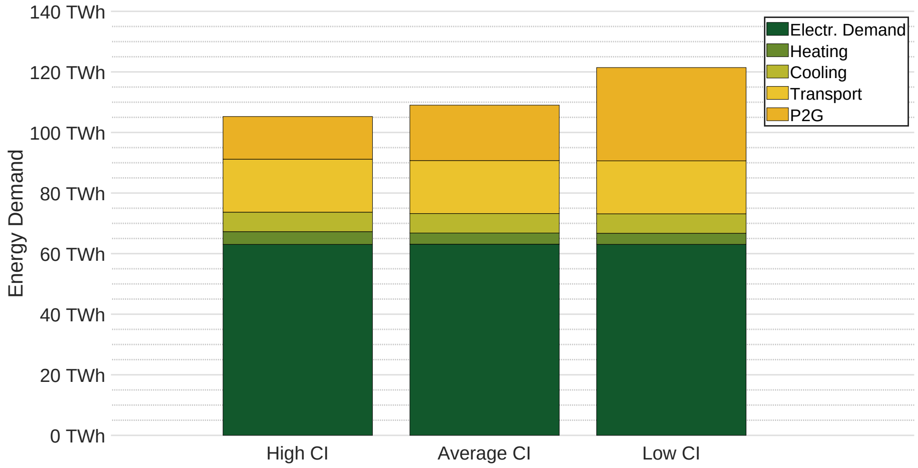


Figure 5.6: Comparison of the electricity demand for each scenario

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 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 at 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.

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 shown in the figure. 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.

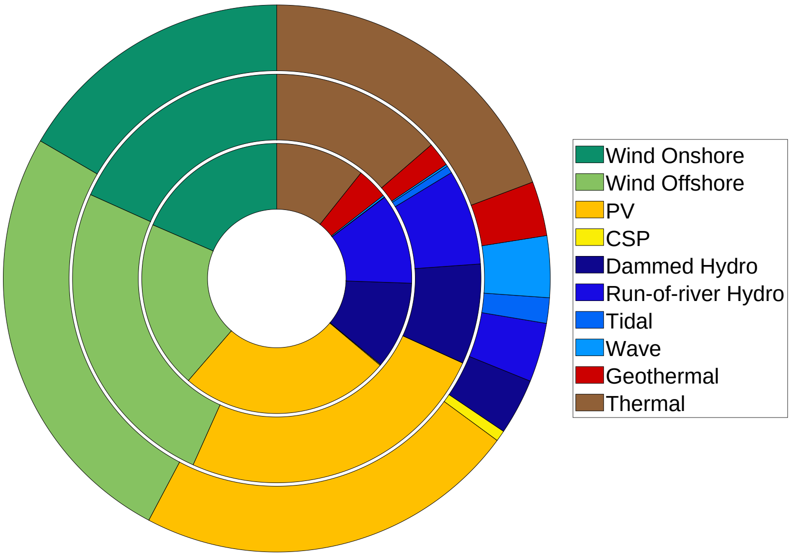


Figure 5.7: Comparison of the share of each technology in the energy production from a wet (inside) over an average (middle) to a dry (outside) year

5.2.4 Import and Export

As mentioned before, the optimization was constrained in terms of the maximum amount that was allowed to be imported and exported. The reason is that models that were developed for other countries expected other countries to absorb their excess electricity production, which could reach more than 20 % of their total production. If every European country plans to export more than it imports, the European energy system will be oversized and costlier than necessary due to overproduction and curtailment. The same applies to the imports. If every country plans to only install varying forms of RE generation and other countries will always be able to provide electricity during times of low domestic energy production, the system cannot work either. Therefore, limits were set in relation to the electricity demand of 90.23 TWh for both imports and exports. In 2016 Portugal exported 14 % of their electricity production [76] and in 2012 17 % of their demand was imported [74]. To set a conservative limit that ensures viable results the limit was set to 5 % for imports and to 10 % for exports of the electricity demand. Figure 5.8 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. For the scenario with a high CI the import is almost diminished to zero. In the low CI scenario the increase is caused by the overall significantly higher electricity demand. This cannot be the cause in the scenario with an average CI, since there is only a minor increase in electricity demand. For this scenario, the increased import is caused by the decreased capacity of the thermal power plants. As explained in subsection 5.2.1, the capacity of these plants has a strong influence on the imported electricity. As they need to cover the moments of high demand and lower power output, the lower their capacity is, the sooner they will operate at their maximum and imports are needed to balance demand and supply.

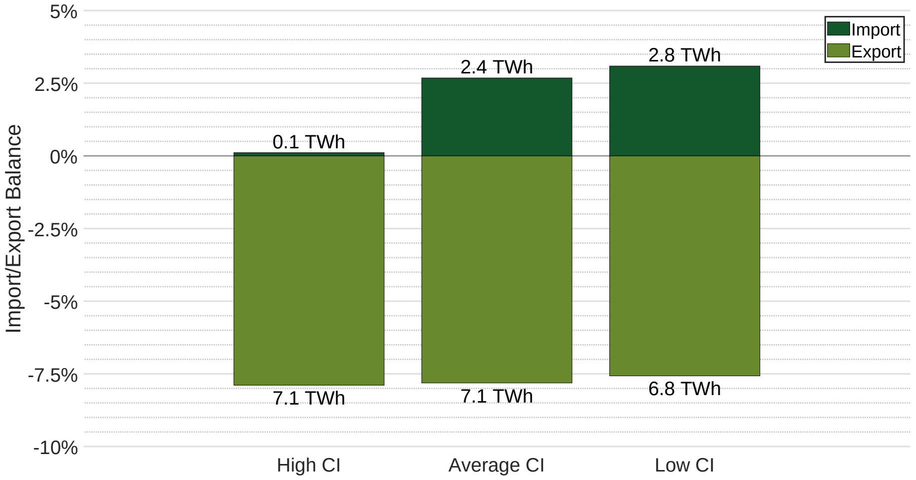


Figure 5.8: Imported and exported electricity of each scenario

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. 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 [140]. Becker et al. calculated a capacity of 4.2 GW, however, based on a coverage percentage of 90 %. In conclusion, the trade-off between thermal power plant and interconnection capacity needs to be made. The former increases the total electricity demand as more SynGas needs to be produced, the latter makes the country less energy independent.

5.2.5 Storage

So far only the generation side of the energy system has been analyzed. However, future systems will need various methods to balance demand and supply. The issue can be eased with DSM measures but not completely. Therefore, storage needs to become part of the electricity system to serve as additional flexibility measure. Please note, that both storage and pump-back capacity of dammed hydropower plants were programmed to increase linearly with the dammed hydro capacity for simplification purposes and are therefore not discussed here. The storage methods that were optimized by the program were hydrogen, CAES and SynGas storage. Further storage technologies were not modeled due to limitations of EnergyPLAN. As explained in subsection 3.3.7, these types of storage rely on the same geological formations. The total available capacity is $1,983\,\mathrm{Mm}^3$, based on [60]. EnergyPLAN needs to know the storage size in GWh though. Therefore a conversion factor was used for each of the storage gases. These were for hydrogen, compressed air and SynGas 889, 6 and $11.91\,{}^{\mathrm{GWh}}/_{\mathrm{Mm}^3}$, respectively. The results of each of the scenarios is presented in Figure 5.9. It can be noted that large scale hydrogen storage, which ranges 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. In the case of CAES, there seems to be a demand, especially in the average and high CI scenarios with a storage amount of around 400 GWh. However, when looking at the results, it can be seen that the CAES system was not used by EnergyPLAN. Therefore, it would have been decreased to 0, if the optimization process had been run for a longer time. Since the additional costs of the system were almost negligible, this would have probably taken an infeasible amount of time. A manual adjustment was more time-efficient. Thus, it can be concluded that both storage types are of little interest in Portugal. The produced hydrogen is directly converted to SynGas while CAES storage is not needed because of the sufficient amount of storage provided by the dammed hydropower plants.

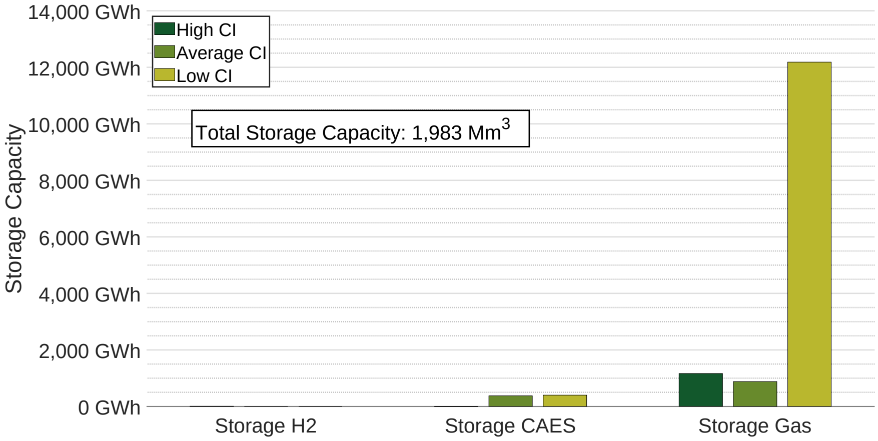


Figure 5.9: Comparison of the storage volume for all three scenarios

The last type of storage is gas. As stated in subsection 3.3.7, the country posseses 333 Mm^3 of gas storage already, which translates to a storage capacity of 3, 967 GWh [76]. Therefore, the amount would already suffice in the first two scenarios. The low CI scenario, on the other hand, states a much higher storage capacity need at over 12 TWh. Once again, this is an imprecision of the optimization. As the expansion of storage capacity is of very low cost, the algorithm does not pay as much attention to it throughout the optimization process. Other similarly priced optimization runs deliver results of as low as 2 TWh. This imprecision becomes especially evident when looking at Figure 5.10. On the left y-axis the storage content is shown over the year of the low CI scenario. On the right side, the charge and discharge rates of the storage is depicted. It shows the volatility of the charge and discharge curve, making it evident that in the future electrolyzers and the SynGas production will need to provide a great amount of flexibility to the system. Regarding the storage content, it can be noted that it never reaches even 3 TWh. Therefore, the proposed storage volume of 12 TWh is oversized for the model.

However, other factors, which affect the necessary size of the storage and are not considered in EnergyPLAN, also play a role. 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. This explains why the storage content is empty when the computation starts and ends. If EnergyPLAN was able to simulate several years, it would be possible to model the behavior of the storage content throughout several years. In this way, it would be possible to tweak the system in a way that would allow to charge the storage during years with a high CI and use the SynGas in years with low output from hydropower plants. This could also be approximated, if it was possible to change the storage content for the beginning and end of the year. Since both options are currently not available, the model cannot give a definite answer to this question. Another issue that was not considered in the optimization process is security. Typically, countries store a higher amount of fuels for times of crisis to ensure their independence. For this reason, France stores enough gas to supply the domestic consumption for 91 days [60] in comparison to 21 in Portugal. REN has a development plan 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

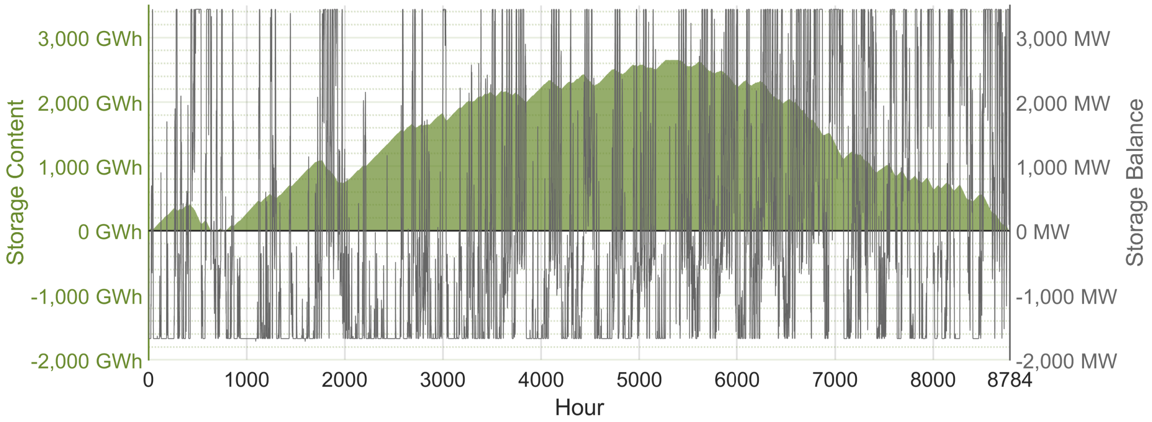


Figure 5.10: Charge/discharge and content of gas storage in the low hydro capability index scenario

demand in 2017 [17]. 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. It would even be possible to exploit less usable storage capacity as 267 days is far above's France's storage security. Overall, Portugal's total available storage capability of 1,650 Mm^3 is more than sufficient across all scenarios and allows enough flexibility to adapt, if more storage capacity is needed for any of the technologies.

