Universidade do Minho
Escola de Engenharia

Maria João Marques Soares

Modeling a renewable electricity system: the Portuguese case

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Tese de Mestrado
Mestrado Engenharia Industrial - Ramo Gestão Industrial

Trabalho efetuado sob a orientação da
Professora Doutora Paula Varandas Ferreira

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DECLARAÇÃO

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Abstract

Renewable energies play a unique role in the sustainable development of countries, promoting the exploitation of natural resources for the production of electricity, heat and biofuels.

Portugal is a country with limited energy resources. The reduction of the external energy dependence is one of the main goals for the future, justifying an increasing cross sector application of renewable energy sources (RES), covering the transport, heating/cooling and electricity production systems.

The present work addresses the Portuguese electricity production sector and aimed to propose and analyze different renewable energy scenarios. For this, the Sustainable Electricity Planning Model was adapted in order to include different RES technologies and following a cost minimization approach, for a 10 years planning period. The work required the collection of data for the full characterization of the technologies, including the estimated power potential, seasonal availability of the resources and costs. The monthly demand projections for the planning models were also required to be estimated departing from the annual forecast for the sector for the next 10 years.

Four scenarios were obtained, each one representing a different contribution of RES to the electricity production. In the first scenario the RES share was assumed to remain equal to 37%, a value close to the one obtained in 2012. As for the other three scenarios, the RES share was increased until reaching 86%, the maximum value possible according to the constraints assumed in the model.

The results demonstrate that the increase of RES will have a strong impact on the total cost of the system, mainly due to the required investment costs. The total cost of the maximum RES scenario is more than double than the one obtained under scenario 1 assumptions. However, the CO_2 emissions would be less than 3% of the total value obtained for scenario 1. Another relevant conclusion of the work is that the increasing of RES power in the system, leads to an increase of both the total installed power and of the electricity production. This demonstrates the need to integrate the electricity system allowing to include the possibility of importations and exportations.

Key-Words: Renewable energy sources, Electricity planning, Electricity scenarios.

Resumo

As energias renováveis desempenham um papel crucial no desenvolvimento sustentável dos países, promovendo a exploração dos recursos naturais para a produção de eletricidade, calor e biocombustíveis.

Portugal é um país com recursos energéticos limitados. A redução da dependência energética externa é uma das principais metas para o futuro, o que justifica uma aplicação intersectorial crescente de fontes de energia renováveis (FER), que abrange o transporte, aquecimento e sistemas de produção de energia elétrica.

O presente trabalho aborda o setor de produção de eletricidade Português e teve como objetivo propor e analisar diferentes cenários de energia renovável. Para isso, o Modelo de Planeamento Sustentável de Eletricidade foi adaptado para incluir diferentes tecnologias FER, seguindo uma abordagem de minimização de custos por um período de 10 anos de planeamento. Para o trabalho foi necessário a recolha de dados para a caracterização completa das tecnologias, incluindo o potencial de energia estimada, a disponibilidade sazonal dos recursos e custos. As projeções mensais da procura para os modelos de planeamento também foram estimadas, tendo como base as previsões anuais para o setor para os próximos 10 anos.

Simularam-se quatro cenários diferentes, cada um representando uma contribuição diferente das FER para a produção de eletricidade. No primeiro cenário a participação FER foi assumida como igual a 37%, um valor próximo ao existente em 2012 em Portugal. Quanto aos outros três cenários, a participação FER foi aumentada até atingir 86%, valor máximo possível definido de acordo com as limitações assumidas no modelo.

Os resultados demonstram que o aumento das FER terá um forte impacto sobre o custo total do sistema, principalmente devido aos custos de investimento necessários. O custo total obtido do cenário com a máxima percentagem de FER é mais do dobro do que o custo obtido no cenário 1. No entanto, as emissões de CO_2 seriam inferiores a 3 % do valor total obtido para o cenário 1. Outra conclusão relevante do trabalho é que o aumento de potência FER no sistema, leva a um aumento tanto da potência instalada como da produção de energia elétrica. Isso demonstra a necessidade de integrar ao sistema elétrico a possibilidade de importações e exportações.

Palavras-chave: Fontes de energia renováveis (FER), Modelo de Planeamento Sustentável de Eletricidade, cenários

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List of abbreviations

ºC – Degree Celsius

CCGT – Combined cycle gas turbine

CFC - chlorofluorocarbon

CHP - Combined Heat and Power

DGEG – Direcção Geral da Energia e Geologia

EU – Europe Union

GHG – Green House Gases

GWh – Giga Watt hour

HCFC - Hydrochlorofluorocarbon

HOMER - Hybrid Optimization Model for Electric Renewables

Km – Kilometer

M - Million

MWh – Mega Watt Hour

NSE - National Strategies for Energy

O&M - Operations and maintenance

OECD - Organisation for Economic Co-operation and Development

OTEC - Ocean Thermal energy conversion

PV – Photovoltaic

REN – Rede Elétrica Nacional

RES – Renewable Energy Sources

SCGT – Simple cycle gas turbine

SEPP - Sustainable Electricity Power Planning

SHP – Small Hydro Power

SRP – Special regime production

t – ton

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PART I – INTRODUCTION

PART I – INTRODUCTION

I.1 Introduction

There are two types of energy: the renewable and non-renewable energy. Both can be used to produce electricity, which is the most popular way too transfer energy from one place to another. Renewable energy is energy which comes from natural resources such as sunlight, wind, rain, tides, waves and geothermal heat, which are naturally replenished. There are many advantages in the use of renewable energies and although the ecological ones are the most reported ones, others such as local and regional development or reduction of the energy deficit of countries should not be overlooked. On the other side, the non-renewable energy is the one that is taken from the sources that are available on the earth in limited quantity or their production is less than its consumption rate. It can be divided into two types: fossil fuels and nuclear fuel. The cost impact is definitely the major argument favoring high fossil fuel scenarios for the energy sector (Ribeiro, Ferreira, & Araujo, 2011) (Connolly D. , Lund, Mathiesen, & Leahy, 2011).

In the past few years we have been called to attention to a phenomenon that is global warming. Global warming is the rise in the average temperature of Earth's atmosphere and oceans that is caused by the changes in atmospheric composition (e.g., increased concentrations of greenhouse gases like CO_2). This is a major challenge facing human kind and is one the strongest arguments in favor of the renewable energy investments.

Another problem we have to try to reach a solution is the external energy dependence of countries or regions. The integrated use of the existing renewable and non-renewable energy technologies would make it possible to reduce dependency on imported fossil fuels or on limited domestic resources, decarbonize electricity, enhance energy efficiency and reduce emissions in the industry, transport and buildings sectors. This would contribute significantly to dampen surging energy demand, reduce imports, strengthen domestic economies, and over time dramatically reduce greenhouse gas (GHG) emissions (Mathiesen, Lund, & Karlsson, 2011) (International Energy Agency, 2012) .

Portugal, in particular, has a relatively dense river network and a highly favorable annual sun exposure. Also, the country has a wide seafront benefiting from the Atlantic winds, which gives it the ability to harness the potential energy of water, sun, waves and wind. Although still strongly relying in fossil fuel consumption, these unique natural conditions in the country are allowing for the use of alternative forms of energy. Therefore, Portugal is in a unique position not only to compensate the deficit of natural non-renewable energy sources but also to be a pioneer in reducing energy dependence on non-renewable energy sources and pollutants, putting themselves at the forefront of the demand for a sustainable development (A página da educação, 2003)

But the fact is that Portugal, according to Direcção Geral da Energia e Geologia (DGEG), in 2011 still had an index of dependence on foreign energy above 75% in terms of sources primary energy. This high dependence on foreign fuels allied to the increasing importance of the themes of sustainability resources and climate change, and also to the need to provide competitive energy services prices to the Portuguese economy can explain the effort to reduce this dependence, focusing mainly on promoting both the use of renewable energy sources (RES) and energy efficiency measures (DGEG - Direcção Geral de Energia e Geologia, 2013).

The National Strategies for Energy (NSE) objectives for Portugal in 2020 included (Gabinete de Estratégia e Estudos, 2011):

- Reducing dependence on foreign energy to 74%, producing 31% of the final energy consumption from renewable resources;
- Increasing, the share of electricity produced from renewables to 60%;
- Increasing energy efficiency by 20%,
- Reducing the energy import balance by 25%, equivalent to reducing imports by 2000 million euros per year.

Other objectives relate to the achievement of targets for reducing energy consumption (20%) and emissions of greenhouse gases (reduction of CO_2 by 20 million t). The strategy also aims to promote the creation of added value and creating sector employment, as well as increase the exportations.

It is already certain that the renewable energies are the solution for the future. The question that remains is why not a 100% RES electricity system? Even under the policies drawn for Portugal, fossil fuel remains as dominant sources of primary energy. It might be wise to accept the eventual depletion of oil (sooner or later) and to reduce demand and improve renewable energy systems. Recent studies addressed in the literature this 100% RES possibility for different countries as surveyed in Cosic and

Duic (2012) and the general conclusion is that this option is feasible even with the current technologies. Energy planning becomes then a fundamental tool to support defensible future strategies (Cosic & Duic, 2012).

To have a future electricity scenario with 100% RES we have to link energy demand, storage and harvesting perfectly. Still it is important to diversify and to combine all the renewable energies such as solar, wind and biomass perfectly. It is a challenge and it is important to provide essential supports for planning a 100% RES electricity system, building different scenarios and analyzing which one would be the most advantageous for Portugal based on economic, environmental and social effects (Krajacic, Duic, & Carvalho, 2011).

I.2 Main objectives

This research project aims to approach the possible development of an electrical system based on 100% renewable production in Portugal, designing scenarios and analyzing them from the cost and emissions perspectives. The research was supported the electricity planning model previous developed and demonstrated for the Portuguese case, adapted to this study with the inclusion of new data and RES technologies (Pereira, Ferreira, & Vaz, 2013) (Pereira, Ferreira, & Vaz, 2011).

The present project has then the following objectives:

- Selection and characterization of renewable technologies for electricity generation;
- Construction of 100% renewable electricity generation scenarios in Portugal;
- Analysis of the economic and environmental performance of the proposed scenarios.

I.3 Structure

This project is divided into 4 parts: Introduction, Literature Review, Model Implementation and Conclusions.

The first part (Part I) corresponds to the introduction and scope of the project, and is composed of four points: framing the problem, identifying the main objective and the present structure.

The second part (Part II) covers the literature review required for a good understanding of all the concepts and present studies on the project. This part presents a contextualization of the electricity generation technologies, with particular attention being given to RES technologies, trends and 100% RES scenarios.

The third part (Part III) corresponds to the case study, and it is here that we find the detailed study of all the objectives listed in Part I. The Portuguese electricity system is briefly introduced and the model implementation is detailed. In this part, the results of the study are presented and analyzed.

The fourth part (Part IV) presents the main conclusions of the research and point directions for future work.

PART II – LITERATURE REVIEW

II.1 – Renewable energy technologies

II.2 – The inclusion of RES in the electricity systems

PART II – LITERATURE REVIEW

Energy sector activities have impact on the environment, particularly in climate changes and, therefore, the definition of energy and environmental policies that should seek to meet the existing synergies, taking into account the implicit contradictions in their respective impacts, are crucial to reduce all the impacts that pollution can create.

An integrated strategy of energy and environmental policies must strike a balance between the technical and economic feasibility and environmental conditions, with due regard to cost-effectiveness and social and economic promotion of sustainable development, bearing in mind security of supply and competitiveness. The electricity sector is particularly relevant and the importance of RES to electricity production is strongly underlined by the European Commission (European Comission, 2014). The forecasts for the electricity sector in Europe indicate an increasing reliance on RES, with fossil fuel and nuclear accounting for about 50% of total electricity generation in 2050 (European Comission, 2013).

The following chapters address different technologies for electricity generation giving a short explanation of how they work and listing the advantages and disadvantages of each. The largest section is dedicated to RES technologies but there is also a section to refer other types of non-renewable energy also important to the electricity economy and production. The inclusion of RES in the electricity systems is addressed discussing models and approaches debated in the literature.

II.1 – Electricity generation Technologies

In the world we are living, energy is crucial and, without it, the society that we know would crumble. As the population grows, the need of energy will exponentially grow a well.

Problems with energy supply and use are related not only to global warming, but also to such environmental concerns as air pollution, acid precipitation, ozone depletion, forest destruction, and emission of radioactive substances.

These issues must be taken into consideration simultaneously if humanity wants to achieve a bright energy future with minimal environmental impacts (Dincer, 2000).

Worldwide speaking, electricity generation will increase by 93% from 2010 to 2040. Coal is the most prominent source of energy and tends to increase. After coal, RES, natural gas and nuclear power are the next fastest-growing generation sources. Fig. 1 demonstrates these forecasts from the International Energy Agency (2013).