5.2.6 Costs

The last aspect that is investigated in this section are the costs of the respective systems and how they compare to the reference model. All scenarios have proven to be technically viable, however, if their costs exceed those of the fossil based system, the likeliness of the system to change decreases. For all scenarios the cost database, found in Appendix B, was used, which models the cost of each technology and fuel by 2050. The results are shown in Figure 5.11, 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 at a total cost of almost 20,000 M€. Their costs range from around 12,800 M€ to 15,400 M€.

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. 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 costs of fossil fuels make up 77 % of the total variable costs. CO_2 emission costs are responsible for another 16 %, decreasing the economic viability of the system even further. In the developed scenarios, the share of the variable costs is much lower. The main variable cost factors in these scenarios are the costs for biomass and the balance of the exported/imported electricity, since fossil fuels are not needed in those systems anymore.

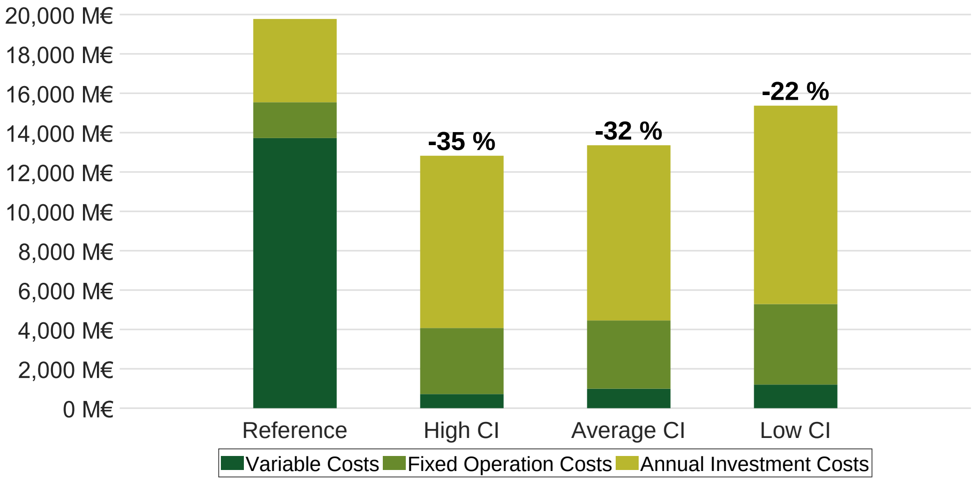


Figure 5.11: Comparison of the total annual costs in 2050

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 between 66 and 68 %, thus, being very similar to the share of the variable costs in the reference model. The reason for these high fixed shares is that variable renewable technologies have very high upfront costs for the erection of the systems. However, as they do not rely on a fuel, their variable costs are much lower. The increase in fixed operation costs is mainly caused by the peripheral industry that allows the flexibility of the system. This includes the electrolyzers and the entire gasification process to produce SynGas.

In conclusion, it is clear that the transition of the energy system is necessary to ensure a reliable, sustainable and competitive supply of energy in Portugal. If the country does not move towards a renewable system, the cost of energy increases making Portuguese products more expensive and less competitive in the world market. Additionally, a self-sufficient energy supply based on renewable energy creates many additional jobs [312] and makes Portugal less dependent on other nations overall.

5.3 Future Energy System

The previous sections have investigated different scenarios for the future of Portugal's energy system, paying special attention to the influence of hydropower. This section 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.

Based on the deliberations in section 5.2 several recommendations can be given for the development of the Portuguese energy system until 2050. To design the future system it is first necessary to know what the average yearly electricity demand will be. At 110 TWh it is set somewhat higher than that of the average CI scenario. The reason behind that is the issue of storage, which was discussed in subsection 5.2.5. EnergyPLAN always calculates for one year at a time. However, in the future, years with higher availability of varying renewable energy sources will be used to produce more SynGas. This gas will be stored in the underground caverns to be used when the availability of the varying resources, specifically hydropower, is low. Since the production of the gas also requires energy, the average demand has to be set higher than that of the average scenario. Once the demand is set, the capacities for the generation technologies can be planned.

The proposed power matrix for 2050 is shown in Figure 5.12, while Table 5.1 contains further details about the development of the Portuguese renewable electricity generation. It can be seen that the system differs greatly from today's. As explained in subsection 5.2.1, Portugal will rely strongly on wind and solar power to cover its demand. Not only onshore wind and solar but also offshore wind uses its full technical potential. Thus, wind and solar power will become the backbone of the energy system. At a combined average electricity production of 82 TWh, they contribute around 75 % of the electricity, as shown in Table 4.4. To achieve these values, a lot of net capacity needs to be added yearly. Onshore wind power is already well developed in Portugal and thus the average expansion is only 73 MW. For

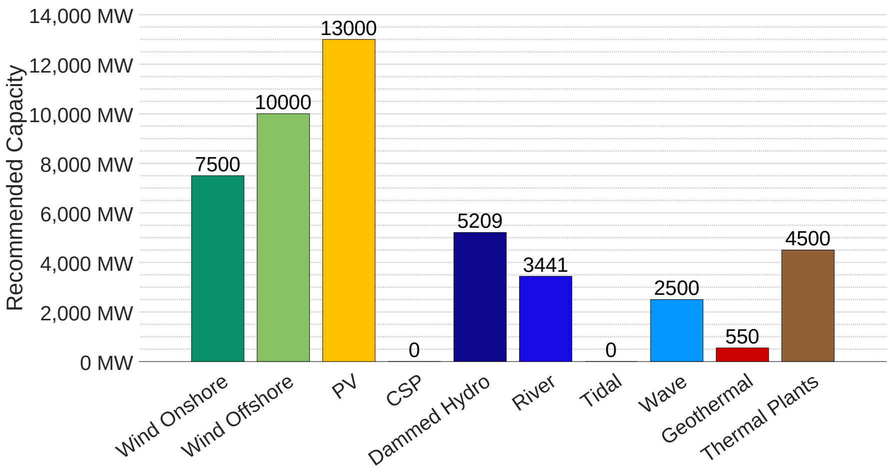


Figure 5.12: Recommended installed capacities for Portugal by the year 2050

the other two technologies this is not the case. As both technologies have no or almost no capacities installed, a sharp increase in capacity installation is required. The yearly net addition is 303 and 379 MW, respectively, for offshore wind and solar power.

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 totaling at 3,441 MW. Dammed hydropower, on the other hand, 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. Thus, the simulation does not consider the development up to that point. It can be the case that at earlier years dammed hydropower is still highly competitive and should therefore be considered. This hypothesis can only be checked, if a model is created for earlier years, which is outside the scope of this thesis. Overall, the contribution of hydropower will shrink to an average of around 16 %.

The electricity generation via biomass in Table 5.1 encompasses biomass and waste. Due to the low usage of biomass for the electricity generation apart from CHP units, biomass was not considered for the future energy system except for the aforementioned industrial CHP. Therefore, the capacity is kept at the level of the expected amount of industrial CHP by 2030 of 560 MW. Biomass and waste have a combined electricity production of around 4 TWh.

Table 5.1: Development of the Portuguese renewable electricity generation until 2050

Technology	**Inst. capacity by 2050 [MW]**	**Avg. yearly added capacity [MW]**	**Avg. produced electricity [TWh]**
Wind Onshore	7,500	73	21
Wind Offshore	10,000	303	32
PV	13,000	379	29
Dammed Hydro	5,209	0	9
River Hydro	3,441	8	9
Wave	2,500	76	2
Geothermal	550	17	4
Biomass & Waste	560	7	4
Total	**42,760**	**855**	**110**

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. For example, the model disregards any energy savings in the traditional, uncoupled electricity demand. A saving of 15 % would be needed to lower the total electricity demand by 6 TWh. As this model does not consider any savings in this sector though, the remaining energy needs to come from elsewhere. The available remaining technologies are CSP, tidal, wave and geothermal power. As shown in subsection 5.2.1, there is no clear winner between the four as they seem to be equally competitive. This thesis recommends the usage of wave and geothermal power to fill the energy gap. This requires an expected installed capacity of around 2,500 MW and 550 MW, respectively. 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 [205]. To build up a wave power industry in Portugal, high domestic demand is crucial. This could enable the technology's breakthrough.

The recommended power matrix results in the electricity evolution, which is depicted in Figure 5.13. The timeframe spans from 1998 to 2050. Please note that before 2010 the electricity production from biomass was estimated, as no reliable source could be found. Before 2005, the production of electricity is mainly split up between hydropower and fossil power plants. Afterwards, onshore wind power is starting to grow in Portugal. Only recently has PV made its entrance in the Portuguese energy system. However, it can be clearly noted that for now its share is marginal despite high solar irradiation in Portugal. From 2016 the values are extrapolated and present average values for each technology. The technologies that will have the biggest change in contribution to the electricity generation will be PV and offshore wind power. As explained before, wind and solar complement each other very well due to their generation pattern throughout the year. In the meantime dammed hydropower will be the first resource to balance out the variations of the other resources [271, 313].

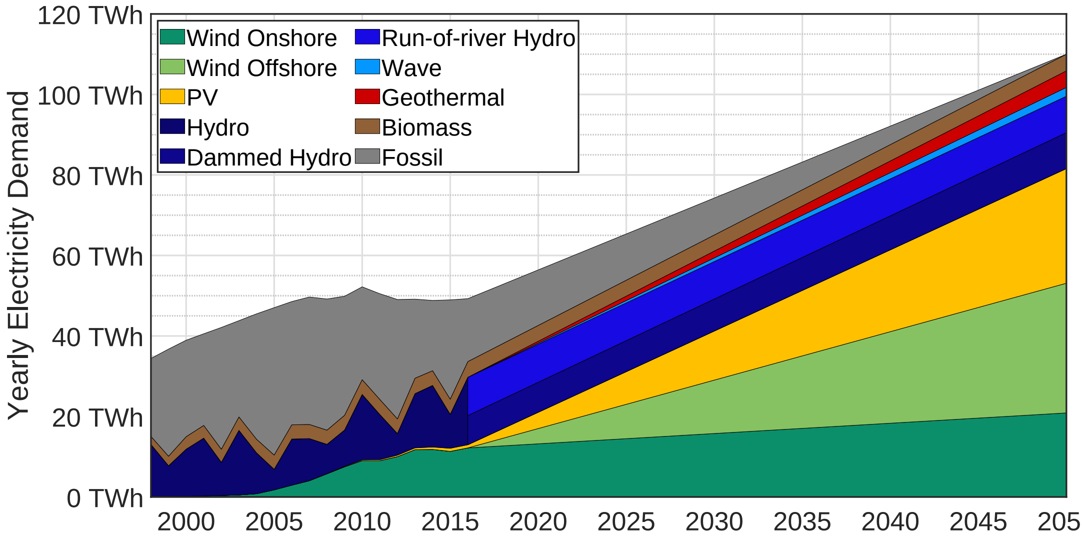


Figure 5.13: Portugal's evolution of electricity demand and production 1998 – 2050 [74–76, 314]

The demand evolution depicted in Figure 5.13 shows a linear evolution of the electricity production. However, this does not depict reality very accurately. First off all, in contrast to solar and wind power, the installation or decommission of hydro and thermal power plants adds or removes significant amounts of capacity at once. Furthermore, onshore wind power is more economical than offshore and thus it is recommended to use Portugal's onshore potential first and shift to offshore turbines afterwards. The last point is the level of maturity of generation technologies that will be necessary in the future. As explained before, wave power is not commercially available. The same goes for geothermal power that uses the HDR technology. Hence, it would be irrational to expect these two technologies to contribute to the Portuguese energy generation in the next decade. All these considerations were taken into account to generate Figure 5.14, 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 to be used until 2024. Thus, the country is able to take advantage of further price drops of offshore wind turbines. Solar wind has a somewhat linear behavior due to its maturity. The dents in the curve are caused by the introduction of wave and geothermal power, respectively. Their expected electricity generation in a linear approach needs to be substituted. As solar power is very competitive in Portugal, this thesis considers it as substitution technology. Regarding hydropower there is very little change expected. There are three plants scheduled to be connected to the grid. The dammed hydropower plant in Gouvães with an installed capacity of 880 MW is scheduled to be in operation by 2021. The run-of-river plants of Daivões and Alto Tâmega with capacities of 114 and 160 MW will go online by 2022 and 2023, respectively [210]. In this roadmap, the remaining technical potential of 285 MW will be operational by 2030, totaling the hydropower capacity at 8,651 MW. 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. The biomass capacity is decreased linearly by 2 MW per year as the capacity needs to be decreased from 624 to 560 MW [17]. However, the type of biomass plants needs to be changed. The currently installed capacity consists of

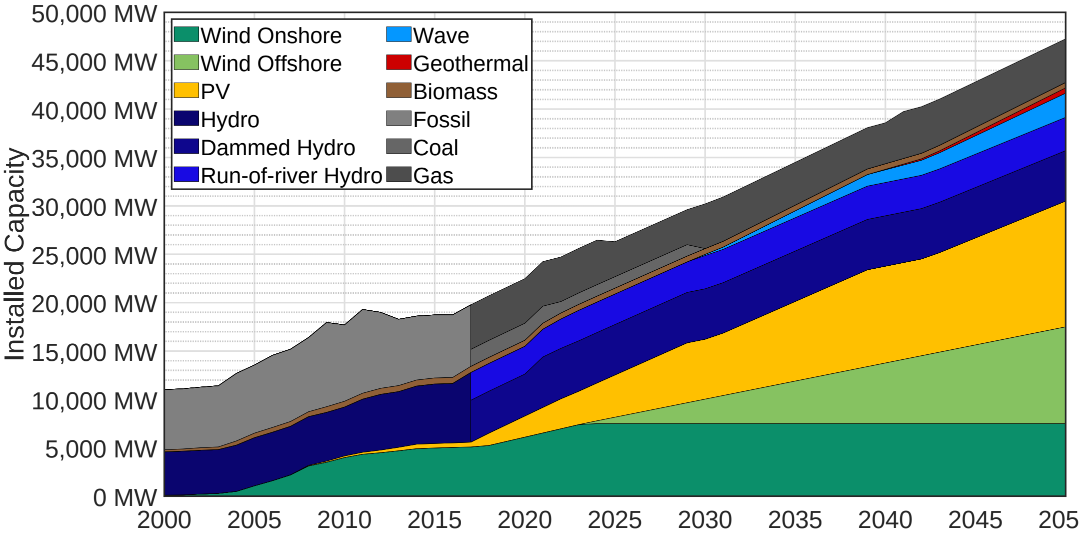


Figure 5.14: Portugal's evolution of the installed capacities considering the technologies' respective maturity until 2050 [17, 69–76]

both CHP and non-CHP plants. Therefore, the capacity of CHP plants will be increased in accordance with Portugal's development plan [210] as there are currently only 351 MW [17]. 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. The smaller power plant in Pego with a capacity of 576 MW will be taken off the grid in 2022, the last plant in Sines in 2030. Regarding gas power, there are currently four major plants in Portugal. However, Tapada Outeiro is scheduled to go offline by 2025. This reduces the current 3,829 to 2,839 MW, which would be the only remaining capacity of major power plants due to the decommission of all coal power plants by 2030 [210]. To counteract this lack of capacity, the roadmap considers the installation of a new gas power plant with a capacity of around 1,000 MW by 2030. Another smaller plant with a capacity of 661 MW is scheduled to go online by 2040 to improve Portugal's flexibility further and raise the total installed capacity of gas power plants 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. What will decrease is their full-load hours as they will serve as a backup when the flexibility of hydro is not enough to cover the demand [315]. The remaining capacity which consists mainly of industrial CHP power plants will need to be decommissioned. As explained in subsection 4.3.4, their electricity and heat generation will be covered otherwise. Most of these power plants are gas fueled, having a share of 95 % of the capacity [17]. 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 %. To obtain a more accurate roadmap it is nevertheless recommended to conduct a thorough study. The corresponding energy production evolution for Figure 5.14 and a table containing the expansion capacity for each year can be found in Appendix C.

Other major parts of the future energy system are the interconnection capacity and even more so the gas generation and storage. Table 5.2 shows the recommended capacities. In terms of interconnection capacity it was already explained in subsection 5.2.4 that according to the results of the scenarios a capacity of around 6.2 GW should be sufficient. However, as the future generation capacity will be around 47 GW, it will be necessary to install slightly more than 7 GW to abide by European regulations. Regarding the gas production, there are two methods, one being biogas and the other SynGas. For the biomass gasification process, the results of the average year were chosen as it was the year that used most of the biomass to produce biogas instead of using it directly in biomass power plants. The conversion of 15 TWh of biomass require a minimum capacity of around 1 GW. For the SynGas production, the results of the dry-year scenario were chosen. The high and average CI scenarios do not consider enough SynGas generation for a low CI scenario. Therefore, the extreme scenario of a dry year fits best to evaluate the necessary capacities. As SynGas relies on electrolyzers to produce first H_2 that then can be converted to SynGas it comes as no surprise for the capacity of the electrolyzers to be bigger. Especially since they also need to produce the 5.2 TWh of H_2 for the transport industry. Therefore, the electrolyzer capacity is 4.2 GW_e while that of the SynGas production is 2.4 GW_e. As explained in subsection 5.2.5, it is difficult to assess the gas storage demand based on the simulations alone. There are more factors that play a role in the considerations than the ones that were used in the optimization. As the main goal was cost reduction of the entire system and gas storage plays an almost marginal part in the total costs, the algorithm

Table 5.2: 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

did not pay much attention to the dimensioning. However, it is possible to compare Portugal's storage capabilities with other countries that are considered to have a reasonably sized gas storage capacity. As said before, France has a capacity equal to 91 days of their domestic gas demand [60]. Considering the extreme scenario of a low CI with a gas consumption of 26 TWh, this translates to a storage capacity of 6.5 TWh. Therefore, it is recommended to expand Portugal's capacity despite the overall decrease of gas usage. Lastly, it should be noted that it would be beneficial to create a separate optimization for the gas production and storage once a path for Portugal's future energy system is decided as this is not the main goal of this thesis. All recommendations are summed up in Table 5.3. The urgency column indicates how fast it should be acted upon the recommendations. It shows that PV and onshore wind power are the most urgent matters as their expansion needs to happen soon. It is followed by offshore wind, run-of-river hydro and thermal plants. Offshore wind will soon be necessary for the Portuguese electricity system and thus its introduction should be properly prepared. Hydro and thermal plants need a longer planning phase due to their size. Thus, planning needs to start soon to stay within the roadmap.

Table 5.3: Summary of recommendation for the generation and storage ranked by urgency from high (5) to low (1)

Technology	Recommendation	Urgency
PV	Quickly install more capacities as good counterbalance to wind and hydro production	5
Onshore Wind	Extend capacities quickly until technical potential is exhausted	5
Offshore Wind	Start building capacities when the potential of onshore wind is exhausted	4
Run-of-river Hydro	Exhaust the full potential of Portugal	4
Thermal Plants	Increase gas power plant capacities to counteract decommission of coal capacities	4
Dammed Hydro	Finish current projects and only extend, if more dammed storage is needed	3
Wave	Install capacities once commercial maturity is reached from around 2030 on	3
Interconnection	Increase capacity according to European legislation	3
Biomass Gasification	Build up capacities to replace natural gas	3
Electrolyzer	Build up capacities to generate hydrogen for the transport sector and SynGas production	3
SynGas	Build up capacities to replace natural gas	3
SynGas Storage	Expand capacities to increase energy security	3
Electricity Storage	Investigate other means of electricity storage and evaluate their use in the future energy system	3
Hydrogen Storage	Verify need and build capacities accordingly	2
Geothermal	Install capacities if necessary and HDR matured from around 2040 on	2
CSP	Await future development as not competitive currently	1
Tidal	Await future development as not competitive currently	1
CAES	Await future development as not competitive currently	1

5.4 Hurdles for the Transformation

Converting Portugal's energy system contains a lot of hurdles that need to be taken into account. Many of them have already been mentioned in chapter 3. This section serves to list them to ensure that the country is well prepared and is able to overcome upcoming obstacles proactively. The hurdles that hinder the transition are contained in Table 5.4. Similar to Table 5.3, they are listed by urgency for a clearer structure and a better understanding of the priorities that need to be set. The highest urgency points are in regard to laying the foundation for a successful transition. They touch the long-term strategy and the market structure. For this reason it contains points such as improving the already developed strategy of NEEAP and preparing the imminent change of the system. Furthermore, the point *Construction Concessions* is in regard to decreasing bureaucratic hurdles that hinder RE technologies from expanding.

The next urgency category touches various topics such as the improvement of the carbon tax system, the erection of an adequate charging infrastructure for a future transport system that primarily relies on electricity and the increase of the renovation rates. These are changes that have still great influence yet are not part of the very foundation of the transition. Nonetheless, they are highly important as they are either imminent or take a long time to take affect and therefore, need to be handled soon.

Recommendations of the third urgency category are those that will become more important in the not so imminent future. Their time-frame is similar to that of the fourth category, however, it is shifted further into the future. For example, non-fossil flexibility capacity is currently less of an issue as there is still enough fossil capacity available to balance out times of low RE output. As 2050 is approached though, these capacities will play a greater role since fossil technologies will fade out until they are non-existent. Therefore, it is necessary to create a system that incentivizes investments in these technologies.

Recommendations of the second category can be seen as fine-tuning of the overall system that need to be kept in mind over the entire duration of the process. Some of these issues will play a greater role in the future but are currently not top-priority. One example for this is the legislative framework for the hydrogen and SynGas production. As these technologies still have to reach its full commercial maturity, they do not play a role yet. Nevertheless, it needs to be kept in mind to deal with the topic when necessary once this point is reached and these gases start replacing fossil fuels. Another issue is that of V2G, which can be a highly useful and cost-efficient tool to balance the grid, however, only if the technology is correctly embedded into the energy infrastructure.

The lowest level is reserved for issues that are far in the future and have a low impact. In this table, the only recommendation is that of the transformation of the domestic maritime and aviation industry. As explained in subsection 3.2.2, they are very difficult to transform and until 2050 there are enough resources to power them with conventional fuels made from renewable resources. The move to hydrogen or other sources will greatly improve their efficiencies, however, they should already be renewable.