The outlook for coal could be altered substantially, however, by any future national policies or international agreements aimed at reducing or limiting the growth of greenhouse gas emissions.

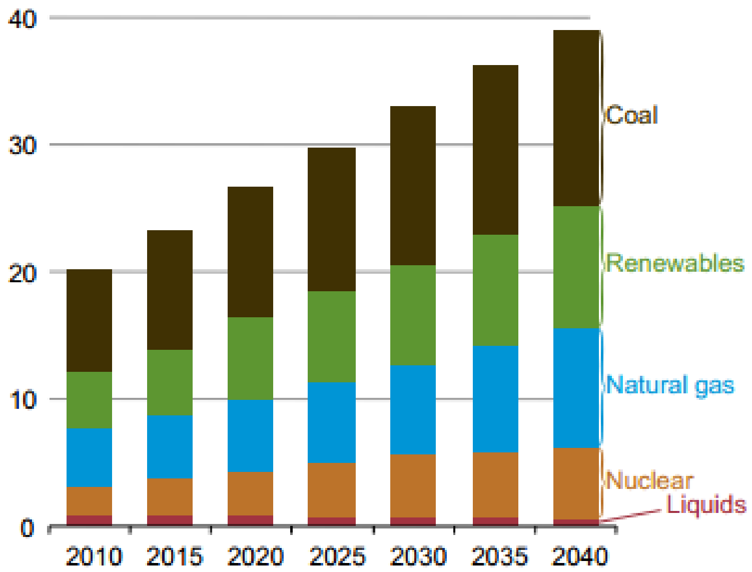


Fig. 1 - World net electricity generation by source (trillion kwh). Source: (International Energy Agency, 2013)

Specifically in Europe, electricity generation increases an average of 1% per year and coal and nuclear are the predominant in 2010 but tend to decrease while renewable energies tend to increase and be the prominent sources for electricity production with an average growth rate of 2.2% per year from 2010 to 2040. As long as European governments support price premiums for renewable electricity, robust growth in renewable generation is likely to continue (International Energy Agency, 2013). Fig. 2 demonstrates these European forecasts and put in evidence the increasing reliance on RES for electricity production.

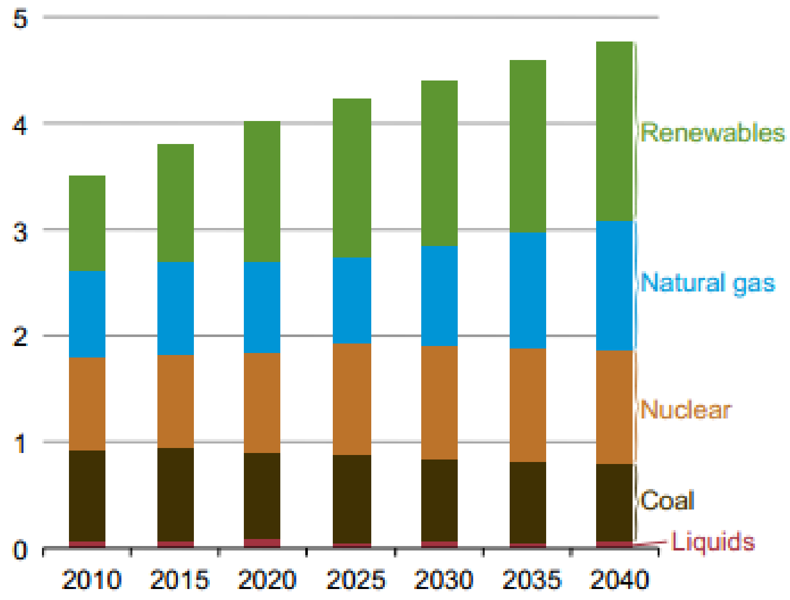


Fig. 2 - Europe net electricity generation by source (trillion kWh) Source: (International Energy Agency, 2013)

II.1.1 - Renewable Energy Sources (RES)

RES that use indigenous resources have the potential to provide energy services with zero or almost zero emissions of both air pollutants and greenhouse gases.

There are different kinds of renewable energy technologies for electricity production, namely:

- Biomass;
- Geothermal;
- Hydropower;
- Ocean;
- Solar Energy;
- Wind.

II.1.1.1 - Biomass

The planet Earth has on its surface a zone where the organisms prosper alive: the biosphere. Biosphere is divided in two different parts: the autotrophy area, where organisms develop living green plants, and the heterotrophic area, in which organisms that directly or indirectly depend on living chlorophyllous plants live. The mass of the biosphere is called biomass (Klass, 1988).

Biomass includes simultaneously both living beings as well as the entire organic product generated by those living beings but which are not completely decomposed into elementary molecules. This biomass contains a chemical energy that, to green plants, comes from the conversion of light energy through the photosynthesis (Klass, 1988).

Solar energy is important for the growth of all of these living beings and thanks to photosynthesis, they produce their biomass though sun light and it is depicted by the following equation:

$$CO_2 + H_2O + light + clorophyl \rightarrow CH_2O + O_2$$

Equation 1 - biomass production

In the previously represented equation, the essential components to photosynthesis are: carbon dioxide (CO_2), light in the visible region of the electromagnetic spectrum, the sensitizing catalyst clorophyll, water (H_2O) and a living plant. Carbohydrate (CH_2O) is the primary organic product from the chemical reaction. Oxygen (O_2) liberated in the process comes from the water (Klass, 1988).

Researches characterize biomass in very different ways, but there is one simple method supported on defining the main types according to biological diversity and similar source and origin. The main types are (Vassilev, Baxter, Andersen, & Vassileva, 2010) (McKendry, 2002):

- Woody plants;
- Herbaceous and agricultural biomass – Grasses and flowers, straws and other residues (like fruits and corn);
- Aquatic biomass - Marine or freshwater algae, macroalgae or microalgae and others;
- Animal and human biomass wastes – bones, manures, etc.
- Biomass mixtures

Biomass is a complex resource that can be processed in many ways leading to a variety of products. Biological routes can convert the carbohydrate portion of the lignocellulosic feedstock into ethanol, an oxygenate that can also be used as a fuel additive. The lignin component cannot be used this way and it is combusted to generate heat and electricity. Gasification provides a way to generate syn-gas and from it the clean conventional fuels: Fischer–Tropsch liquids, methanol, and others. In the next diagram it is possible to see some examples of products according to the process type (Chum & Overend, 2001):

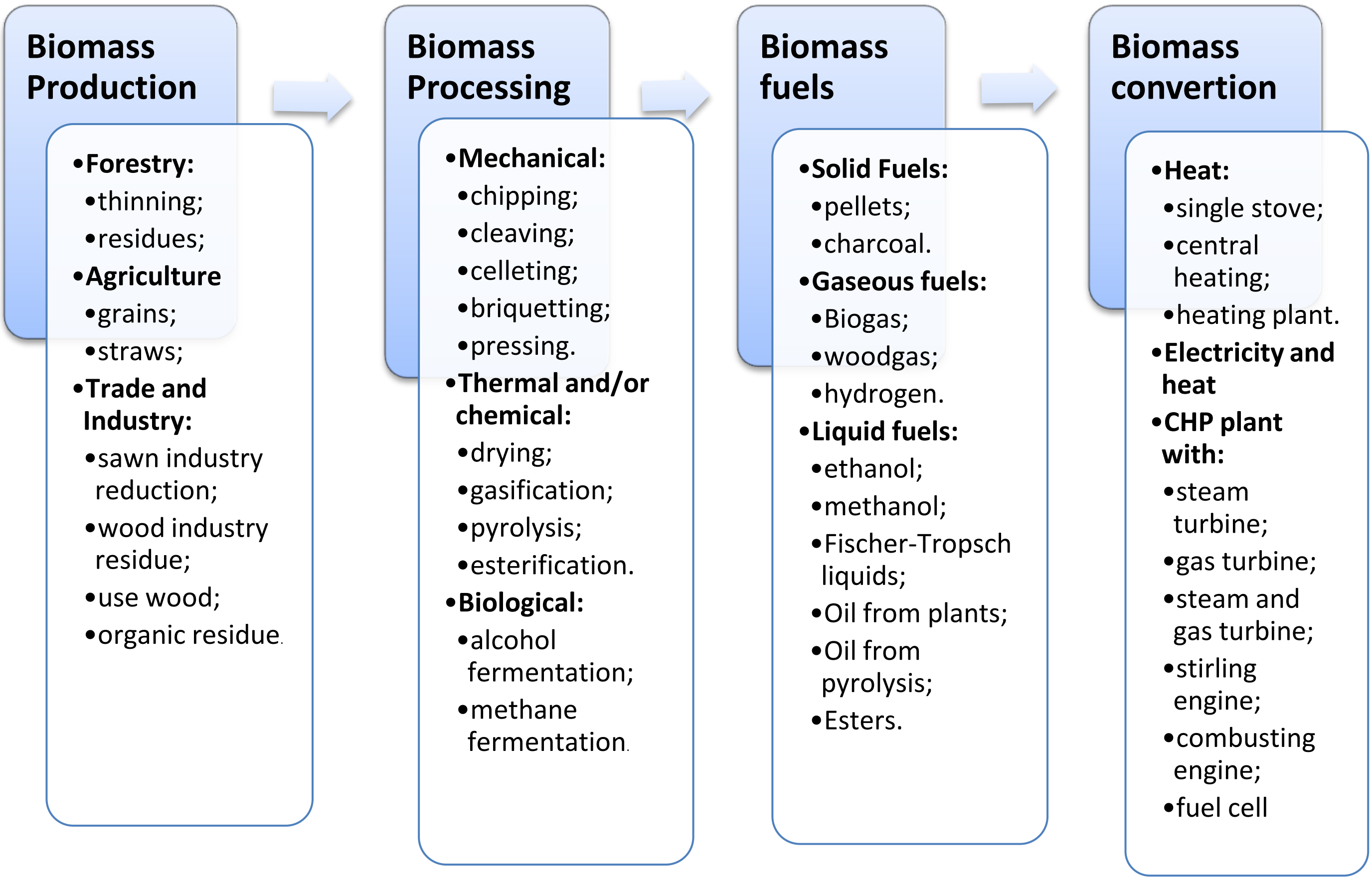


Fig. 3 - Multiple energy options from biomass. Source: own elaboration based on: (Chum & Overend, 2001)

Some of the major advantages and disadvantages of biomass are shown in table 1.

Table 1 - Major advantages and disadvantages of biomass. Source: own elaboration based on: Saidur, Abdelaziz, Demirbas, Hossain, & Mekhiler, 2011 and Vassilev, Baxter, Andersen, & Vassileva, 2010

Advantages	Disadvantages
• Renewable energy source for natural biomass; • CO_2 neutral conversion and climate change benefits; • Large availability and relatively cheap resource; • Diversification of fuel supply and energy security; • Rural revitalization with creation of new jobs.	• Low energy density; • Could contribute to global warming and particulate pollution if directly burned; • Possible soil damage and loss of biodiversity; • Possible dangerous emissions during heat treatment; • Regional availability.

The major advantages of biomass are related to the environmental benefits and its renewable characteristics. However, aspects such as the potential for diversification of fuel supply and the contribution to regional development though local job creation should also be considered. On the other hand, the biomass CO_2 neutrality is not consensual and its burning can pose air pollution problems. The competition with food crops for land and the soil damages are also frequently seen as important drawbacks for dedicated biomass production (Rathmann, Szklo, & Schaeffer, 2010). Regional availability can be an issue because the production of biomass products require some land where they can easily be planted and raised. As biomass use for energy can release gases like methane in atmosphere, it can only be produced in those areas which are quite far from residential homes (Vassilev, Baxter, Andersen, & Vassileva, 2010).

II.1.1.2 - Geothermal

Geothermal energy is the heat that comes from Earth's interior. The heat is brought close to the surface, due to crustal movements, by intrusion of molten magma and the movement of groundwater and reservoirs of hot water where the heat accumulation is due to particular geological conditions of the crust such that the geothermal gradient reaches anomalously high values. Although this fact is generally not noticed, we are not aware of its existence because the temperature of rocks increases with depth, proving that a geothermal gradient exists: this gradient averages 30°C/km of depth (Barbier, 2002).

Fig. 4 describes this geothermal electricity generation process. The use of geothermal electricity is achieved through drilling wells so that they reach reservoirs, bringing to the surface the steam from the hot high pressure water, driving the steam and hot water to separate units in geothermal power turbines. The thermal energy is converted into electrical energy. The geothermal cooled fluid is injected back to the reservoir where it is reheated, preserving the equilibrium and sustainability of the resource. Geothermal fields are generally systems with a continuous circulation of heat and fluid, where fluid enters the reservoir from the recharge zones and leaves through discharge areas (hot springs, wells) (Barbier, 2002).