Despite the vast number of recommendations, the table is far from complete and many more issues will emerge during the transition. This needs to be kept in mind when tackling the issues as flexibility and adaptability are key to an efficient and smooth transition towards a renewable and cost-efficient system.

Table 5.4: List of topics to tackle for a successful transformation of the energy system listed by urgency

Measure	Recommendation	Urgency
Smart Energy System	Quickly implement measures to couple the three main energy sectors	5
NEEAP strategy	Create long-term strategy for the efficiency market	5
Electricity Market	Change market that allows investment-based RE technologies to make up most of energy generation [147, 316]	5
Construction Concessions	Minimize hurdles for the installation of new RE generation technologies	5
Grid Flexibility	Strengthen grid to accommodate the feed-in of electricity on all voltage levels	4
Carbon Tax	Restructure mechanism to ensure meeting Portugal's carbon emission goals	4
Technology Integration	Ensure fast adaptation of future upcoming technologies	4
Charging	Provide adequate and uniform charging infrastructure to avoid bottlenecking transition to electric vehicles	4
Individual Transport	Provide more alternatives to individual transport to increase passenger efficiency	4
Goods Transport	Move more good transportation from the roads onto the railways	4
Renovation Rates	Improve housing framework to stimulate renovation	4
Thermal Efficiency	Update insulation requirements to accommodate climate change	4
Industry	Set industry targets to be met to allow companies to plan for the future	4
Vehicle Fleet	Promote more efficient cars, especially BEVs	4
Flexibility Capacity	Create adequate compensation system for flexibility measures, e.g. DSM and operating reserve	3
Smart Grid	Gradually introduce smart features into the grid such as smart meters	3
Network Charges	Change framework to accommodate energy transition according to other studies [317]	3
European Integration	Create an electricity market that integrates seamlessly into a unified European one	3
Interconnection	Increase own connection but also urge the extension of the connection between Spain and France	3
Trucks	Develop unified European system to overcome the hurdles imposed by long-distance road transport	3

Table 5.4: List of topics to tackle for a successful transformation of the energy system listed by urgency

Measure	**Recommendation**	**Urgency**
Renovation Deadlines	Set future deadline at which existing buildings need to meet thermal insulation regulations	3
Heating & Cooling	Promote complete change towards high-efficiency electric solutions and to a minor extent biomass	3
Technical Potential	Assess and reevaluate potential of RE in a set interval to ensure validity of the figures	3
Low-level PV Production	Ensure that distribution grid is not overexerted by generation on the consumer side by introducing limits for the maximum feed-in power of a system	2
Electricity Pricing	Introduce flexible electricity pricing schemes to make use of DSM potential	2
Curtailment vs. Storage	Investigate the benefits of both and decide which to apply when and where	2
Hydrogen & SynGas	Provide legislative framework to allow economical production of storage gases	2
V2G	Create adequate technology and legislative framework to allow the usage of BEVs as flexibility source	2
Dwelling stock oversight	Improve oversight measure since currently insufficient	2
Ships & Airplanes	Promote switch to new technologies once available	1

Chapter 6

Conclusion

This thesis investigated how to turn Portugal's entire energy sector sustainable in order to comply with world-wide and European goals to alleviate the effect of climate change. The results have proven that the country is well able to achieve a green, yet economical energy system that allows it to become entirely energy independent.

The first chapter introduced all major technologies that are needed for this transition for both energy generation and storage. The characteristics, especially the influence of the different timescales, were explained in great detail to obtain a better understanding of their advantages as well as disadvantages. Hydro and wind power are already proving their reliability in Portugal in particular. Concerning storage technologies, most of them have not yet reached the level of maturity that most of the generation technologies have. However, Portugal has large water reservoirs due its large-scale use of dammed hydropower. As this is the by far most mature technology and has been applied for decades, it is less dependent on the technology advancements of other storage technologies and is able to balance the grid very well already. This gives Portugal a decisive advantage in comparison to most European countries.

The second chapter described Portugal's current situation and the challenges it is facing in the energy sector. The part gave a better understanding of the circumstances that the country is in and which actions to take to advance. It was shown that Portugal's electricity sector is already well underway due to its historically strong use of hydropower and its strong rise of wind power. Although the country is well connected to its neighboring country Spain, it needs to ensure that the Iberian peninsula becomes integrated into the European electricity market by strengthening connections to France.

The heating and cooling sector is posing little to no issues regarding the source of energy. Portugal has traditionally been using biomass and electricity as main source for its air-conditioning. Therefore, a switch to a system completely based on the two should be no problem. The most important part is the switch from inefficient technologies to efficient ones, specifically heat pumps. The much bigger issue at hand is the poor insulation quality of the country's dwelling stock. This is the most pressing matter that needs to be tackled by incentivizing renovations and setting minimum standards reached at a future point in time.

The transport sector is currently trailing behind its goals and is facing one of the greatest challenges. To achieve a sustainable transport sector, most of it needs to shift towards electricity. This is especially true for road-based transport. This change needs to be accompanied by a well planned charging infrastructure to avoid bottlenecking the transition. For the maritime and aviation sector, the energy will still come from liquid fuels, however, they will be produced based on biomass. Furthermore, the move towards public transportation and goods transportation via railroad is highly encouraged as it greatly improves efficiency.

The legislative side needs to accompany all these changes to allow the creation of an interconnected smart energy system. This results in many adjustments across all aspects of the energy sector. Be it the electricity market itself that is currently not made for investment-based RE generation technologies, over the grid that needs to become more flexible to incorporate more variable power generation to the legal framework for G2V and V2G compensation. As there is no country that has made this transition, it will be a great challenge and the exchange about concepts with other countries should be expedited, especially within the European Union.

The third chapter discussed energy modeling and its optimization. At first the tool, which was used for the analysis, EnergyPLAN, was introduced and its characteristics and limitations explained. Afterwards, the other tool, which was used for the optimization of the energy system, MATLAB, was discussed. However, this was kept to a minimum as it was not the main focus of this thesis. A reference model was created in EnergyPLAN to demonstrate the validity of the model. Once a sufficiently precise model existed, an optimization framework was created in which the algorithm had to operate. This included many predictions for the evolution of the energy sector. As most energy demands will be covered by electricity, the demand increased by 83 %. A main driver for this evolution was the industry sector. Traditionally it produced large shares of the necessary process heat and electricity itself. Since parts came from fossil sources, the share of that production needs to be replaced by renewable power generation.

The results chapter analyzed the results of the optimization process. The high dependence of Portugal on hydropower was considered by varying its capability index to simulate a wet, average and dry year. All scenarios were analyzed to examine the results' validity. Afterwards, the scenarios were compared among each other in terms of installed capacity, electricity demand, electricity production, import and export, storage, and costs. The results showed a sharp increase in the total installed capacity across all scenarios from 19.8 GW in 2017 to 40.9 to 52.1 GW caused by the strong rise of the electricity demand. This rise, however, was accompanied by a sharp decrease of primary energy use by around 40 %. Every scenario showed a strong dominance of wind and solar technologies. Combined their share of the total energy production was between 64 and 68 %. Due to the imposed limitations regarding the maximum importable and exportable amount of electricity, both stayed well below 10 %. The storage via dammed hydropower proved to be sufficient in Portugal's case and CAES was disregarded. However, the results indicated that an increase in gas storage capacity was recommended. All scenarios beat the reference model clearly concerning costs. The least favorable scenario resulted in savings of 22 % while the best one saved 35 %.

Based on the results from the scenarios, a future energy system was created that allows the country to be both sustainable and economical. Additionally, a table listed the level of urgency for each technology to be implemented. It showed that wind and solar will be the main sources of energy as both of them are highly competitive. Therefore, it was recommended that the first technologies to use are onshore wind and especially PV as its potential is very high while the installed capacity in Portugal is still very low. Once the potential of onshore wind is exhausted, offshore wind sites should be built to cover the increasing electricity demand. Hydropower will still play a role yet not to the same extent as today. The remaining potential of run-of-river plants is used while the capacity of dammed hydropower is kept at the currently planned level. The future energy system is based on future technologies to only a minor extent, which shows that most of the technologies to create a renewable energy system already exist. The new technologies are wave and HDR geothermal power. However, these are planned to be used at a later point in time once they have reached commercial maturity and are therefore less urgent. On top of that, the capacity of gas power plants needs to be expanded to balance out the variation in the future. This is a highly urgent matter as in the upcoming decade all coal power plants will be decommissioned as well as almost 1 GW of gas capaciy. These capacities will need to be replaced as gas power plants will be needed to balance out the variable output of the other generation technologies. Unlike nowadays, the gas will be produced renewably. The two types of gas will be biogas and SynGas. The infrastructure for their production will need to be built in the future to ensure the flexibility of Portugal's energy system.

The thesis proved that Portugal has the technical potential to shift their entire energy demand to renewable resources. This will not only decrease the country's dependence on other nations, it will also drive the costs for energy down, therefore, increasing its competitiveness. Many hurdles are to overcome to reach the goal, as shown in this thesis, however, none of them are impossible. The move to renewable energy is without alternative to reach European GHG emission goals. For future work, it is recommended to further investigate the path towards 2050 and Portugal's role inside the European energy market to ensure a smooth transition. To do so, the created model and especially the code can be used. Since the code is able to optimize any energy system, it is possible to be applied to not only to Portugal but any country.

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Appendix A

Code

A.1 Run

```
%------------------------------------------------------------------------------------------------------------%
% Script that gathers all information and runs the optimization
%
% Created in MATLAB R2018a(9.4)
%
% Created by: Markus Doepfert
%
% e-Mail: markus.doepfert@tecnico.ulisboa.pt
%------------------------------------------------------------------------------------------------------------%

%% General settings
clc, clear
set(groot,'defaultFigurePosition',[1 1 1920 916],...
          'DefaultLineLineWidth',2,'defaultAxesFontSize', 26)

%% Load all variables that are required for the optimization
Setup_Optimization

%% Algorithm settings
% Number of cores to run simulation on
inp.cores   = 1;            % # of cores

% Depending on algorithm different parameters need to be set, e.g. agents
C.n_agents  = 300;          % number of agents
C.n_runs    = 25;           % number of maximum runs

% Other criteria
C.figure   = 5;             % creates a figure every nth iteration
C.n_change = [10 5];        % stopping criteria: [min. change of optimization in MEuro, over n runs]
C.reduce   = [100 5 50];    % reduction: [by how many, after how many runs, min agents]
```

```
C.a        = [0.4 0.9];     % parameters to change closing—in behavior: [percentage of runs to set point,
     relative value of point]

%% Start pool
% Check for parallel computation and start pool accordingly
poolobj = gcp('nocreate'); % if pool exists, do not create new one
if inp.cores > 1
    if isempty(poolobj)
        parpool('local',inp.cores)
    elseif ~isempty(poolobj) && poolobj.NumWorkers == inp.cores
        disp('Pool already running. No new pool was created.')
    elseif ~isempty(poolobj) && poolobj.NumWorkers ~= inp.cores
        disp('Pool with wrong number of workers running. Pool is replaced by a correctly sized one.')
        delete(gcp)
        parpool('local',inp.cores)
    end
end

%% Run Optimization
% Start GWO optimization
[topagents,info] = GWO(C,Caps,inp,dir);

% Stop parallel pool
if ~isempty(poolobj)
    delete(gcp)
end

%% Create files of the top 3 solutions
% create files to be used in EnergyPLAN for the alpha, beta and delta wolf
createtopfiles(dir,info.names,topagents.values)

disp('Computation finished.')
```

A.2 Setup_Optimization

```
%_____________________________________________________________________________________________________________%
% Script that provides all the information that is needed for the optimization, e.g. min/max capacities of
% technologies, paths for the files, domain knowledge for advanced initialization of agentpool, etc.
%
% Created in MATLAB R2018a(9.4)
%
% Author: Markus Doepfert
%_____________________________________________________________________________________________________________%

%% Capacity range of technologies

% Creation of EnergyPlan-compatible list of names
Caps.names = cell(1,10);
for r = 1:7
    Caps.names(1,r) = {['input_RES',num2str(r),'_capacity']};
end
Caps.names(8:10) = [{'input_GeoPower_cap'},{'input_cap_pp2_el'},{'input_hydro_cap'}];

% Names for labeling
inp.techs = {'Wind Onshore','PV','Wind Offshore','River',...
             'Tidal','Wave','CSP','Geothermal','Thermal Plants',...
             'Dammed Hydro'};

inp.dvars = {'Pump-back Capacity','Water Supply','Storage Dams',...
             'Transmission Capacity','Share PP2 Gas',...
             'Share PP2 Biomass','Efficiency PP2','Biomass Input',...
             'Storage H2','Produced SynGas','Electrolyser Capacity',...
             'Storage CAES','Charge Capacity CAES',...
             'Discharge Capacity CAES','Storage Gas'};

% Capacity ranges
Caps.min = [5090        % wind onshore currently installed
             490        % PV currently installed
               0        % wind offshore currently installed
            3188.5      % river hydro installed by 2030
               0        % tidal
               0        % wave
               0        % CSP
               0        % geothermal
            3123        % thermal plants
            5209.3]';   % dammed hydro installed by 2030

Caps.max = 1e3*[7.5 13 10 3.441 1 7.7 12 .75 20 6.4]; % maximum potential

%% Include agents manually
% allows to include agents manually that are either a guess or from
% previously computed runs (allows to continue with computation)
```

```
inp.initvalue = [];
inp.initdvar  = [];

%% Paths and Folder definitions

% Path where EnergyPLAN executable is located
dir.energyPlanPath = 'energyPLAN.exe';
% Path of reference file
dir.inputFilePath = 'energyPlan Data\Data\Portugal_2050.txt';
% Path of output folder to store results in
dir.outputFolder = 'Outputs\';

% Check if output folder exist, if not it is created.
if exist(dir.outputFolder,'dir')~=7
    mkdir(dir.outputFolder);
end
% Check if the final letter of dir.outputFolder is "\". If not, add it.
k = strfind(dir.outputFolder,'\');
if k(end)~=length(dir.outputFolder)
    dir.outputFolder=[dir.outputFolder,'\'];
end

%% Other requirements and information

inp.ElDemand        = 90.23;    % electricity demand [TWh]
inp.Importmax       = 0.05;     % how much can be imported (e.g. 5%)
inp.Exportmax       = 0.1;      % how much can be exported (e.g. 10%)
inp.StorageCapacity = 1983;     % storage capacity for gases [Mm3]
inp.Biomassmax      = 42.5;     % maximum available biomass in PT [TWh]
inp.CO2             = [41 100]; % [original amount of CO2 [Mt], amount to save in %]

% Domain knowledge about influence of technologies on emissions (EM) and
% annual costs (AC)
% Technologies: W_on PV W_off River Tidal Wave CSP Geo PP2 Dammed
%  1 = positive impact
%  0 = no knowledge
% −1 = negative impact
inp.DomKnow = [ 1  1  1 1  1  1  1  1 0 1     % EM
               −1 −1 −1 1 −1 −1 −1 −1 0 1];   % AC
```

A.3 GWO

```
%____________________________________________________________________________________________________________%
% Function that sends the energy system setups to EnergyPLAN and evaluates the results using the objective
% function. Using the GWO algorithm, the setups are adjusted and reeavaluated until a stopping criteria is met
%
% Developed in MATLAB R2011b(7.13)
% Edited in MATLAB R2018a(9.4)
%
% Created by: Markus Doepfert
% Inspired by: Seyedali Mirjalili
%
% Main paper: S. Mirjalili, S. M. Mirjalili, A. Lewis
%             Grey Wolf Optimizer
%             Advances in Engineering Software
%             DOI: 10.1016/j.advengsoft.2013.12.007
%
% Input parameters:
%     C:      structure array containing various parameters for the optimization process
%     Caps:   structure array containing the parameters for the capacities of the energy
%             generation technologies
%     input:  structure array containing various parameters, e.g. maximum biomass usage in TWh and
%             maximum import/export in %
%     dir:    structure array containing the paths of the files
%
% Output parameters:
%     topagents:  structure array containing the results for the alpha, beta and delta wolf
%     info:       structure array containing information about the convergence behavior
%____________________________________________________________________________________________________________%

function [topagents,info]=GWO(C,Caps,input,dir)
%% Initialize the positions of search agents
if length(input.DomKnow) == length(Caps.max) % check if input correct
    REc.vars = aInitVar(Caps,input.DomKnow,C.n_agents); % capacity positions (advanced)
    disp('Initial positions are created with advanced algorithm.')
else
    REc.vars = InitVar(Caps,C.n_agents);    % capacity positions (simple)
    disp('Initial positions are created with simple algorithm.')
end
REc.names     = Caps.names;
[REd,~] = depvar(REc.vars,input);       % dependent variables positions
% REd variables that depend on Storage
dStore = {'input_H2storage_trans_cap',...
          'input_storage_pump_cap',...
          'Input_GasNetStorage'};
dim = size([REc.vars REd.vars],2); % capacitiy and dependent variables

%% Replace agents if manual input is desired
% input.initvalue and input.initdvar contain agents' information
```

```
% checks if input.initvalue is empty or only contains zeros
if ~isempty(input.initvalue) && all(all(input.initvalue))
    n_ag = size(input.initvalue,1); % number of agents in input.init
    REc.vars(1:n_ag,:) = input.initvalue;
    REd.vars(1:n_ag,:)  = input.initdvar;
    disp('Agents succesfully replaced.')
end

%% Pre-processing
% initialize alpha, beta, and delta_pos
Alpha_val   = zeros(1,dim);
Alpha_score = inf;  % change this to -inf for maximization problems
Beta_val    =zeros(1,dim);
Beta_score  =inf;   % change this to -inf for maximization problems
Delta_val   =zeros(1,dim);
Delta_score =inf;   % change this to -inf for maximization problems

% initialize results
Convergence_curve       = zeros(1,C.n_runs);
Convergence_curvemax    = Convergence_curve;

% loop variables
TAC     = zeros(1,C.n_agents); import = TAC; export = TAC;
CO2     = TAC; biomass = TAC; Error = TAC; fitness = TAC;
CO2save = input.CO2(1)*(100-input.CO2(2));  % min. CO2 to be saved

%% Waitbar
h = waitbar(0,'Please wait...','Name','Status of optimization',...
            'CreateCancelBtn','setappdata(gcbf,''canceling'',1)');
setappdata(h,'canceling',0);
text = '%d run(s) of %d completed';  % waitbar text in loop

%% Optimization
lc = 0;                                             % loop counter
waitbar(lc/C.n_runs,h,sprintf(text,lc,C.n_runs))        % update waitbar
% Main loop
while lc < C.n_runs
    %% Correct capacity values if necessary
    % Return back the search agents that go beyond the search space
    Flag4input.max  = REc.vars>Caps.max;
    Flag4input.min  = REc.vars<Caps.min;
    REc.vars        = (REc.vars.*(~(Flag4input.max+Flag4input.min)))+...
                      Caps.max.*Flag4input.max+Caps.min.*Flag4input.min;

    %% Create Input Structure
    RE.names = [REc.names REd.names];
    RE.vars  = [REc.vars REd.vars];

    %% Computation of new dependent variables and correction of storage
```

```
[RE,storage] = depvarloop(RE);
storage(storage<=0) = 1e-6;         % to make sure no NaN are created

% Return storage capacity to limit if beyond boundaries
Storage.tot = sum(storage);
Storage.max = Storage.tot>input.StorageCapacity;
Storage.min = Storage.tot<0;
storage = (Storage.tot.*(~(Storage.max+Storage.min)))+...
           input.StorageCapacity.*Storage.max+0.*Storage.min;
ratio_storage = storage./Storage.tot;
for r = 1:numel(dStore)     % update GWh storage capacities
    ind = strcmp(RE.names,dStore(r));
    RE.vars(:,ind) = RE.vars(:,ind).*ratio_storage';
end

%% Call EnergyPlan
if input.cores == 1 % check if to run in parallel or not
    for r = 1:size(RE.vars,1)  % run for every agent
        % Call EnergyPlan
        Results = energyPlanC(dir,RE.names,RE.vars(r,:));

        % Save target values for each search agent
        TAC(r)     = Results.TotalAnnualCosts;          % total annual costs [MEuro]
        import(r)  = Results.Import/input.ElDemand;     % ratio import/demand
        export(r)  = Results.Export/input.ElDemand;     % ratio export/demand
        CO2(r)     = Results.CO2;                       % total CO2 emissions
        biomass(r) = Results.Biomass-input.Biomassmax;  % excess of biomass [TWh]
        Error(r)   = Results.Error;                     % check for errors
    end
else
    [TAC,import,export,CO2,biomass,Error] = energyPlanp(dir,input,RE.names,RE.vars);
end

%% Find best agents
% Result corrections
biomass(biomass<0) = 0; % no negative values

% Objective function
fitness(CO2>CO2save) = TAC(CO2>CO2save).*...    % CO2 above threshold
    (1+(import(CO2>CO2save)/input.Importmax).^30+...
    (export(CO2>CO2save)/input.Exportmax).^30+...
    0.2*((1+5*lc/C.n_runs)*CO2(CO2>CO2save)+biomass(CO2>CO2save)+Error(CO2>CO2save)));
fitness(CO2<=CO2save) = TAC(CO2<=CO2save).*...  % CO2 below
    (1+(import(CO2<=CO2save)/input.Importmax).^30+...
    (export(CO2<=CO2save)/input.Exportmax).^30+...
    0.2*(biomass(CO2<=CO2save)+Error(CO2<=CO2save)));

% Find the 3 best scores from the computations
% Update Alpha, Beta, and Delta
```

```
    if min(fitness) < Alpha_score
        [Alpha_score, ind]  = min(fitness);
        fitness(ind)        = Inf;              % "deletes" lowest value
        Alpha_val           = RE.vars(ind,:);
    end
    if min(fitness) < Beta_score
        [Beta_score, ind]   = min(fitness);
        fitness(ind)        = Inf;              % "deletes" lowest value
        Beta_val            = RE.vars(ind,:);
    end
    if min(fitness) < Delta_score
        [Delta_score, ind]  = min(fitness);
        Delta_val           = RE.vars(ind,:);
    end

    %% Simulate wolfs closing in on prey
    % simulate different hunting behavior of wolfs
    if numel(C.a) == 2          % a decreases parabolically from 2 to 0
        np = [round(C.a(1)*C.n_runs) C.a(2)*2]; % find x,y of point for polyfit
        f  = polyfit([0 np(1) C.n_runs-1],...   % 2nd degree function
                     [2 np(2) 2-(C.n_runs-1)*2/C.n_runs],2);
        a  = polyval(f,lc);
        if a > 2
            a = 2;
        end
    else
        a = 2-lc*2/C.n_runs;    % a decreases linearly from 2 to 0
    end

    %% Update the position of search agents
    r1      = rand(size(RE.vars));
    r2      = rand(size(RE.vars));
    A1      = 2*a*r1-a;                         % Equation (3.3)
    C1      = 2*r2;                             % Equation (3.4)
    D_alpha = abs(C1.*Alpha_val-RE.vars);   % Equation (3.5)-part 1
    X1      = Alpha_val-A1.*D_alpha;        % Equation (3.6)-part 1
    r1      = rand(size(RE.vars));
    r2      = rand(size(RE.vars));
    A2      = 2*a*r1-a;                         % Equation (3.3)
    C2      = 2*r2;                             % Equation (3.4)
    D_beta  = abs(C2.*Beta_val-RE.vars);        % Equation (3.5)-part 2
    X2      = Beta_val-A2.*D_beta;              % Equation (3.6)-part 2
    r1      = rand(size(RE.vars));
    r2      = rand(size(RE.vars));
    A3      = 2*a*r1-a;                         % Equation (3.3)
    C3      = 2*r2;                             % Equation (3.4)
    D_delta = abs(C3.*Delta_val-RE.vars);   % Equation (3.5)-part 3
    X3      = Delta_val-A3.*D_delta;        % Equation (3.5)-part 3
    RE.vars = (X1+X2+X3)/3;                 % Equation (3.7)
```

```

% Make sure that no negative values exist
RE.vars(RE.vars<0) = 0;

lc                 = lc+1;              % loop counter

%% Reduce pool of agents if desired
if numel(C.reduce) == 3                                                 % check if input correct
    if mod(lc,C.reduce(2)) == 0                                         % check if nth run reached
        if size(RE.vars,1) > C.reduce(3)                                % check if enough agents available
            if size(RE.vars,1)-C.reduce(1) > C.reduce(3)                % check by how many to reduce
            else
                C.reduce(1) = size(RE.vars,1) - C.reduce(3);
            end
                [~,Ind]     = maxk(fitness,C.n_agents);                 % rank results
                RE.vars     = RE.vars(Ind([1:2 3+C.reduce(1):end]),:);  % exclude worst
                TAC         = TAC(1:end-C.reduce(1));
                import      = import(1:end-C.reduce(1));
                export      = export(1:end-C.reduce(1));
                CO2         = CO2(1:end-C.reduce(1));
                biomass     = biomass(1:end-C.reduce(1));
                Error       = Error(1:end-C.reduce(1));
                fitness     = fitness(1:end-C.reduce(1));
                C.n_agents  = C.n_agents-C.reduce(1);                   % new # agents
            fprintf('Current number of agents: %.f.\n',C.n_agents)
        else
            warning('Agent pool cannot be further reduced.')
        end
    end
else
    warning('Reduction process not possible due to incorrect input.')
end

%% Create REc and REd for subsequent compuations
REc.vars = RE.vars(:,1:10);
REd.vars = RE.vars(:,11:end);

%% Save relevant data
Convergence_curve(lc)    = Alpha_score;                     % best agent
Convergence_curvemax(lc) = max(fitness(fitness<inf));   % worst agent

%% Waitbar, figures, other stopping criterions
% Update waitbar
waitbar(lc/C.n_runs,h,sprintf(text,lc,C.n_runs))

% Create figure
if rem(lc,C.figure) == 0
    figure(1), clf
    plot(Convergence_curve(1:lc))
```

```
        grid minor
        ylabel('Total Annual Costs in MEuro')
        xlabel('Runs')
    end

    % Check if optimization canceled
    if getappdata(h,'canceling')
        break
    end

    % Check if second stopping criterion is fulfilled
    if lc > C.n_change(2)
        if Convergence_curve(lc—C.n_change(2))—Convergence_curve(lc) < C.n_change(1)
            break
        end
    end
end

%% Gather output data
topagents.score             = [Alpha_score; Beta_score; Delta_score];
topagents.values            = [Alpha_val; Beta_val; Delta_val];
info.convergence_curve      = Convergence_curve(1:lc);
info.convergence_curvemax   = Convergence_curvemax(1:lc);
info.names                  = RE.names;

%% Waitbar: end optimization
waitbar(1,h,'Optimization completed.')
pause(0.5)
close all force

end
```