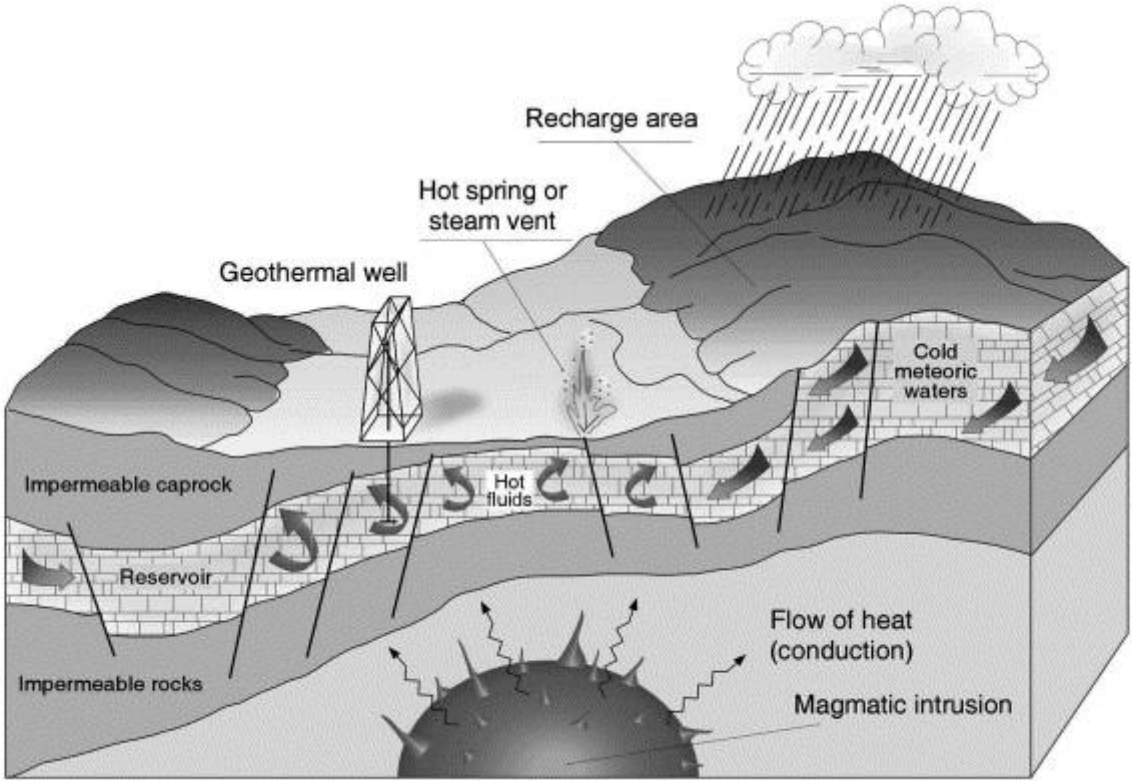


Fig. 4 - Achievement of geothermal energy (Barbier, 2002)

There two types of geothermal energy (Barbier, 2002):

- **High enthalpy geothermal energy –** is the geothermal application with more visibility and perhaps, the most important in economic terms. It is related to the production of electricity from water vapor from geothermal origin with a temperature superior than 150ºC, in power plants with steam turbines and condensing unit.
- **Low enthalpy geothermal energy –** results from the existence of average or slightly higher than the average geothermal gradients. These gradients appear due to the existence of deep aquifers (between 1000 to 2000 m), with fluid temperatures between 50 to 100°C. The fluid (water, sometimes with high salinity) is extracted by means of pumps circulators of water.

Geothermal utilization is divided into two categories: electricity production and direct uses. Conventional electricity power production is limited to fluid temperatures above 150°C, but considerably lower temperatures can be used in binary cycle systems, also called organic Rankine cycles, (in this case the outlet temperatures of the geothermal fluid are commonly above 85°C). For direct uses, the ideal temperature of thermal waters for space heating is about 80°C. However, larger radiators in the houses or the use of heat pumps or auxiliary boilers means that thermal water with temperatures only a few degrees above ambient temperature can be used beneficially (Barbier, 2002). Fig. 5 shows possible geothermal applications according to the different temperatures.

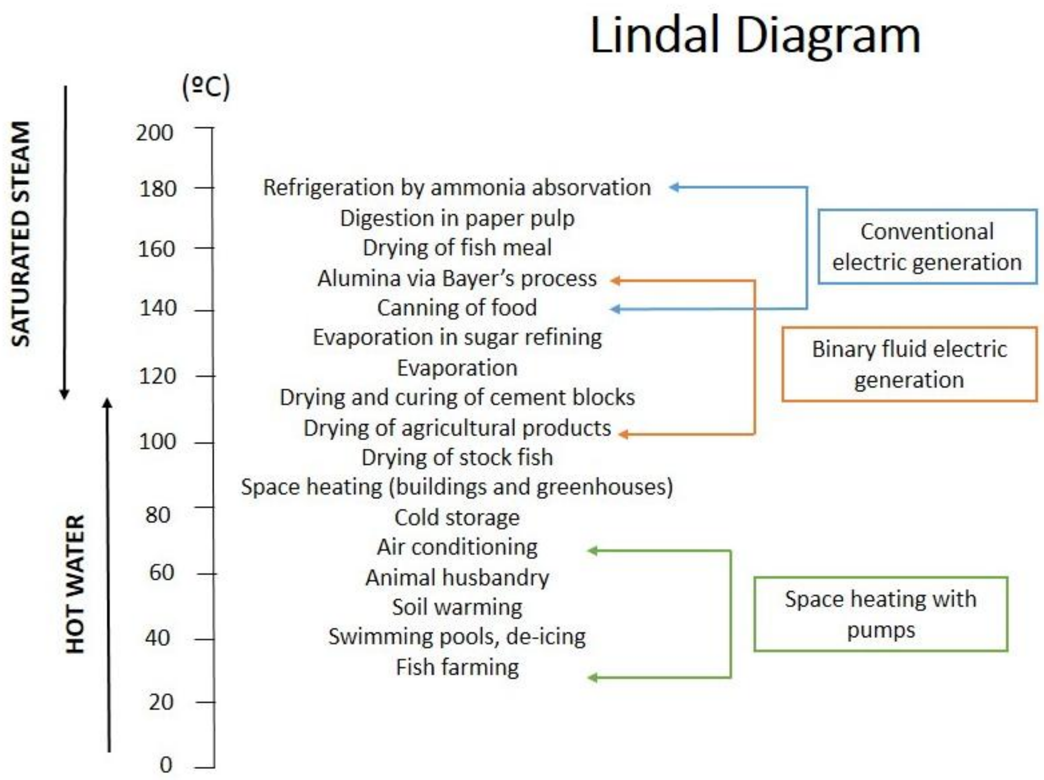


Fig. 5 - The Lindal diagram on typical fluid temperatures for direct applications of geothermal resources Source: Own elaboration based on: (Barbier, 2002)

Some of the major advantages and disadvantages of biomass are shown in Table 2.

Table 2 - Advantages and disadvantages of geothermal energy. Source: Own elaboration based on (Portal Energia, 2013)(Akorede, Hizam, & Pouresmaeil, 2010)

Advantages	Disadvantages
• Geothermal power stations do not require fuel burning to manufacture the steam to move the turbines; • Electricity generation with geothermal energy reduces emissions; • The area of land required for geothermal power stations is smaller per MW than almost every other type of power plants; • Geothermal power plants are projected to work 24 hours per day, all year; • The process is resistant to energy interruptions due to atmospheric conditions, natural catastrophes or political decisions that can interrupt fuel transportation; • Power plants can have modular designs, with additional units installed in increments as needed to fit the growing demand of electricity; • Running costs for the plants are very low as there are no costs for purchasing, transporting, or cleaning up of fuels to generate the power;	• If not used in small areas where the heat from the Earth's interior comes to the surface through geysers and volcanoes, soil drilling for pipes can be expensive; • This system has a high initial cost. The maintenance of the heat suction pump is cheap against the high cost of maintenance of the pipes (where water causes corrosion and mineral deposits); • Anti-gelling used in cold areas are pollutants: although they have low toxicity, some of them produce CFCs and HCFCs; • In many cases, a plant that has been extracting steam and turning it into power for many years may suddenly stop producing steam.

As in other RES the major disadvantage of geothermal power production seems to be related to the high investment costs. The economic interest of these projects largely depends on the availability of high enthalpy geothermal energy resources, which is limited to few regions in the planet.

II.1.1.3 - Hydropower

Moving water creates energy that can be captured and transformed into electricity that is called hydropower. Rain or melted snow, usually originating in hills and mountains, create streams and rivers that eventually run to the ocean. The energy of that moving water can be substantial.

A typical hydropower plant is a system that has three main parts: an electricity plant where the electricity is produced; a dam that can be opened or closed to control water flow; and a reservoir where water can be stored. The water behind the dam flows through an intake and pushes against blades in a turbine, causing them to turn. The turbine spins a generator to produce electricity. The amount of electricity that can be generated depends on how far the water drops and how much water moves through the system. The electricity can then be transported over long-distance electric lines to homes, factories, and businesses (National Geographic, 2013).

Hydropower industry is used both for water management and electricity production. The advantages and disadvantages of hydropower utilization can be divided into 3 categories: Economic, social and environmental aspects, as described in the following tables 3 to 5 (Yüksel, 2008).

Table 3 - Economic advantages and disadvantages of hydropower. Source: Own elaboration based on (Yüksel, 2008)

Advantages	Disadvantages
• It does not require a lot of maintenance which reduces the costs; • Provides high energy efficiency rate; • Hydro Plants have a very long life of around 50- 100 years; • Avoids fossil fuel consumption; • Provides reliable service.	• High initial investment; • Requires long term planning and agreement.

Table 4 - Social advantages and disadvantages of hydropower. Source: Own elaboration based on: (Yüksel, 2008) (Koch, 2002)

Advantages	Disadvantages
• Secure water supply, irrigation for food production and flood control; • Increasing of recreational opportunities, improved navigation, the development of fisheries, cottage industries, etc. • Creates jobs opportunities.	• Involuntary displacement of people from the area to be inundated; • Waterborne disease signs must be checked; • Requires management of competing water uses.

Table 5 - Environmental advantages and disadvantages of hydropower. Source: own elaboration based on (Yüksel, 2008) (Koch, 2002)

Advantages	Disadvantages
• No Greenhouse Gas Emissions/Air Pollution; • Neither consumes nor pollutes the water; • Often creates new freshwater ecosystems with increased productivity.	• Can have negative effects on aquatic and riparian ecosystems; • Barriers for fish migration; • Sediment composition and transport may need to be monitored; • Water quality needs to be managed.

Large hydropower investments, although being a renewable energy option, are frequently prone to controversy and face negative reaction from local population and environmental groups. This is mainly due to the impacts on the ecosystem, the loss of land and the need to displace people from their homelands. However, hydropower plants present important advantages related to their long life, the ability to manage watercourses, their energy storage capacity and their contribution to the dynamic management of the electricity system due to their quick reaction time.

Small hydro power plants (SHP) usually do not have any dam or barrage. If they exist, they are small, usually just a weir, and generally little or no water is stored.

Normally SHP has a capacity up to 10 MW. The power available is directly proportional to the product of pressure head and volume flow rate.

Water is diverted through an intake at a weir that is barrier across the river which maintains a continuous flow through the intake. Before descending to the turbine, the water passes through a settling tank which the water is slowed down sufficiently for suspended particles to settle out. A pressure pipe, known as a penstock, conveys the water to the turbine that converts the mechanical energy into electricity (Paish, 2002).

Pumped hydroelectricity power plants store energy as water in an upper reservoir, pumped from another reservoir at a lower elevation. During periods of high electricity demand, power is generated by releasing the stored water through turbines in the same manner as a conventional hydropower station. During periods of low demand (usually nights or weekends when electricity is also lower cost), the upper reservoir is recharged by using lower-cost electricity from the grid to pump the water back to the upper reservoir.

The difference between pumped storage stations and traditional hydroelectric stations is that the first ones are a net consumer of electricity, due to hydraulic and electrical losses incurred in the cycle of pumping from lower to upper reservoirs. However, these plants are typically highly efficient (round-trip efficiencies reaching greater than 80%) and can prove very beneficial in terms of balancing load within the overall power system (Electric Storage Association, 2013).

Run of river are those hydro power plants which have no water reservoir, or have it in smaller dimensions. Opting for the construction of this plants means to choose not to keep a stock of water that could be accumulated in a dam. The power comes from the potential energy of water driving a water turbine and generator (Faria, 2012).