A.4 aInitVar

```
%------------------------------------------------------------------------------------------------------------%
% Function to create the inital values for all relevant values using and advanced method that is based on
% domain knowledge
%
% Created in MATLAB R2018a(9.4)
%
% Author: Markus Doepfert
%
% Main paper: Md Shahriar Mahbub , Markus Wagner, Luigi Crema
%             Incorporating domain knowledge into the optimization of energy systems
%             Applied Soft Computing
%             DOI: 10.1016/j.asoc.2016.06.013
%
% Input parameters:
%     Caps:       structure array containing the parameters for the capacities of the energy
%                 generation technologies
%     DomKnow:    matrix containing information about characteristics of technology
%     n_Agents:   number of agents to be created
%
% Output parameters:
%     Positions:  matrix containing the values of each technology for each agent
%------------------------------------------------------------------------------------------------------------%
function Positions = aInitVar(Caps,DomKnow,n_Agents)

b = 2; % adjusts how likely it is to approach extreme values
delta = zeros(n_Agents,length(DomKnow));
delta(:,DomKnow(1,:)==1)  = rand(n_Agents,numel(nonzeros(DomKnow(1,:)==1))).^(1/(b+1));        % positively impacts emissions
delta(:,DomKnow(1,:)==0)  = rand(n_Agents,numel(nonzeros(DomKnow(1,:)==0)));                   % no impact on emissions
delta(:,DomKnow(1,:)==-1) = 1-(1-rand(n_Agents,numel(nonzeros(DomKnow(1,:)==-1)))).^(1/(b+1)); % negatively impacts emissions

Positions = round(delta.*(Caps.max-Caps.min)+Caps.min,4);

end
```

A.5 InitVar

```
%_____________________________________________________________________________________________________________%
% Function to create the inital values using a simple equal distribution
%
% Created in MATLAB R2018a(9.4)
%
% Author: Markus Doepfert
%
% Input parameters:
%     Caps:       structure array containing the parameters for the capacities of the energy
%                 generation technologies
%     n_Agents:   number of agents to be created
%
% Output parameters:
%     Positions:  matrix containing the values of each technology for each agent
%_____________________________________________________________________________________________________________%
function Positions = InitVar(Caps,n_Agents)

Positions=round(rand(n_Agents,numel(Caps.max)).*(Caps.max-Caps.min)+Caps.min,4);

end
```

A.6 depvar

```
%___________________________________________________________________________________________________________%
% Function that computes all subsequent variables depending on the computed capacities in REvalue
%
% Created in MATLAB R2018a(9.4)
%
% Created by: Markus Doepfert
%
% Input parameters:
%       REvalue:        capacities of the RE generation technolgies
%     input:    miscallenous information about limiting parameters, e.g. total storage capacity
%
% Output parameters:
%     REdvar:           values for the dependent variables
%
% Notes:
%     Variables are sorted according to the structure in EnergyPlan (V13.2)
%___________________________________________________________________________________________________________%

function [dvar,Storage]  = depvar(REvalue,input)
%% Setup
n_age   = size(REvalue,1);      % number of agents
Storage = zeros(3,n_age);

%% Demand

% Electricity
% no variables to set --> electricity demand set

% Heating
% no variables to set --> heating demand set

% Cooling
% no variables to set --> cooling needs set

% Industry and Fuel
% no variables to set --> will be covered by electricity in the future
% biomass is kept at same level

% Transport
% no variables to set --> values are according to the shares of
% Quaschning's study "Sektorkopplung"

% Water
% no variables to set

%% Supply

```

```
% Heat and Electricity
% no variables to set

% Electricity Only
% Pump–back capacity
REdvar.input_hydro_pump_cap     = REvalue(:,10)'*2437/3278.3;           % pump back capacity of dams [MW]
% Dammed water supply based on dry–avg–wet year
REdvar.input_hydro_watersupply  = REvalue(:,10)'*7.966/3287.3/1.33;     % dammed hydro water supply [TWh]
% Storage Reservoir
REdvar.input_hydro_storage      = REvalue(:,10)'*3188/3287.3;           % Storage of dams [GWh]
% Transmission Capacity
REdvar.input_max_imp_exp        = sum(REvalue,2)'*0.15;                 % import/export transmission [MW]

% Heat Only
% no variables to set

% Fuel Distribution
% PP2 (Fixed)
REdvar.input_fuel_PP2_3 = 20*rand(1,n_age);                                         % share of gas
REdvar.input_fuel_PP2_4 = 20*rand(1,n_age);                                         % share of biomass
REdvar.input_eff_pp2_el = (0.7*REdvar.input_fuel_PP2_3+0.4*REdvar.input_fuel_PP2_4)./...
                           sum([REdvar.input_fuel_PP2_3; REdvar.input_fuel_PP2_4]); % efficiency of PP2

% Waste
% no variables to set

% Liquid and Gas Fuels
    % Biofuels
    % no variables to set

    % Biogases
    REdvar.Input_GasiBiomassInput = rand(1,n_age)*10;               % arbitrary maximum input of 10 TWh

    % Hydrogen
    Storage(1,:) = input.StorageCapacity.*rand(1,n_age);            % H2 storage [Mm3]
    REdvar.input_H2storage_trans_cap = 889*Storage(1,:);            % H2 storage [GWh]

    % Electrofuels
    REdvar.Input_CO2HydroSynGridGas = input.ElDemand*rand(1,n_age);     % Gas produced from H2 and CO2 [TWh]

    % Hydrogen (continuation)
    REdvar.input_cap_ELTtrans_el    = 130*REdvar.Input_CO2HydroSynGridGas+...
                                      1600;     % electrolyser capacity for SynGas and Transport H2 [MWe]

    % Gas to Liquid
    % no variables to set

% CO2
% no variables to set
```

```

%% Balancing and Storage

% Electricity
% CAES
Storage(2,:)                  = (input.StorageCapacity-Storage(1,:)).*...
                                 rand(1,n_age);             % CAES Storage [Mm3]
REdvar.input_storage_pump_cap = 6*Storage(2,:);             % Storage Capacity [GWh]
REdvar.input_cap_pump_el      = 2*Storage(2,:);             % Charge Capacity [MW]
REdvar.input_cap_turbine_el   = REdvar.input_cap_pump_el;       % Discharge Capacity [MW]

% Thermal Storage
% no variables to set

% Liquid and Gas Fuel
Storage(3,:)               = (input.StorageCapacity-Storage(1,:)-Storage(2,:)).*...
                              rand(1,n_age);                % Storage Capacity Ngas [Mm3]
REdvar.Input_GasNetStorage = 11.91*Storage(3,:);            % Storage Capacity Ngas [GWh]

%% Gather all relevant variables and names
dvar.names = fieldnames(REdvar)';
dvar.vars  = zeros(n_age,length(fieldnames(REdvar)));

for r = 1:size(dvar.vars,2)
    dvar.vars(:,r) = REdvar.(dvar.names{r})';
end

% Correct fieldnames of Fuel Distribution
ind = strfind(dvar.names,'input_fuel_PP2');
ind = find(not(cellfun('isempty', ind)));
for r = 1:numel(ind)
    dvar.names(ind(r)) = {[dvar.names{ind(r)}(1:end-2),'[',dvar.names{ind(r)}(end),']']};
end
```