Run-of-river power plants need to be built on a river with a steady flow. These plants can only have storage for a maximum of 48 hours of water supply. Fig. 6 describes the operation of a run-of-river power plant. The main structure is simply to redirect water flow from a dam (a small headpond) towards the penstock (delivery pipe), which feeds the water downhill to the power station. The natural force of gravity generates the energy used to spin the turbines located in the power station which converts the energy to electricity. After this process, the water is redirected back to the natural flow of the river (Cleantech, 2013).

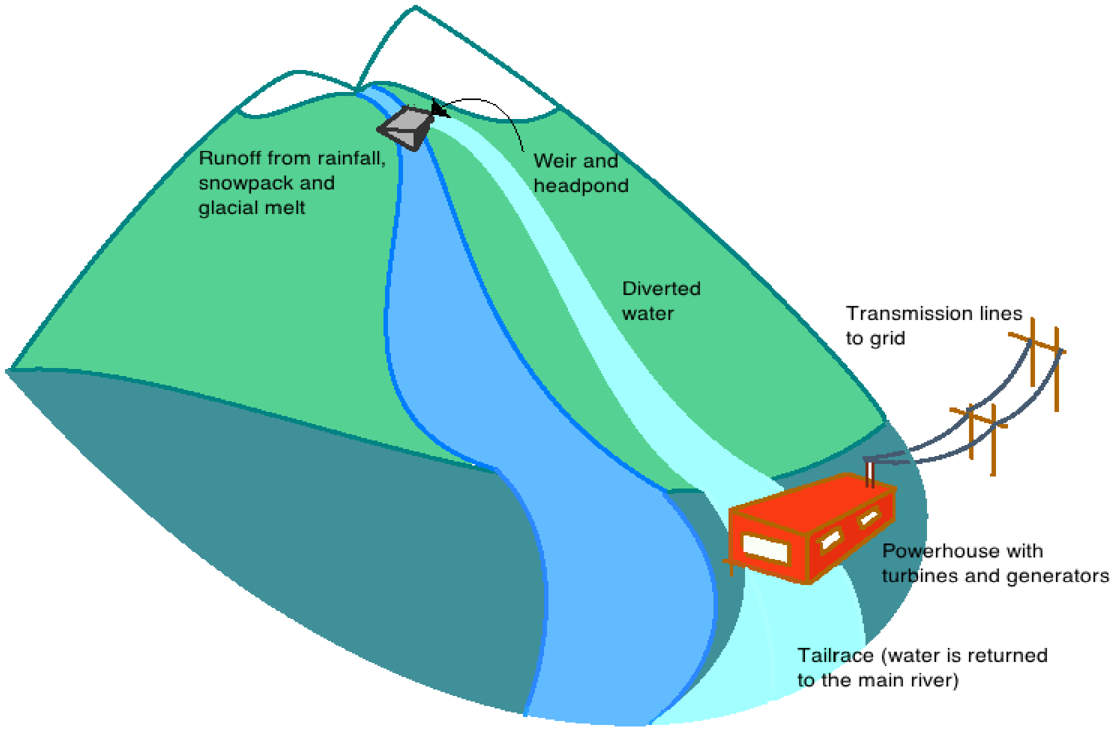


Fig. 6 - Diagram of a Run of river power plant (EnergyBC, 2013)

Run of river does not require damming like large hydro projects and it has low transportation costs because electricity can be transmitted simply by connecting to the local grid with a small percentage of transmission loss. However, Run of river projects normally produce at a smaller scale than other forms hydro power plants with dams and it can also affect natural habitats.

II.1.1.4 - Energy from de Ocean

There are different sources of renewable energy from the ocean, namely ocean thermal energy conversion (OTEC), wave energy or tidal energy.

OTEC was formulated long ago as a way to recover some of the solar energy stored in warmer oceans. It generates electricity indirectly from solar energy by harnessing the difference of temperature between the sun-warmed surface of tropical oceans and the colder deep waters. This procedure happens with the mechanical work in a Rankine cycle, a process which converts thermal energy into kinetic energy via turbines. The turbines can then be used to drive generators, producing electricity (Pelc & Fujita, 2002).

Because of the low efficiency of the process, electricity generation would require very large seawater flow rates of the order of several cubic meters per second per megawatt (Nihous, 2007).

There are two major OTEC facility designs:

- **Open-cycle -** Warm surface boils and generates steam water due to the exposition to a vacuum. The cold water from the ocean is then pumped through a condenser, to condense the team. This constant vaporization and condensation is used to drive a turbine, converting thermal energy into mechanical energy.
- **Closed-cycle** – Creates fresh water as a byproduct. A working fluid with a low boiling point (i.e., ammonia) is used in place of seawater. Both the warm and cold water are passed through heat exchangers which transfer the heat to the working fluid, which then vaporizes and condenses as in the open-cycle facility, driving a turbine and converting thermal energy into mechanical energy.

The main difference between closed and open cycles relies on the relative efficiency. In spite of the higher complexity of closed-cycles, they are significantly more efficient and result in greater output due to the greater efficiency of the working fluid (National Oceanic and Atmospheric Administration, 2009).

Wave energy comes from the winds as they blow across the oceans. This energy transfer provides a natural concentration of wind energy in the water near the surface. Once created, waves can travel thousands of kilometers and loose only a few of their energy.

The energy fluxes occurring in deep water sea waves can be very high. The power in a wave is proportional to the square of the amplitude and to the period of the motion. Therefore, long period (~7–10 s), large amplitude (~2 m) waves have energy fluxes normally averaging between 40 and 70 kW per m width of oncoming wave. Nearer the coastline the average energy intensity of a wave decreases due to interaction with the seabed. Energy dissipation in near shore areas can be compensated for by natural phenomena such as refraction or reflection, leading to energy concentration (’hot spots’) (Clément, et al., 2002). An important advantage of wave power is that it is available up to 90 percent of the time (Pelc & Fujita, 2002).

Tidal energy is the energy dissipated by tidal movements, which derives directly from the gravitational and centrifugal forces between the three elements: earth, moon and sun. A tide is the regular rise and fall of the surface of the ocean due to the gravitational force of the sun and moon on the earth and the centrifugal force produced by the rotation of the earth and moon about each other (Rourke, Boyle, & Reynolds, 2010).

Tidal power has the distinct advantage of being highly predictable, compared to solar, wind, and wave energy because it occurs twice a day. The energy caption is made through a dam that only captures the energy of the water flowing out of the estuary from high to low tide.

Pelc and Fujita (2002) argue that it is now known that tidal barrages can harm the environment so, recent innovations explore the options of tidal fences and tidal turbines. Tidal fences consist of turbines stretching entirely across a channel where tidal flow sets up relatively fast currents. The turbines are designed to allow the passage of fish, water and sediment through the channel.

II.1.1.5 - Solar Energy

The sun is our main source of energy, ensuring the existence of life on earth. This is a feature virtually inexhaustible and perpetual when compared with our existence on this planet.

In its center, in a region called the solar photosphere, the energy from fusion reactions of the nuclei of hydrogen atoms, helium nuclei, is radiated into space in the form of electromagnetic energy, in a speed of 300000 km per second. This energy, to reach the Earth's atmosphere can be absorbed or reflected by its various components.

The spectral distribution of the radiation is composed by radiation in the range of ultraviolet rays (7%), visible light (47%) and infrared rays (46%).

After going through the atmosphere, on a day of relatively clean sky, solar radiation reaches the Earth's surface with a lower power than 30% in top of the same, that is, approximately 1000 W/m^2 (DGEG - Direcção Geral da Energia e Geologia, 2013).

The Sun supplies annually, to the Earth's atmosphere, an enormous amount of energy (valued at 1.5 x 1018 kWh), corresponding to about 10,000 times the world energy consumption recorded during the same period. However, this source is considered too dispersed, with the advantages and disadvantages that it gives (DGEG - Direcção Geral da Energia e Geologia, 2013).

The sun energy is used mostly for (DGEG - Direcção Geral da Energia e Geologia, 2013):

- Heating and lightning buildings, heating water to swimming pools, especially in social equipment, supplying domestic hot water domestic sectors, services, industry and agriculture;
- Producing high temperatures used for processing steam or generating electricity, through technologies of radiation concentration.
- Producing electricity though the photovoltaic effect converting solar radiation into electricity

Table 6 describes the main advantages and disadvantages of the use of the solar energy for electricity production.

Table 6 - Advantages and disadvantages of solar energy for electricity production. Source: Own elaboration based on (Portal das Energias Renováveis, 2013)

Advantages	Disadvantages
• It does not cause pollution during its use; • Low maintenance; • Solar collector technology have high power while its cost is reducing; • Availability in remote or difficult places to reach avoiding high investments in transmission lines.	• Locations in medium and high latitudes suffer sudden production falls during the winter months due to lower daily availability of solar energy. • Places with frequent cloud cover, tend to have daily production variations. • The storage of electricity from solar energy is still inefficient when

	compared for example to fossil fuels. • There is a production quantity variation according to climate conditions (rain, snow) which requires a storage solution for places where solar panels are not connected to the power transmission network.

Solar power plants can represent an important contribute to ensure access to electricity in remote regions, avoiding high grid transmission expansion costs. However, the costs remain as a fundamental barrier to the effective spreading of these technologies. Also the storage requirements impose higher costs to the system and pose additional technical challenges.

II.1.1.6 - Wind Energy

The power of the wind has been used for at least the past 3000 years. But it was on the 20^{th} century that the first wind turbine was developed. It was evolving through the years and, by the end of the 90's, wind energy has re-emerged as one of the most important sustainable energy resources (Herbert, Iniyan, Sreevalsan, & Rajapandian, 2007). The wind is in fact a form of solar energy. It is originated from the uneven heating of the atmosphere by the Sun, associated to the irregularities of the Earth's surface and the movement of Earth's rotation. The wind regime is influenced by the shape of the ground, by the plans of water and the ground cover (DGEG - Direcção Geral de Energia e Geologia, 2013).

Wind turbines convert the kinetic energy of the wind into mechanical energy. This mechanical energy can be used for many activities (grinding grain, pumping water) or to power a generator that turns it into electricity that can be injected into the electricity field and distributed to population. Wind power can also have a decentralized application, used only to provide electricity at a particular location located far from the electricity distribution network to consumers.

Wind turbines have blades that are put in motion by the action of passage of the wind. With this movement, mechanical energy powers an electricity generator that produces electricity. Wind turbines of today can be one of two types (Ackermann & Söder, 2000):

- **Horizontal-axis -** like the old mills. They consist of a tower and a nacelle that is mounted on the top of a tower. The nacelle contains the generator, gearbox and the rotor. Different mechanisms exist to point the nacelle towards the wind direction or to move the nacelle out of the wind in case of high wind speeds.
- **Vertical-axis -** Known by the French scientist Darrieus that invented it, this turbines have the advantage that they operate independently of the wind direction and that the gearbox and generating machinery can be placed at ground level.

The technology of wind turbines has evolved greatly due to technological advances of materials, engineering, electronics and aerodynamics. In general the wind turbines are grouped in a certain place, where the wind conditions are favorable. The energy produced by any wind turbine substantially increases with wind speed. So wind turbines are installed in areas where the wind potential is higher. As the wind speed is affected by soil, relief and increases with height above the ground, the turbines are mounted on high towers (DGEG - Direcção Geral de Energia e Geologia, 2013).

Electricity produced by them is incorporated into the power grid and distributed to consumers in the same way that conventional thermal power stations do.

Table 7 summarizes the main advantages and disadvantages of the use of wind energy for electricity production.

Table 7 - Advantages and disadvantages of wind energy for electricity production. Source: Own elaboration based on (Portal Energia - Energias Renováveis, 2013)

Advantages	Disadvantages
• It is inexhaustible; • It does not emit greenhouse gases or generate waste during electricity production;	• The intermittency, i.e., electricity is produced whenever the wind blows, turning difficult to manage their integration in the grid; • Impact on birds habitat: mainly by

• The wind farms are compatible with other land uses such as agriculture and animal creation; • Wind turbines do not require fuel supply and require few maintenance;	the shock of these in blades and changes in habitats; • Impact noise: the sound of the wind hitting the blades producing a continuous noise; • Visual impact, especially for the residents around, as the installation of wind farms generates a large modification of the landscape.

As most RES, the cost of wind power plants can still be a problem. However the technology is already operating in a commercial scale and is largely disseminated which allowed reducing costs significantly and increasing its economic interest. The variability of the electricity production is a major disadvantage for the grid managers and local and regional negative impacts, such as noise or landscape effects are frequently reported as negative aspects of these plants.

II.1.1.7 - Non-RES

It is also important to highlight other sources of electricity generation technologies that can resource fossil fuel, such as cogeneration, Simple Cycle Gas Turbine (SCGT), Combined Cycle Gas Turbine (CCGT) and coal power plants.

Cogeneration (Combined Heat and Power or CHP) is an electricity production process that combines head and power from renewable or fossil fuels. The main difference between cogeneration and the regular dedicated electricity production is the percentage of energy waste. Cogeneration has as efficiency that can reach 90% or more against 40% of the regular process, as the heat is also used.

To implement a cogeneration process is necessary to have a consuming installation that can make good use of the heat which is provided from the unit.

Cogeneration systems can be divided into three main types of technologies, namely: Alternative engines, gas turbine and steam turbines.

The alternative engines can be diesel cycle or Otto cycle. The first ones are fueled primarily by fuel oil or diesel and the second ones are with gaseous fuels (natural gas, biogas or propane). Gas turbines run mainly with natural gas and steam turbines generate electricity by the expansion of the steam produced in a boiler, resourcing to different renewable or non-renewable fuels (COGEN Portugal, 2013).

Table 8 describes the main advantages and disadvantages of the cogeneration Technologies.

Table 8 - Advantages and disadvantages of cogeneration. Source: Own elaboration based on (COGEN Europe, 2013)

Advantages	Disadvantages
• Low emissions in particular of $CO_{2;}$ • Move towards more decentralized forms of electricity generation; • High efficiency, avoiding transmission losses and increasing flexibility in system use.	• Only suitable where there is a need for both electricity and heat on site; • High capital costs; • Not long term sustainable when based on fossil fuel technology.

SCGT consist of a gas turbine that is connected to an electrical generator. Modern gas turbines use a gas compressor, fuel combustors and a gas expansion turbine. Energy is added to the compressed air by burning liquid or gaseous fuel in the combustor which allows air compression. The hot, compressed air is expanded through a gas turbine, which drives both the compressor and an electricity power generator (Siemens, 2013). Table 9 describes the main SCGT advantages and disadvantages.

Table 9 - SCGT advantages and disadvantages. Source: Own elaboration based on (Siemens, 2013)

Advantages	Disadvantages
• Low investment costs; • High operational flexibility, allowing to be started up quickly, bringing electricity on-line whenever it is needed;	• Less efficient than combined cycles;

Combined cycle power plants are characterized by combining the operation of a gas turbine and subsequent electricity generation and a steam turbine making use of the waste heat from the gas turbine to produce steam and subsequently generating electricity. This combination of two power generation cycles enhances the efficiency of the plant.

Most of the CCGT and SCGT operate using clean energy sources as is the case of natural gas. However, other fossil fuels can also be used for thermal power production, in particular resourcing to steam turbines technologies. Such is the case of coal.

Coal is a combination of solid, combustible, sedimentar and organic rocks that are composed mainly of carbon hydrogen, oxygen, sulphur and moisture and other components. Coal is formed from vegetation that has been consolidated between other rocks and modified by the effects of pressure and heat over millions of years.

Coal has many important uses worldwide. One of most significant uses of coal is electricity generation. Nowadays40% of the electricity consumption is provided by coal and its use has been growing. The last decade’s growth in coal use has been driven by the economic growth of developing economies because it is cheap, abundant, accessible, widely distributed and easy energy to transport, shore and use (International Energy Agency, 2013).

II.2 – The inclusion of RES in the electricity systems

In this chapter, RES power market trends are the focus, addressing the forecasts for the sector and reviewing a few papers debating the possibility of achieving full renewable electricity systems.

II.2.1 - RES market trends

According to the European Commission, the structure of power generation will change significantly in the future. The RES target will cause a major increase in generation from renewables, which continues up to 2030 and will result on a reduction of the share of other power technologies. Fig. 7 presents some figures for the power sector, demonstrating the important role of RES in the next years.

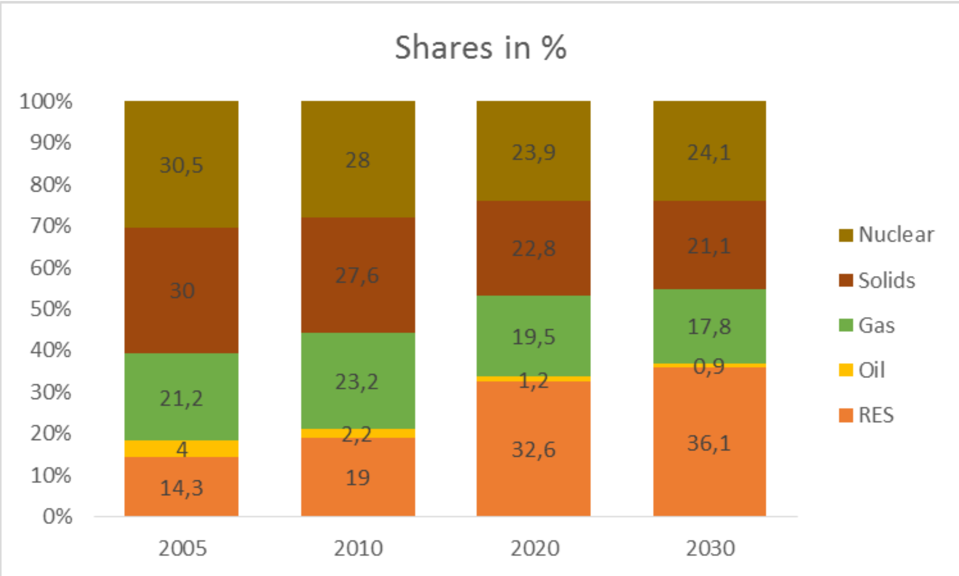
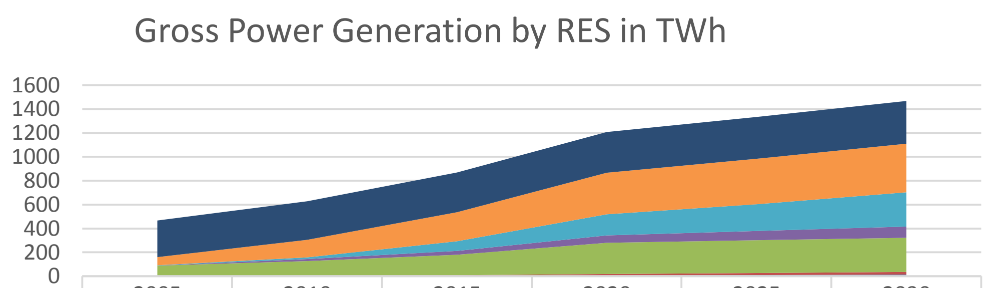


Fig. 7 - Power Generation Structure in Europe (European Commission, 2009)

Fig. 8 describes the expected RES evolution from the year 2005 to 2030, detailing the forecasted electricity production from each technology in Europe.



	2005	2010	2015	2020	2025	2030
Hydro	307	323	333	341	350	358
Wind onshore	68	147	243	348	381	407
Wind Offshore	2	14	81	177	224	287
Solar	1	17	32	62	77	94
Biomass/Waste	84	120	171	261	275	286
Geothermal	5	7	8	12	17	22
Tidal, etc	0	0	1	7	10	14

Fig. 8 - Power Generation from RES in Europe (European Commission, 2009)

In general, the electricity generation from RES is expected to present a major expansion. Hydropower production will remain stable but is shares will be decreasing considerably. Wind onshore, wind offshore and solar photovoltaic should present a major growth. Geothermal and tidal technologies both expand but its contribution remains relatively low. . Biomass will have a high increase due to the further implementation of the cogeneration directive. Biomass is seen as a particularly interesting technology as it represents a non-intermittent RES supply option (European Commission, 2009).

RES are expected to reach a 20% share of the total gross final energy demand according to the target for that year. The 10% renewable energy in the transport sector target is also expected to be met in 2020. To achieve the 20% overall target the percentage of RES in heating and cooling should increase to about 21% and the share of RES should further increase to 22.2% by 2030, driven mainly by a stable rise in the electricity sector and a slight increase in the transport sector (European Commission, 2009). Fig. 9 presents a few RES indicators, demonstrating the expected rising importance of RES for heating and cooling, for transports and for electricity sectors. In fact, between 2000 and 2030 the contribution of RES to the total demand will pass from 7.6% to 22.2% in Europe.

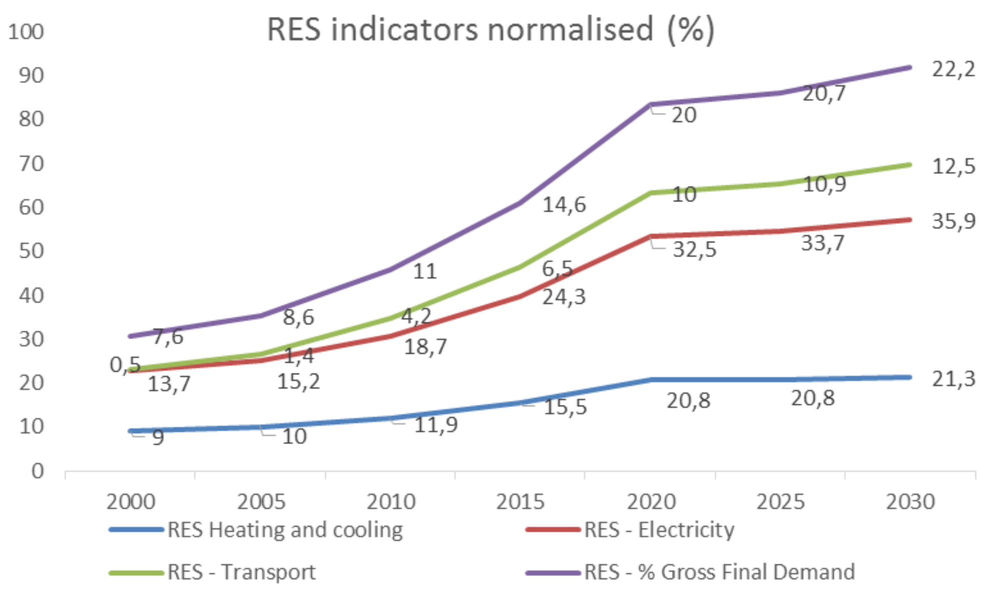


Fig. 9 - RES Indicators (European Commission, 2009)

II.2.2 - 100% RES electricity systems

To achieve a 100% RES system in the future departing from the complex power system of today, there is no singular definitive or correct route, but rather a number of differing but complementary paths (Krajacˇic, Duic, & Carvalho, 2011).

From a technical and operational perspective, optimization criteria include fuel savings, CO_2 emissions, reserve/back-up capacity, required condensing mode power generation, minimization of import/export, and the elimination of excess power generation.

Beside economic issues, technical problems are another challenge because of the intermittency of some resources (wind, solar and wave) even on minute or hourly levels. Other sources like hydropower and biomass are not intermittent but are more variable on a seasonal level (Krajacˇic, Duic, & Carvalho, 2011). In addition, fuel importations and CO_2 prices are essential for the analysis.

According to Mathiesen, Lund and Karlson (2011), it is possible to divide in three parts the methodology for analyzing the technologies in the renewable energy systems:

- The data and technology input phase: this phase has a creative sub-phase that can involve the inputs from experts, a detailed analytical phase involving the technical and economic analyses of the overall system, and possible feed-back regarding each individual proposal.
- Adjusting energy systems technically and insuring flexibility: it is crucial to ensure the flexibility and balance between electricity production and consumption with regard to the system's efficiency and its ability to ensure stability of the electricity grid.
- Main technological and social results: strategic electricity planning model that simulates different scenarios with an input/output model. Inputs can be demands, capacities of the technologies included, demand distributions, and fluctuating renewable energy distributions. A high number of technologies can be included for simulation. Outputs can be energy balances, resulting annual productions, fuel consumption, and import/exports.

The calculations in the Energy Plan have been made by comparing different scenarios considering some aspects like costs, CO_2 emissions and the different technologies (Mathiesen, Lund, & Karlsson, 2011).

Some authors studied the possibility to implement a 100% RES system in different countries. In 2010 Ireland had only 3% of renewable energy. Connolly, Lund, Mathiesen and Leahy (2011) used the tool EnergyPlan to simulate all energy-systems behavior that need to be considered when integrating renewable energy: the electricity, heat, and transport sectors. This study illustrated the options available to Ireland to achieve a 100% renewable energy-system. It also demonstrated the importance of designing an effective energy-system, as the same demand can be supplied with much less energy if the energy-system is designed correctly.

Also in 2010, The Australian case was studied in order to achieve a 100% RES power system. This research demonstrated that 100% renewable electricity in 2010 was possible with some particular renewable energy generation mixes including high levels of variable resources such as wind and solar. The principal challenge is found to be meeting peak demand on winter evenings following overcast days when Concentrating Solar Thermal storage is partially charged and sometimes wind speeds are low. The model handles these circumstances by combinations of an increased number of gas turbines and reduction in winter peak demand (Ellsiton, Diesendorf, & MacGill, 2012).