A.7 depvarloop

```
%____________________________________________________________________________________________________________%
% Function that computes all subsequent variables depending on the computed capacities in REvalue and
% the looped values in depvar
%
% Created in MATLAB R2018a(9.4)
%
% Created by: Markus Doepfert
%
% Input parameters:
%       REvalue:        capacities of the RE generation technolgies
%     input:    miscallenous information about limiting parameters, e.g. total storage capacity
%
% Output parameters:
%     REdvar:           values for the dependent variables
%
% Notes:
%     Variables are sorted according to the structure in EnergyPlan (V13.2)
%____________________________________________________________________________________________________________%

function [RE,Storage]  = depvarloop(RE)
%% Supply

% Electricity Only
% Pump-back capacity
RE.vars(:,11) = RE.vars(:,10)'.*2437/3278.3;       % pump back capacity of dams [MW]
% Dammed water supply
RE.vars(:,12) = RE.vars(:,10)'.*7.966/3287.3/1.33;      % dammed hydro water supply [TWh]
% Storage Reservoir
RE.vars(:,13) = RE.vars(:,10)'.*3188/3287.3;       % Storage of dams [GWh]
% Transmission Capacity
RE.vars(:,14) = sum(RE.vars(:,1:10),2)'.*0.15;      % import/export transmission [MW]

% Fuel Distribution (Fixed)
RE.vars(:,17) = (0.7*RE.vars(:,15)+0.4*RE.vars(:,16))./...
                 sum(RE.vars(:,15:16),2);       % efficiency of PP2 due to different fuels
RE.vars(isnan(RE.vars(:,17)),17) = 0.5;     % ensure there are no NaN

% Liquid and Gas Fuels
% Hydrogen
Storage(1,:)  = RE.vars(:,19)/889;          % H2 storage [Mm3]
RE.vars(:,21) = 130*RE.vars(:,20) + 1600;       % electrolyser capacity for SynGas and Transport H2 [MWe]

%% Balancing and Storage

% Electricity
% CAES
Storage(2,:)  = RE.vars(:,22)/6;        % CAES storage [Mm3]
```

```
RE.vars(:,23) = 2*Storage(2,:);         % Charge Capacity [MW]
RE.vars(:,24) = RE.vars(:,23);          % Discharge Capacity [MW]

% Liquid and Gas Fuel
Storage(3,:)  = RE.vars(:,25)/11.91;    % Storage Capacity Ngas [Mm3]

end
```

A.8 energyPlanC

```
%____________________________________________________________________________________________________________%
% Function that passes over the agents to EnergyPlan to evaluate their performance
%
% Created in MATLAB R2018a(9.4)
%
% Created by: Pedro Cabrera
% Edited by: Markus Doepfert
%
% Input parameters:
%         pathd:        structure array containing the paths of the files
%         varargin:     cell containing the values of each parameter and the corresponding name for each agent
%
% Output parameters:
%     Results:  values that will be needed in the objective function
%
% Subfunctions: changeInputEnergyPlanp, resultsEnergyPlan
%____________________________________________________________________________________________________________%

function Results = energyPlanC(pathd,varargin)

%% Folder and file definitions
%Definition of a new input file from reference input file and new changes.
inputFilePath  = [pathd.inputFilePath(1:end–4) '_tmp.txt'];
[Success, Msg] = copyfile(pathd.inputFilePath, inputFilePath);
assert(Success, Msg)    % check if creation was succesful

% Definition of output file name
k              = strfind(inputFilePath,'\');
outputFilePath = [pathd.outputFolder pathd.inputFilePath(k(end)+1:end–4), '_out'];

%% Function that changes input reference file.
names  = varargin{1};
values = varargin{2};
% Call to function that changes inputs.
changeInputEnergyPlanp(pathd.inputFilePath,inputFilePath,names,values);

%% EnergyPLAN is executed.
executionString = sprintf('"%s" –i "%s" –ascii "%s"', pathd.energyPlanPath, inputFilePath, outputFilePath);
system(executionString);

%% Desired results are obtained from the output file.
Results = resultsEnergyPlan(outputFilePath);

delete(inputFilePath)
delete(outputFilePath)

end
```

A.9 changeInputEnergyPlanp

```matlab
%____________________________________________________________________________________________________________%
% Function that changes the reference input file to create a new one with the changed parameters
%
% Created in MATLAB R2018a(9.4)
%
% Created by: Pedro Cabrera
% Edited by: Markus Doepfert
%
% Input parameters:
%     inputFilePath:  name of the input file
%     outputFilePath: name of the output file
%     names:          names of the parameters to be changed
%     values:         vales of the parameters to be changed
%
% Output parameters:
%     none
%____________________________________________________________________________________________________________%

function changeInputEnergyPlanp(inputFilePath,outputFilePath,names,values)
        warning('off','all')
        % Read txt into cell A
        fid    = fopen(inputFilePath,'rt', 'n', 'UTF16LE');
        i      = 1;
        tline  = fgetl(fid);
        A{i,1} = tline;
        while ischar(tline)
            i = i+1;
            tline = fgetl(fid);
            A{i,1} = tline;
        end
        fclose(fid);

       A{1,1} = 'EnergyPLAN version';
       A{2,1} = [];
       A      = A(~cellfun('isempty',A));

       % Change cell A 1st cell contains names, 2nd values
       names = strcat(names,'=');
       for i = 1:length(names)
           try % try without blank before the name
               tf = strcmp(A,names(i));     % check name from 1st cell
               tf = circshift(tf,1);
               if iscellstr(values(i))==1   % check if text or number
                   A{tf} = values(i);
               else
                   A{tf} = sprintf('%1.4f',values(i));
               end
```

```
           catch % try with blank before the name (sometimes necessary)
               names(i) = strcat({' '},names(i));
               tf = strcmp(A,names(i));     % check name from 1st cell
               tf = circshift(tf,1);
               if iscellstr(values(i))==1   % check if text or number
                   A{tf} = values(i);
               else
                   A{tf} = sprintf('%1.4f',values(i));
               end
           end
       end

        % Write cell A into txt
        fid = fopen(outputFilePath, 'Wt');
        for i = 1:numel(A)
            if A{i+1,1} == −1
                fprintf(fid,'%s', A{i,1});
                break
            else
                fprintf(fid,'%s\n', A{i,1});
            end
        end
        fclose(fid);
        warning('on','all')
end
```

A.10 resultsEnergyPlan

```
%________________________________________________________________________________________________________%
% Function that changes the reference input file to create a new one with the changed parameters
%
% Created in MATLAB R2018a(9.4)
%
% Created by: Markus Doepfert
% Inspired by: Pedro Cabrera
%
% Input parameters:
%     outputFilePath: name of the output file
%
% Output parameters:
%     Criteria:       structure array with the results of the criteria that are relevant for the obj. function
%________________________________________________________________________________________________________%

function Criteria = resultsEnergyPlan(outputFilePath)

% Scan in output file
fid = fopen(outputFilePath,'rt');
A = textscan(fid, '%s', 'delimiter', '\n');
A = A{1,1};

%% Criteria
% Total annual costs [MEuro]
key = 'TOTAL ANNUAL COSTS';
index = strfind(A{68},key);
Criteria.TotalAnnualCosts = sscanf(A{68}(index + length(key):end), '%g');

% Imported/Exported electricity [TWh]
key = 'Percent';
index = strfind(A{85},key);
Exchange = sscanf(A{85}(index + length(key):end), '%g');
Criteria.Import = Exchange(1); % imported electricity [TWh]
Criteria.Export = Exchange(2); % exported electricity [TWh]

% CO2 [Mt]
key = 'CO2-emission (corrected)';
index = strfind(A{18},key);
Criteria.CO2 = sscanf(A{18}(index + length(key):end), '%g');

% Biomass [TWh]
key = 'Biomass Consumption';
index = strfind(A{34},key);
Criteria.Biomass = sscanf(A{34}(index + length(key):end), '%g');
Criteria.Biomass = Criteria.Biomass(1);

% Errors
```

```
Criteria.Error = contains(A(2),'WARNING');

% Close file to avoid having too many files open simultaneously
fclose(fid);

end
```

A.11 energyPlanp

```
%____________________________________________________________________________________________________________%
% Function that passes over the agents to EnergyPlan to evaluate their performance
% Unlike energyPlanC, function computes several systems in parallel
%
% Created in MATLAB R2018a(9.4)
%
% Created by: Markus Doepfert
% Inspired by: Pedro Cabrera
%
% Input parameters:
%         pathd:        structure array containing the paths of the files
%     input:    structure array containing various variables, e.g. electricity demand
%         varargin:     cell containing the values of each parameter and the corresponding name for each agent
%
% Output parameters:
%     TAC:        vector that contains the total annual costs of each agent
%     import:     vector that contains the relative imported electricity
%     export:     vector that contains the relative exported electricity
%     CO2:        vector that contains the emitted CO2 amount
%     biomass:    vector that contains the excess amount of biomass used
%     Error:      vector that contains the information if an error occured
%
% Subfunctions: changeInputEnergyPlanp, resultsEnergyPlan
%____________________________________________________________________________________________________________%

function [TAC,import,export,CO2,biomass,Error] = energyPlanp(pathd,input,varargin)
%% Parallel processing setup
% Create necessary variables
n_agents        = size(varargin{2},1);
Inputs          = cell(n_agents, 1);    % temporary input files
Outputs         = cell(n_agents, 1);    % temporary output files
values          = cell(n_agents, 1);    % temporary cells containing agents' values
TAC             = zeros(1,n_agents);    % total costs
import          = TAC;                  % ratio import/generation
CO2             = TAC;                  % imported energy
Error           = TAC;                  % generated energy
ElDemand        = input.ElDemand;       % to avoid broadcast variables
Biomassmax      = input.Biomassmax;     % to avoid broadcast variables
inputFilePath   = pathd.inputFilePath;  % to avoid broadcast variables
energyPlanPath  = pathd.energyPlanPath; % to avoid broadcast variables

%% Folder and files definitions
% Definition of output file name
k              = strfind(inputFilePath,'\');
outputFilePath = [pathd.outputFolder inputFilePath(k(end)+1:end-4), '_out'];
% Create all directories for the subsequent parallel computations
for r = 1:n_agents
```

```
    % Definition of a new input file from reference input file
    Inputs{r}      = [pathd.inputFilePath(1:end-4) '_tmp' num2str(r) '.txt'];
    [Success, Msg] = copyfile(pathd.inputFilePath, Inputs{r});
    assert(Success, Msg)    % check if creation was succesful
    % Defintion of a new output file for results
    Outputs{r}     = [outputFilePath num2str(r) '.txt'];
end

%% Reshape varargin
names = varargin{1,1};
for r = 1:n_agents
    values{r,1} = varargin{1,2}(r,:);
end

%% EnergyPLAN is executed in parallel and results are obtained
% Constant values to avoid reloading values every single time
iFP  = parallel.pool.Constant(inputFilePath);
ePP  = parallel.pool.Constant(energyPlanPath);
Ns   = parallel.pool.Constant(names);
Ins  = parallel.pool.Constant(Inputs);
Outs = parallel.pool.Constant(Outputs);

parfor rr = 1:n_agents
    % Change the inputs
    changeInputEnergyPlanp(iFP.Value, Ins.Value{rr}, Ns.Value, values{rr});

    % Execute EnergyPlan
    executionString = sprintf('"%s" -i "%s" -ascii "%s"', ePP.Value, Ins.Value{rr}, Outs.Value{rr});
    system(executionString); % execution of EnergyPLAN.

    % Obtain results
    Results = resultsEnergyPlan(Outs.Value{rr});

    % Save target values for each search agent
    TAC(rr)     = Results.TotalAnnualCosts;
    import(rr)  = Results.Import/ElDemand;
    export(rr)  = Results.Export/ElDemand;
    CO2(rr)     = Results.CO2;
    biomass(rr) = Results.Biomass-Biomassmax;
    Error(rr)   = Results.Error;

    % Delete files again to minimize output
    delete(Inputs{rr})
    delete(Outputs{rr})
end

end
```

A.12 createtopfiles

```
%____________________________________________________________________________________________________________%
% Function that creates txt–files from the information of the three best results to be used in EnergyPLAN
%
% Edited in MATLAB R2018a(9.4)
%
% Author: Markus Doepfert
%
% Input parameters:
%     dir:        structure array containing the paths of the files
%     varargin:   cell containing the names and the corresponding values that are changed in the input file
%                 to create the output file
%
% Output parameters:
%     none
%____________________________________________________________________________________________________________%

function createtopfiles(dir,varargin)

tops = {'alpha','beta','delta'};

for r = 1:numel(tops)
% Definition of a new input file from reference input file and new changes
outputFilePath = [dir.inputFilePath(1:end–4) '_' tops{r} '.txt'];
[Success, Msg] = copyfile(dir.inputFilePath, outputFilePath);
assert(Success, Msg)    % check if creation was succesful

% Call to function that changes inputs and creates output file
names = varargin{1};
values = varargin{2}(r,:);
changeInputEnergyPlanp(dir.inputFilePath,outputFilePath,names,values);
end
```

Appendix B

Costs

These are the costs used to calculate the overall costs in each scenario. The sections correspond to the way the costs are set up in EnergyPLAN.