New Zealand was also a target of a study in 2010. Between 2005 and 2007, the country hydro generation dominated energy production with 60% of installed capacity and only 32% of energy was produced by Non-RES technologies. Generation mixes providing 100% renewable electricity system for New Zealand were proposed, and the generation mixes comprised 53–60% hydro, and replacing the 32% of non- RES by 22–25% wind, 12–14% geothermal, 0–12% additional peaking plant, 0.8–0.9%, wood thermal and 0.2–0.3% biogas generation. Wind spillage was minimized, however, a degree of residual spillage was considered to be an inevitable part of incorporating non-dispatchable generation into a stand-alone grid system. Load shifting was shown to have considerable advantages over installation of new peaking plant (Mason, Page, & Williamson, 2010).

The topic of fully RES power system is then being debated across Europe and although a few studies Krajacˇic, Duic, & Carvalho (2011) and Fernandes and Ferreira (2014) already made an attempt to address the Portuguese case, the issue remains far from being fully explored. Next sections will focus on the proposal and application of an optimization approach to analyze high RES systems for the Portuguese electricity system.

PART III – MODEL IMPLEMENTATION

PART III – MODEL IMPLEMENTATION

III. 1 - Detailed Methodology

Upon completion of all the research carried out in order to be able answer all the needs that a project of this scale requires, it is necessary to make decisions regarding the most advantageous way to conceive the project and reach conclusions.

The case study starts with identifying the context of the problem. So, it is crucial to start this phase describing the current state of the Portuguese market for renewable energies. To characterize the Portuguese case the following indicators were used:

- Energy dependence rate;
- Electricity demand;
- Electricity production.

This analysis was made using data from DGEG and REN.

Subsequently, it is important to perform an analysis of different models of strategic planning of energy to meet the different alternatives and the advantages and disadvantages of each model.

After the analysis, it is decided to use SEPP-UM model and the next step is to define the model with its functions, constrains and scalars (Pereira, Ferreira, & Vaz, 2011).

Once the model is defined, it is possible to simulate different scenarios till reach a maximum percentage of renewable energies. Those scenarios were analyzed carefully considering cost, CO_2 emissions and electricity production.

III.2 - Modeling a renewable electricity system: the Portuguese case

III.2.1 - Context of the problem

III.2.1.1. - The Portuguese electricity system

Portugal is a country with limited indigenous energy resources, including those which provide most of the energy needs of most developed countries (such as fueloil, coal and gas).

The scarcity of fossil resources leads to a high dependence on foreign energy (79.3% in 2011), including imports of primary sources of fossil origin. It is important to increase the contribution of renewable energy to reduce this high dependence. The energy dependence rate has been decreasing since 2005, despite suffering a slight increase in 2008 compared to 2007 as we can see in Fig. 10.

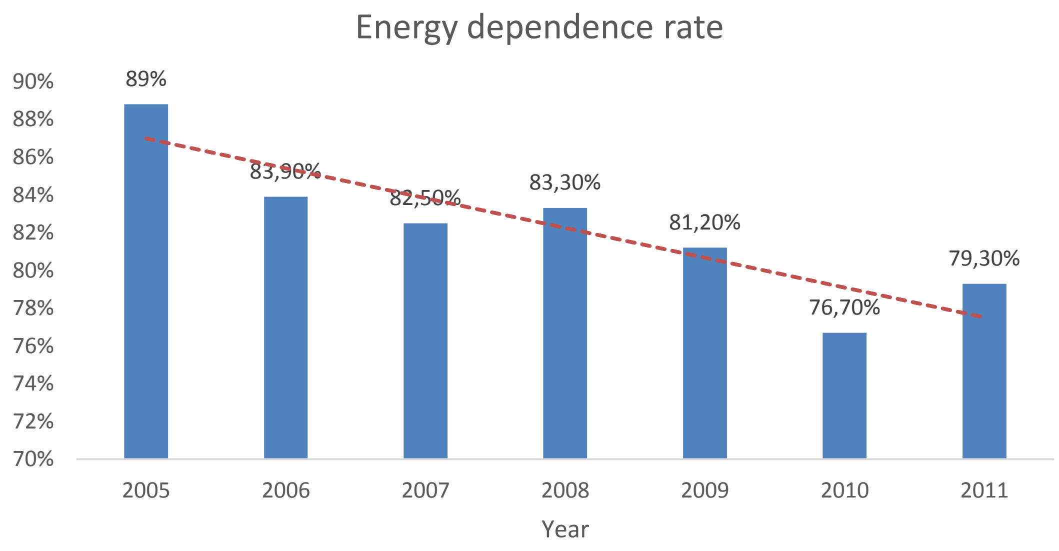


Fig. 10 - Energy dependence rate (%) (Direcção Geral da Energia e Geologia, 2013)

The following Fig. 11 shows the evolution of Primary Energy consumption in Portugal for the period 2000-2011.

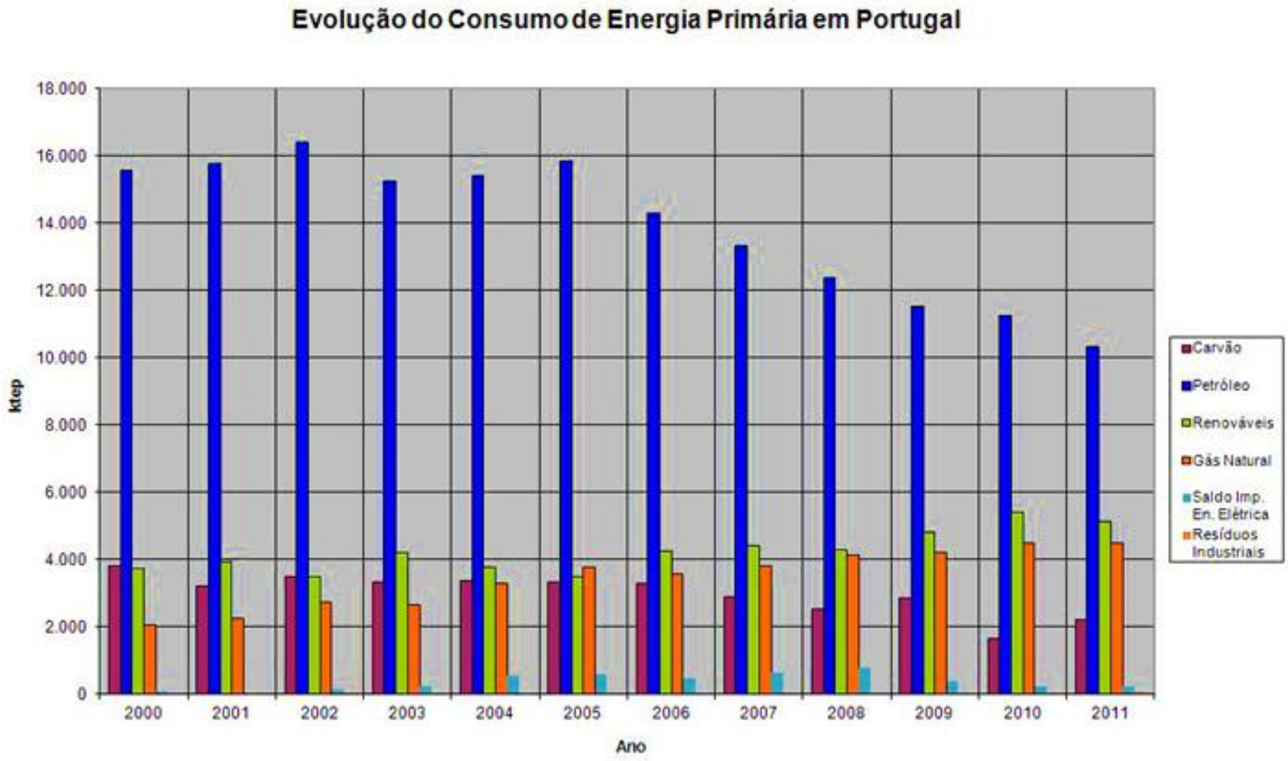


Fig. 11 - Evolution of Primary Energy consumption in Portugal (Direcção Geral da Energia e Geologia, 2013)

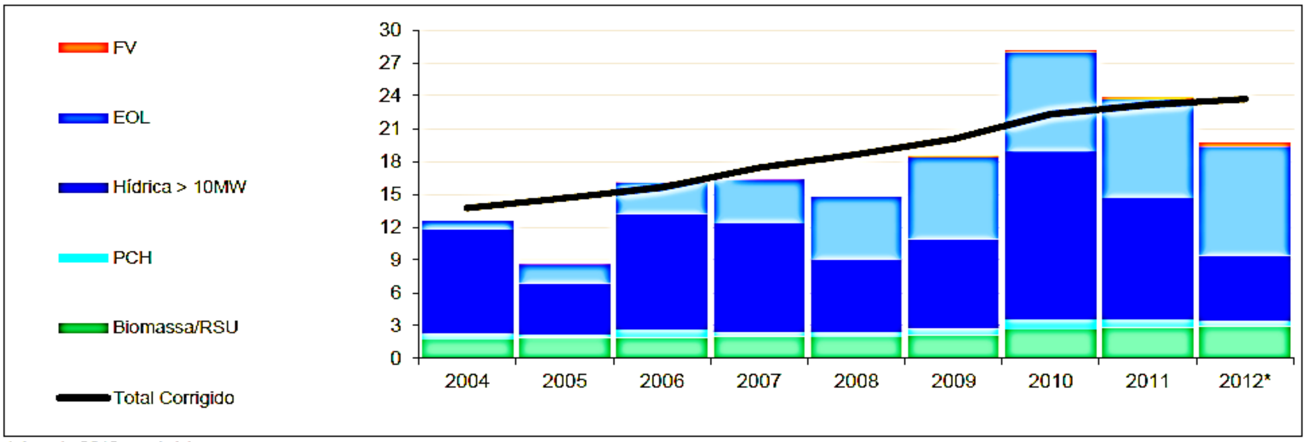
According to Fig. 11, oil has an essential role in the structure of supply, representing 45.9% of total consumption of primary energy in 2010, against 48.7% in 2010.

Natural gas contributed in the past decade to diversify the structure of energy supply and reduce external oil dependence. In 2011, natural gas represented 9.9% of the total primary energy consumption against 19.5% in 2010.

Coal consumption, represented, in 2011, 9.9% of total primary energy consumption. For the future years, a progressive reduction of the weight of coal in electricity production is expected, due to its impact on CO_2 emissions (Direcção Geral da Energia e Geologia, 2012).

In 2011, the contribution of renewable energy for the total primary energy consumption was 22.8% against 23.4% in 2010. This small reduction was mainly due to the less favorable rain conditions in 2011.

It is however notable the growth of installed RES power capacity in the past few years. This resulted in an increasing pattern of the electricity production from RES in 2011 when 25 612 GWh of electricity were produced from RES. Fig. 12 presents the evolution of this RES electricity production, demonstrating once more this increasing trend.



* Ano de 2012 provisório

Fig. 12 - Electricity produced from RES (TWh) (Direcção Geral da Energia e Geologia, 2012)

In Fig 13, it is possible to see the evolution of electricity generated fom RES (GWh) in each Portugal's District. Clearly Coimbra and Viseu are the cities presenting higher production levels with approximately 2 600 GWh each in 2012. It is important to refer that the chart excludes mini-production, micro-production and autonomous production (Direcção Geral da Energia e Geologia, 2013).

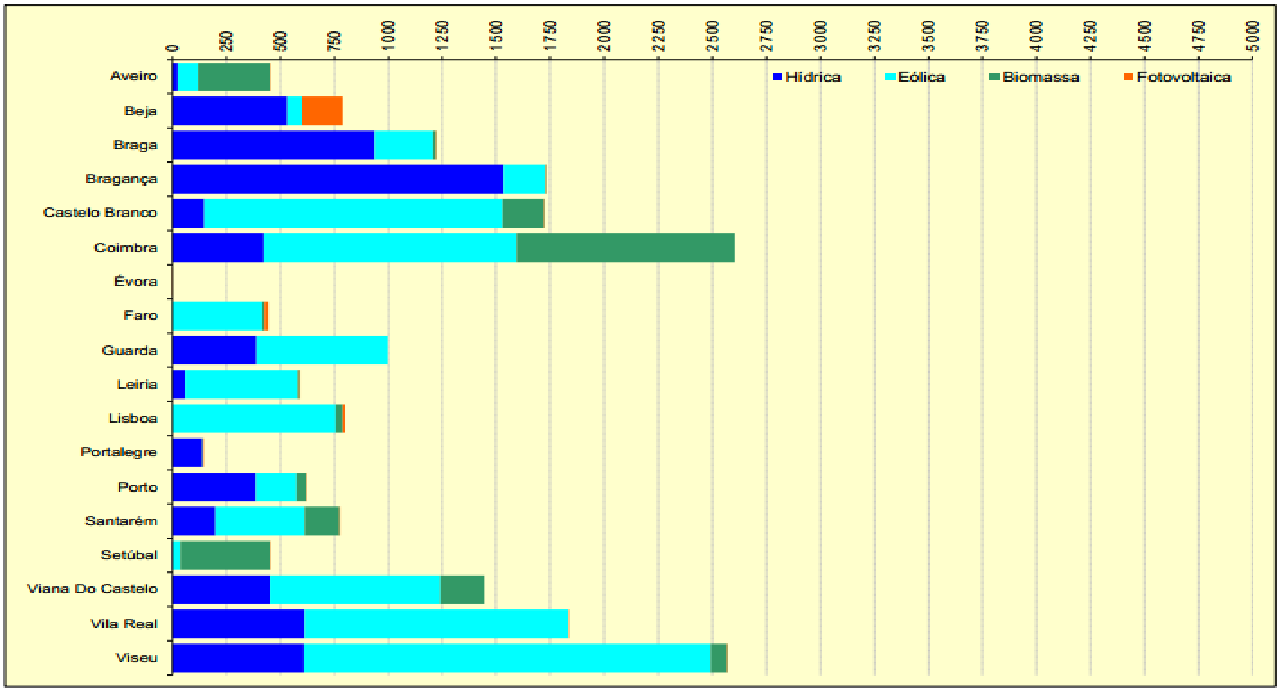


Fig. 13 - Production of electricity from renewable sources by district in 2012 (GWh) (Direcção Geral da Energia e Geologia, 2013)

Comparing Portugal with the others OECD countries, Portugal is in second place considering the share of utilization of RES, after Sweden, with 35%. (Direcção Geral da Energia e Geologia, 2013).

Table 10 - International comparison among OECD countries. Own elaboration based on (Direcção Geral da Energia e Geologia, 2013)

Country	RES 22012 GWh	% RES 2012	% in 2012			
			Hydro	Wind	Biomass + Biogas	Others
Sweden	96 511	66,1	53,9	4,6	7,4	-
Portugal	19 079	35,0	9,8	18,8	5,4	1,0
Spain	86 510	30,3	7,2	17,2	1,7	4,2
Austria	47 085	66,1	55,6	3,5	6,6	0,5
Denmark	14 497	40,7	-	28,8	11,8	-
Finland	28 087	32,0	19,1	0,6	12,3	-
Italy	89 720	26,4	12,3	3,9	3,0	7,2
Germany	136 814	22,9	3,6	7,7	6,9	4,7
Ireland	5 247	18,7	2,9	14,3	1,6	-
France	81 237	15,7	10,9	2,9	1,0	0,9
UK	41 141	11,0	1,4	5,2	4,1	0,4

III.2.2 - The strategic electricity planning model (SEPP)

The increasing use of RES from electricity production can bring considerable benefits from the environmental and external energy dependence points of view. However, the grid management can be more complex as higher shares of RES of variable output are included in the system.

To help analyzing the intermittent nature of RES and the fluctuations in their intensity throughout the day and the requirements of the storage system, a strategic electricity planning models (SEPP) should be used. Computer models have been developed and have become usual tools for energy planning and optimization of the energy systems that aim to increase the share of renewable energy (Lund, Duić, Krajacˇić, & Carvalho, 2007). This section describes a few of these planning models aiming to show how they can be used on the analysis of highly RES systems. A detailed revision of these and other models and software may be found in Connolly, Lund, Mathiesen and Leahy (2010).

III.2.2.1 - HOMER energy

HOMER (Hybrid Optimization Model for Electric Renewables) is a computer model that simplifies the task of designing distributed generation systems - both on and off-grid.

The software simulates an energy system by making balance calculations by hour. It compares the electricity and thermal demand to the energy that the system can supply in one hour, and calculates the flows of energy to and from each component of the system. For systems that include batteries or fuel-powered generators, it also decides for each hour how to operate the generators and whether to charge or discharge the batteries (National Renewable Energy Laboratory, 2011).

The model includes most of the relevant technologies, but not all of them. For example, the model does not support reversible hydro, which is often the cheapest way to store energy in systems of such potentials.

After these energy balance calculations, HOMER determines if it is possible to meet the electricity demand under the conditions that are specified, and estimates the cost of installing and operating the system over the lifetime of the project. The system cost calculations account for costs such as capital, replacement, operation and maintenance, fuel, and interest.

After the simulation that the model is able to do, optimization procedures will be conducted a list of configurations, sorted by net present cost (sometimes called lifecycle cost) will be displayed. Those configurations can then be used to compare system design options. It is also capable of sensitivity analysis, For example, if wind speed is defined as a sensitivity variable, HOMER will simulate system configurations for the range of wind speeds specified by the user (National Renewable Energy Laboratory, 2011).

HOMER has a large number of users and it is applicable to many situations. For example, Mondal and Denish (2010) used this software to study hybrid systems for decentralized power generation in Bangladesh. Another example of application was the simulation of off-grid generation options for remote villages in Cameroon by Nfah, Ngundam and Schmid (2008).

III.2.2.2 - RETScreen software

RETScreen is a clean energy project analysis software. It helps to define if a proposed renewable energy, energy efficiency or cogeneration project makes financial sense (RETScreen, 2013).

The technologies included in RETScreen’s project models are all-inclusive, and include both traditional and non-traditional sources of clean energy as well as conventional energy sources and technologies. A sampling of these project models includes: energy efficiency (from large industrial facilities to individual houses), heating and cooling (e.g., biomass, heat pumps, and solar air/water heating), power (including renewables like solar, wind, wave, hydro, geothermal, etc. but also conventional technologies such as gas/steam turbines and reciprocating engines), and combined heat and power (or cogeneration).

The disadvantage of this software is that it does not provide tools for joint energy balancing with different RES (RETScreen, 2013).

The RETScreen model was used by Himri, Stambouli and Draoui (2009) to perform the economics feasibility study of the wind farms in three locations in Algeria: Adrar, Timimoun and Tindouf. Another example of application is the one used by Alonso-Tristán, González-Peña, Díez-Mediavilla, Rodríguez-Amigo and García-Calderón (2011), to study a small hydropower plant in Spain from an economic and energetic perspective.

III.2.2.3 - EnergyPLAN

The EnergyPLAN model is a software designed for energy systems analysis. It is a deterministic model which optimizes the operation of a given energy system on the basis of inputs and outputs defined by the user. Inputs can be capacities, demand, costs and regulation strategies considering import/export and excess of electricity production. Outputs are the energy balances and resulting annual productions, fuel consumption, import/export of electricity, and total costs including income from the exchange of electricity.

Inputs can be divided into four categories considering technical analysis (EnergyPlan):

1. Annual heating and electricity consumption, including flexible demand and, if any, the transport sector's consumption too.
2. The capacity of PV and Wind Power, including a moderation factor that is used to adjust the relationship between the wind capacity and the correlating electricity production. This part also defines solar thermal and industrial CHP heat production inputs to district heating.
3. The capacity and efficiency of CHP units, boilers, heat pumps and power stations.
4. Technical limitations like the minimum percentage of CHP and power plant needed by the load to retain grid stability and the maximum percentage of heat pump to produce heat, with the purpose to achieve the right efficiency of the heat pumps.

EnergyPLAN is an hour simulation model so it is able to analyze the influence of fluctuating RES on the system as well as weekly and seasonal differences in electricity and heat demands and water inputs to large hydro power systems.

It optimizes the operation of a given system and it can be used for identifying possible investments. It has also the advantage of being very fast when performing calculations (Lund, Duić, Krajac˘ić, & Carvalho, 2007).

EnergyPLAN provides a choice between two different regulation strategies for a given system as opposed to models in which a specific institutional framework is incorporated. The first strategy is meeting heat demand: In this strategy, all units are producing solely according to the heat demands. In district heating systems without CHP, the boiler simply supplies the difference between the district heating demand and the production from solar thermal and industrial CHP. For district heating with CHP, the units are given priority according to the following sequence: Solar thermal, industrial CHP, CHP units, heat pumps and peak load boilers. The second strategy is meeting both heat and electricity demands: the export of electricity is minimized mainly by replacing CHP heat production by boilers or by the use of heat pumps. This strategy increases electricity consumption and decreases electricity production simultaneously, as the CHP units must decrease their heat production (EnergyPlan).

EnergyPLAN is one of the most used models. For instance, it was used by Lund and Mathiesen (2009) to analyze and simulate 100% renewable energy system for Denmark in years 2013 and 2050. The energy system analysis methodology includes hour by hour computer simulations leading to the design of flexible energy systems with the ability to balance the electricity supply and demand. The results are energy balances to year 2050 with 100% renewable energy from biomass and combinations of wind, wave and solar power; and for year 2030, 50% renewable energy. Many more examples exist for other systems and other countries like, for example, Duquette, Wild and Rowe (2014) with the study of the potential benefits of widespread combined heat and power based district energy networks in the province of Ontario and Hong, Lund and Möller (2012) with the study of the importance of flexible power plant operation for Jiangsu's wind integration.

III.2.2.4 - H_2RES

The H_2RES model is designed for the hourly balancing between demand, appropriate storages and supply energy from various sources like wind, solar, hydro, geothermal, biomass, fossil fuels or mainland grid. The main purpose of this model is energy planning of isolated areas which operate as dependent systems but it can also be used to plan energy systems for single wind, hydro or solar power producer connected to bigger power system. Figure 14 describes the main components of H2RES model. (H2RES, 2013)

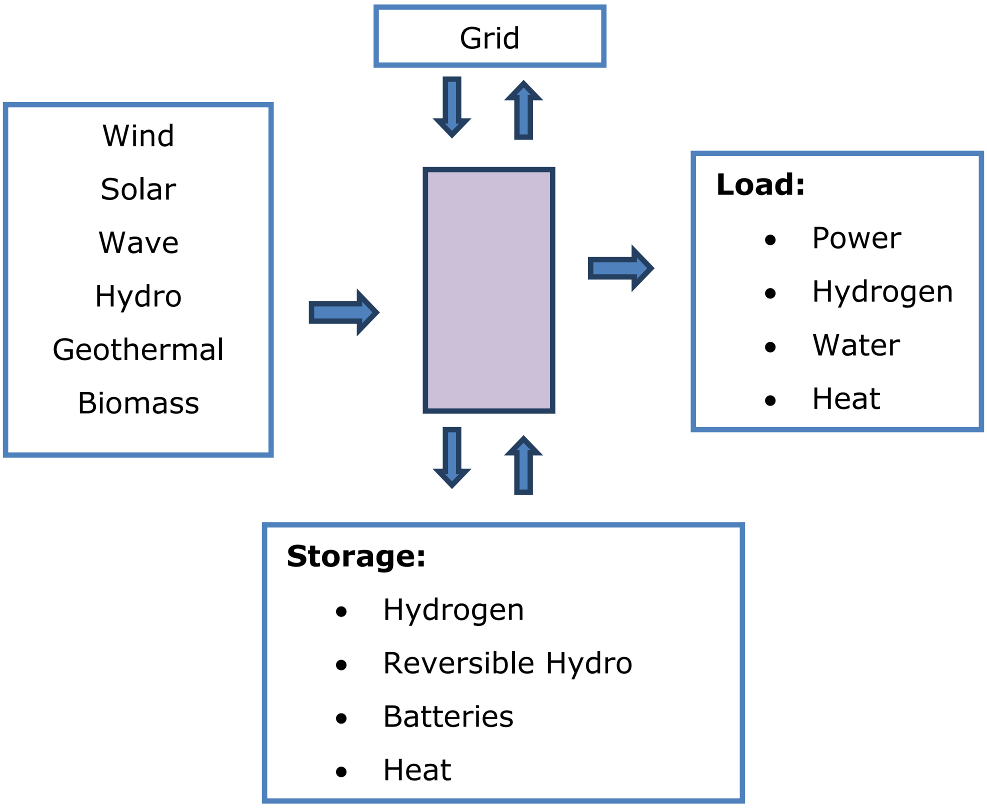


Fig. 14 - H_2RES model (H2RES, 2013)

The system has different modules (H2RES, 2013):

- Wind module uses the wind velocity data at 10m height, adjusts them to the wind-turbine hub level and, for a number defined by the user of wind turbines, converts the velocities into the output.
- Solar module converts the total radiation on the horizontal surface into the inclined surface, and then into the output.
- Hydro module takes into account precipitation data, water collection area and evaporation data based on the reservoir free surface to predict the water net inflow into the reservoir.
- Biomass module takes into account the feedstock information, the desired mix of feedstocks, conversion processes (combustion, gasification and

digestion) and desired output production (power, heat or combined heat and power).