B.1 General

CO_2 price (included in marginal production prices):	46.6 €/ton$_{CO_2}$
Interest rate:	3 %

B.2 Investment and Fixed O&M

Please note that only the subsections that were actually used in the simulations are shown here.

B.2.1 Heat and Electricity

Table B.1: Costs of investment and fixed O&M for heat and electricity

Prod. Type	Unit	Investment [M€/unit]	Period [Years]	O&M [% of Inv.]
Small CHP units	MW_e	1.2	25	3.75
Large CHP units	MW_e	0.79	25	3.8
Heat Storage CHP	GWh	3	20	0.7
Waste CHP	TWh/a	215.6	20	7.4
Absorp. HP (Waste)	MW_{th}	0.4	20	4.7
Heat Pump Gr. 2	MW_e	2.9	25	2
Heat Pump Gr. 3	MW_e	2.9	25	2
DHP Boiler Gr. 1	MW_{th}	0.1	35	3.7
Boilers Gr. 2 and 3	MW_{th}	0.075	35	1.47
Electr. Boiler Gr. 2 and 3	MW_e	0.1	35	3.7
Large Power Plants	MW_e	0.95	27	3.3
Nuclear	MW_e	3.02	30	1.96
Interconnection	MW	1.2	40	1
Pump (CAES)	MW_e	0.35	30	1.5
Turbine (CAES)	MW_e	0.35	30	1.5
Pump Storage (CAES)	GWh	0.3	30	1.5
Industr. CHP Electr.	TWh/a	68.3	25	7.3
Industr. CHP Electr.	TWh/a	68.3	25	7.3

B.2.2 Renewable Energy

Table B.2: Costs of investment and fixed O&M for renewable energy

Prod. Type	Unit	Investment [M€/unit]	Period [Years]	O&M [% of Inv.]
Wind	MW_e	0.9	30	2.88
Wind Offshore	MW_e	2.12	30	3.22
PV	MW_e	0.69	40	1
Wave Power	MW_e	1.6	30	2
Tidal Power	MW	5.33	20	3.66
CSP	MW	5.98	25	8.2
Run-of-river Hydro	MW_e	3.3	50	2
Dammed Hydro Power	MW_e	3.3	50	2
Dammed Hydro Storage	GWh	7.5	50	1.5
Dammed Hydro Pump	MW_e	0.6	50	1.5
Geothermal Electr.	MW_e	4.03	20	3.5
Geothermal Heat	TWh/a	250	25	2.45
Solarthermal	TWh/a	307	30	0.15
Heat Storage	GWh	3	20	0.7
Industr. Excess Heat	TWh/a	40	30	1

B.2.3 Liquid and Gas Fuels

Table B.3: Costs of investment and fixed O&M for liquid and gas fuels

Prod. Type	Unit	Investment [M€/unit]	Period [Years]	O&M [% of Inv.]
Biogas Plant	TWh/a	240	20	7
Gasification Plant	MW	0.32	25	7
BioGas Upgrade	MW	0.3	15	18.8
Gasification Upgrade	MW	0.3	15	18.8
BioDiesel Plant	MW_{bio}	1.89	20	3
BioPetrol Plant	MW_{bio}	0.44	20	7.7
BioJetfuel Plant	MW_{bio}	0.44	20	7.7
CO_2 Hydrogenation	MW	0.4	15	3
Chemical Synthesis	MW	0.55	20	3.5
Electrolyser	MW_e	0.28	15	3
Hydrogen Storage	GWh	20	50	0.5
Gas Storage	GWh	0.081	50	1
Oil Storage	GWh	0.023	50	0.6
Methanol Storage	GWh	0.052	50	0.6

B.2.4 Heat Infrastructure

Table B.4: Costs of investment and fixed O&M for heat infrastructure

Prod. Type	Unit	Investment [M€/unit]	Period [Years]	O&M [% of Inv.]
Indv. Boilers	1000-units	5.8	21	2.6
Indv. CHP	1000-units	12	10	0
Indv. Heat Pump	1000-units	11.5	20	1.5
Indv. Electric Heat	1000-units	8	30	1
Indv. Solar Thermal	TWh/a	1233	30	1.22

B.3 Fuel

Table B.5: Fuel costs

	Coal	Fuel Oil	Diesel/ Gasoil	Petrol/ Jetfuel	NGas	LPG	Waste	Biom.	Dry Biom.	Wet Biom.
Fuel Price [€/GJ]	3.4	16.1	20	20.6	12.2	22.1	0	8.1	6.3	0
Fuel Distrib. [€/GJ]										
Biomass Conv.								1.19	0.54	1.49
Central CHP & Power Stations	0	0.262			0.41		0	1.19		
Dec. CHP, Indu.	0	1.9			2		0	1.2		
Ind. Households	0		2.08		3.15			3		
Transportation (Road and Train)			2.1	2.084	0			1.2		
Transport (Air)				0						

B.4 Variable O&M

B.4.1 District Heating and CHP Systems

Table B.6: Costs of variable O&M for district heating and CHP system

Boiler	0.15 €/$\mathrm{MWh_{th}}$
CHP	2.7 €/$\mathrm{MWh_{e}}$
Heat Pump	0.27 €/$\mathrm{MWh_{e}}$
Electric Heating	0.5 €/$\mathrm{MWh_{e}}$

B.4.2 Power Plants

Table B.7: Costs of variable O&M for power plants

Hydro Power	1.19 €/$\mathrm{MWh_{e}}$
Condensing	2.636 €/$\mathrm{MWh_{e}}$
Geothermal	15 €/$\mathrm{MWh_{e}}$
GTL M1	1.8 €/$\mathrm{MWh_{fuelinput}}$
GTL M2	1 €/$\mathrm{MWh_{fuelinput}}$

B.4.3 Storage

Table B.8: Costs of variable O&M for storage

Electrolyser	0 €/$\mathrm{MWh_{e}}$
Pump	1.19 €/$\mathrm{MWh_{e}}$
Turbine	1.19 €/$\mathrm{MWh_{e}}$
V2G Discharge	0 €/$\mathrm{MWh_{e}}$
Hydro Power Pump	1.19 €/$\mathrm{MWh_{e}}$

B.5 External Electricity Market

Table B.9: Costs of the external electricity market

Price Distribution	Spanish spot market prices 2016
Addition Factor	0 €/MWh
Multiplication Factor	2
Price Elasticity	0
Basic Price Level for Price Elasticity	150 €/MWh

Appendix C

Roadmap of Portugal's Capacity Expansion

The section contains the according energy production evolution according to Figure 5.14 as well as a table that contains the corresponding rates for each year.

C.1 Energy Production Evolution

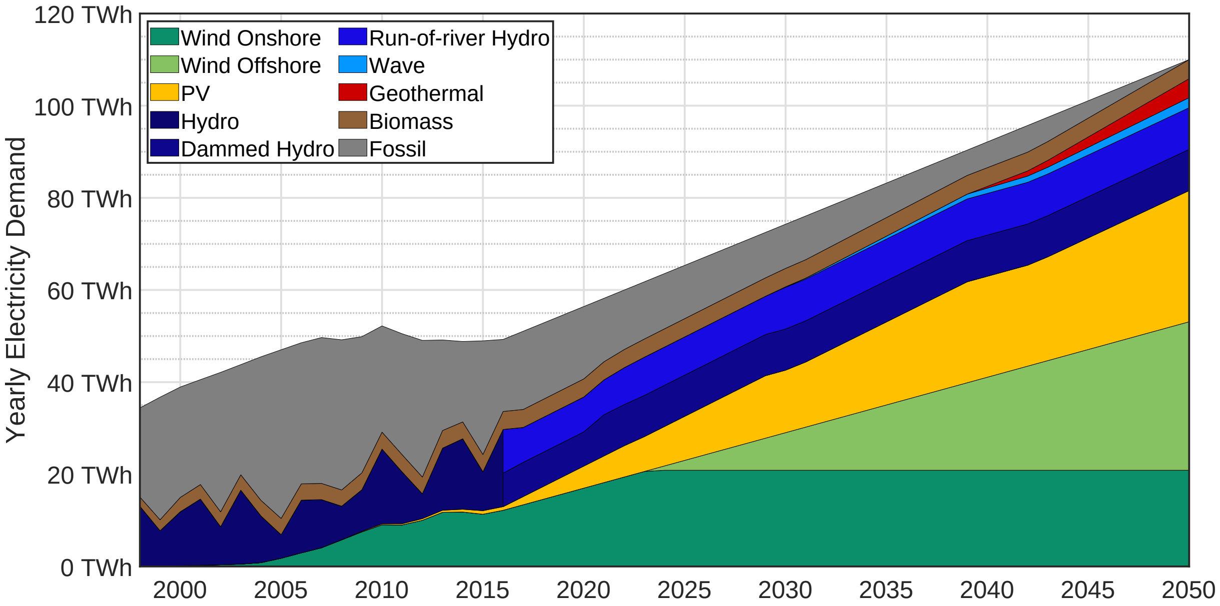

Figure C.1: Portugal's evolution of the energy production considering the technologies' respective maturity until 2050 [74–76, 314]

C.2 Capacity Expansion per Year

Table C.1: Yearly expansion rate of Portugal's capacities for each technology until 2050

Year	Onshore	Offshore	PV	Dam	River	Wave	Geo.	Biom.	Coal	Gas	Total
2018	152	0	779	0	0	0	0	-2	0	0	930
2019	432	0	456	0	0	0	0	-2	0	0	887
2020	432	0	456	0	0	0	0	-2	0	0	887
2021	432	0	456	880	0	0	0	-2	0	0	1,767
2022	432	0	456	0	164	0	0	-2	-576	0	475
2023	432	0	356	0	114	0	0	-2	0	0	901
2024	97	290	456	0	0	0	0	-2	0	0	841
2025	0	373	456	0	0	0	0	-2	0	-990	-162
2026	0	373	456	0	0	0	0	-2	0	0	828
2027	0	373	456	0	0	0	0	-2	0	0	828
2028	0	373	456	0	0	0	0	-2	0	0	828
2029	0	373	456	0	0	0	0	-2	0	0	828
2030	0	373	0	0	285	119	0	-2	-1,180	1,000	596
2031	0	373	262	0	0	119	0	-2	0	-39	714
2032	0	373	444	0	0	119	0	-2	0	-39	895
2033	0	373	444	0	0	119	0	-2	0	-39	895
2034	0	373	444	0	0	119	0	-2	0	-39	895
2035	0	373	444	0	0	119	0	-2	0	-39	895
2036	0	373	444	0	0	119	0	-2	0	-39	895
2037	0	373	444	0	0	119	0	-2	0	-39	895
2038	0	373	444	0	0	119	0	-2	0	-39	895
2039	0	373	444	0	0	119	0	-2	0	-39	895
2040	0	373	0	0	0	119	50	-2	0	622	1,163
2041	0	373	0	0	0	119	50	-2	0	-39	502
2042	0	373	0	0	0	119	50	-2	0	-39	502
2043	0	373	281	0	0	119	50	-2	0	-39	782
2044	0	373	388	0	0	119	50	-2	0	-39	890
2045	0	373	388	0	0	119	50	-2	0	-39	890
2046	0	373	388	0	0	119	50	-2	0	-39	890
2047	0	373	388	0	0	119	50	-2	0	-39	890
2048	0	373	388	0	0	119	50	-2	0	-39	890
2049	0	373	388	0	0	119	50	-2	0	-39	890
2050	0	373	388	0	0	119	50	-2	0	-39	890