- Geothermal module functions as base load, where the installed power generates electricity for the system continuously, except when it is in maintenance.
- Load module, based on a given criteria for the maximum acceptable renewable electricity in the power system, integrates a part or all of the available renewables output into the system and either stores or discards the rest of the renewable output.
- Storage module manages the need of energy storage to achieve the goal defined by the user;
- Grid is the network and the way the model combines all energies to optimize de model.

H2RES was used in many studies, one of them is the optimization of integration of hydrogen usage with intermittent RES on the example of one isolated island, Porto Santo in Portugal (Martins, et al., 2009). It was also used to study Portugal's energy system planning and technical solutions for achieving 100% RES electricity production by Krajacˇic, Duic and Carvalho (2011). According to their study, 100% RES solution favoured hydro and wind power. Wind power should be implemented using installations with big reversible or pumped hydropower plants and could be achieved by installing bigger wind turbines and storage systems.

III.2.2.5 – Sustainable Electricity Power Planning (SEPP)

This model is built in an incrementally and centrally planned perspective. Economic and environmental criteria are included in the objective functions, aiming to minimize total generation costs such as investment and operation costs of power generation units and environmental impacts proxy by the minimization of greenhouse gases emission, measured by CO_2 (Pereira, Ferreira, & Vaz, 2011).

To understand the model's operation it is important to divide it into two main set of equations: the objective functions and the constraints.

There are two objective functions, one for the cost measured in monetary units and the other for the environmental burden, measured in tons of CO_2 emissions of the system.

The first one set up by the sum of fixed and variable costs. The fixed costs are related to both the investment cost of the new power plants and to all fixed Operations and Management (O&M) costs. The capital investment cost is obtained through the sum of annuities over the planning period, assuming the uniform distribution of the investment cost during the plant lifetime.

The second objective function is described as the sum of the total CO_2 emissions released from all power plants during the entire planning period.

Constraints equations are described as conditions to the model formulation and, with them it is possible to define values of the decisions variables that are viable. SEPP UM includes the following constraints equations (Pereira, Ferreira, & Vaz, Electricity 2011):

- **Demand Constraints**: The total power generation from all power units must meet the system load demand at each month of each year of the planning period, including the pumping consumption.
- **Power Capacity Constraints**: Assuming as constant the availability factor of each thermal power plant included in the planning, for each month of each year during the entire planning period, the power output of each power plant must be less or equal to the available installed power.
- **Renewable Constraint**: enforce the model to ensure at least a pre-defined minimum level of electricity generation from RES.
- **Reserve Constraints**: Ensures the security of the system, taking into account the non-usable capacity, which includes the capacity that cannot be scheduled due to reasons like the temporary shortage of primary energy resources, affecting in particular the hydro and wind power plants.
- **Capacity constraints**: For thermal power units, relates the total modules number with the installed power.
- **Wind Constraints**: Wind power generation capacity must be equal to the total installed power taking into account the monthly wind availability.
- **Large Hydro Constraints**: The production of run-of-river power plants must be equal to the installed power, taking into consideration the average monthly availability of these units. It is important too to ensure a minimum

share of the new run-of-river power plants on the hydropower system under analysis and it is important to define a minimum and maximum reservoir level.

- **Pumping constraints**: Two reservoirs are taken into account. The upper one storages water from inflows and from pumping itself, while the lower one storages water already used for electricity generation that may be pumped again later to the upper level. Also two set of constraints are necessary to model the year transition from December to January for consecutive years.

SEPP, although a very recent software, was used to study the electricity system of Portugal by Pereira, Ferreira and Vaz (2011). The study lead to the proposal of different scenarios for a 10 years planning period and demonstrated that to decrease CO_2 emissions, the least expensive way is to replace coal by CCGT and by wind power production.

III.2.3. - Case study: Modeling a renewable electricity system - the Portuguese case

In this chapter the simulation of the Portuguese Electricity System using the model SEPP is presented. Different scenarios were defined according to current energy status and assuming also policies for the 100% system renewable.

Initially the assumptions used for different scenarios are presented, followed by a description of the obtained results from the model application. Four different scenarios were proposed and analyzed for the Portuguese electricity system:

- Scenario 1: Reference scenario based on the year 2012.
- Scenario 2: With a 50% share of renewable energies.
- Scenario 3: With a 75% share of renewable energies.
- Scenario 4: With maximum percentage of renewable energies allowed by the software.

All four scenarios were modeled assuming a cost minimization approach.

III.2.3.1- Model formulation

To formulate the general model it is essential to define the variables, parameters and scalars. The terms adopted for the model include:

- sets, corresponding to the indices representing for example power plants or time periods;
- equations, corresponding to objective functions and constraints;
- parameters and scalars, corresponding to given data

Table 11 describes the changes made to the initial formulation of the model described in Pereira, Ferreira and Vaz, (2011).

Table 11 - Changes in the initial formulation of the SEPP model

	Initial formulation	Changes
Sets	**Existent power units:** coal (a, b and c), ccgt (a and b), onshore, offshore, fueloil, wind, hydro, hydro - pumping, run of river	**Existent power units initial power units:** coal (a, b and c), ccgt (a and b), onshore, offshore, fueloil, wind, hydro, hydro - pumping, run of river, sun power, SHP, biomass
	New units coal (a, b and c), ccgt (a and b), onshore, offshore, fueloil, wind, hydro, hydro - pumping, run of river	**New units** coal (a, b and c), ccgt (a and b), onshore, offshore, fueloil, wind, hydro, hydro - pumping, run of river, sun power, SHP, biomass
	Existent units coal, ccgt, onshore, offshore, fueloil, wind, hydro, hydro - pumping, run of river	**Existent units** coal, ccgt, onshore, offshore, fueloil, scgt, wind, hydro, hydro - pumping, run of river, sun power, SHP, biomass
		new sun power
		Existent sun power units
		Existent SHP units
		New SHP units
		new biomass power units
		existent biomass power units
Scalars		Sun power scalars
		SHP scalars
		Biomass scalars
		Biomass potential
		Sun potential
		SHP potential
Equations		New sun power constraint
		Existent sun power constraint
		Sun power potential
		New SHP constraint

		Existent SHP constraint
		SHP potential
		New biomass power constraint
		Existent biomass power constraint
		Biomass potential
Constraints	**Renewable constraints:** coal (a, b and c), ccgt (a and b), onshore, offshore, fueloil, wind, hydro, hydro - pumping, run of river	**Renewable constraints:** Added Sun, SHP and Biomass power constraints
		New and existent sun power constraints
		Sun potential constraints
		New and existent SHP constraints
		SHP potential constraints
		New and existent biomass power constraints
		Biomass potential constraints
	Marginal Reserve constraints: coal (a, b and c), ccgt (a and b), onshore, offshore, fueloil, wind, hydro, hydro - pumping, run of river	**Marginal Reserve constraints:** Added Sun power, SHP and Biomass constraints
Parameters		New and existent sun power parameters
		New and existent SHP parameters
		New and existent Biomass power parameters

In summary, for the analysis of the 4 scenarios the SEPP model had to be adapted in order to include other RES technologies. This implied making changes to the original code, with the redefinition of parameters, variables and equations, and also to collect additional data that allowed for the full characterization of these new power options. The model initially included the following energy sources: coal (a, b and c), ccgt (a and b), wind (onshore and offshore), fuel oil, hydro, hydro with pumping, “run of river” and SRP (special regime production) that initially was cogeneration, solar, SHP and biomass. In the new formulated model three energy sources were added to the optimization procedure, namely solar, small-hydro and biomass. Now SRP is restricted to cogeneration.

With the addition of new RES, it is important to adapt the scalars, parameters, equations and constrains.

In the model, existent and new power units are treated independently. Existent power units are the ones already installed in Portugal. New power units are the ones that the system proposes to install.

The model formulation assumes that the inclusion of new thermal power plants to the system is limited to a set certain of values corresponding to the capacities of the power groups available in the market. As such, for coal and CCGT the modular capacity of new thermal plants is described in Table 12.

Table 12 - Modular capacity of new thermal power groups (MW)

Thermal energy	Capacity (MW)
Coal_a	300
Coal_b	400
Coal_c	750
Ccgt_a	505
Ccgt_b	848

Table 13 and 14 describe the economic data included in the cost objective function, namely plant life time, CO_2 emission costs, investment costs, fuel costs, pumping costs and O&M costs.

Table 13 – Cost data for the new power plants

Energy	Life time (days)[1]	Investment cost (€)[1]	Fixed O&M (€/MW)[3]	Variable O&M (€/MWh)[4]	Pumping cost (€/MWh)[5]	Fuel Price (€/MWh)[6]
Coal (a, b and c)	40	1 576 975	10	2	0	10,8
Ccgt (a and b)	30	790 132	19 000	1,2	0	39,54
Onshore	25	1 736 004	25 000	2	0	0
Offshore	25	2 994 678	76 000	2	0	0

Run of river	50	1 527 096	10 790	2,71	0	0
Hydro – pumping	50	2 752 188	10 790	2,71	1,5	0
Hydro	50	1 376 094	10 790	2,71	0	0
Sun	25	4 635 080	50 000	0	0	0
SHP	20	2 036 800	40 736	0	0	0
Biomass	20	2 500 000	40 000	0,004	0	0

[1] (Fernandes L. , 2012)
[3] (Fernandes L. , 2012), (Energinet, 2013), (Energy Technology Systems Analysis Programme, 2013)
[4] (Carneiro, 2011)
[5] (Pereira, Ferreira, & Vaz, 2011)
[6] (Pereira, Ferreira, & Vaz, 2011)

Table 14 - Cost data for the existing power plants (Pereira, Ferreira, & Vaz, 2013)

Energy	Variable O&M (€/MWh)	Pumping cost (€/MWh)	Fuel Price (€/MWh)
Coal	2,2	0	13,4662
Ccgt	1,32	0	45,17
Fueloil	2,2	0	67,62
Wind	2	0	0
Run of river	2,71	0	0
Hydro – pumping	2,71	1,5	0

The fixed share of O&M includes all costs, which are independent of how the plant is operated, e.g. administration, operational staff, planned and unplanned maintenance, payments for O&M service agreements, network use of system charges, property tax, and insurance.

The variable O&M costs include consumption of auxiliary materials (water, lubricants, fuel additives), treatment and disposal of residuals, output related repair and maintenance, and spare parts (however not costs covered by guarantees and insurance) (Energinet, 2013).

It was assumed that fuel price would grow 3, 9% per year (Pereira, Ferreira, & Vaz, 2011).

Table 15 presents the assumed CO_2 emissions for thermal power plants. All RES power plants were considered to be carbon free technologies.

Table 15 - CO_2 emissions value of each unit in t/MWh (Entidade Reguladora dos Serviços Energéticos, 2012) (Fernandes L. , 2012)

Energy	Emissions Value
Coal (a, b and c)	0.677
Coal (existent)	0.844
Ccgt (a and b)	0.323
Ccgt (existent)	0.369
Fueloil	0.8441

The possible loss of power groups is relevant for the computation of reserve requirements. For this, it was assumed that the possible loss of RES power output would be given by the average unavailability of these technologies in a year. The values were computed as described in the following equation, using information from 2012 (REN, 2012) and the obtained results are listed in Table 16.

$$Availability\ factor = 1 - \frac{total\ production}{hours\ per\ hear * installed\ capacity}$$

Equation 2 - Availability factor

Table 16 - RES unavailability factor (REN, 2012)

Energy	Availability factor
Wind	0.73
Hydro	0.3
SRP	0.5
Solar	0.81
SHP	0.83
Biomass	0.22

Table 17 describes the monthly demand of the electricity system in 2012. For the following years a growth of 2, 4% per year was assumed (Direcção Geral da Energia e Geologia, 2012).

Table 17 - Monthly demand (MGWh) (Direcção Geral da Energia e Geologia, 2012)

Month	Demand
Jan	4 441
Feb	4 441
Mar	4 441
Apr	5 031
May	5 031
Jun	5 031
Jul	3 998
Aug	3 998
Sept	3 998
Oct	6 351
Nov	6 351
Dec	6 351

The model is built on an incremental way, departing from the existing conditions and allowing for the inclusion of new power plants. Table 18 describes the existing power plants in Portugal assumed to be the starting point of the optimization procedure.

Table 18 - Installed power of existing units (MW) (REN, 2012) (Direcção Geral da Energia e Geologia, 2012)

Energy	Installed power
Coal	1756
Ccgt	3829
Fueloil	946
Wind	4194
Run of river	2588
Hydro - pumping	1057,3
Storage hydro	2651
Sun	220
SHP	417
Biomass	105
SRP	1300

Monthly electricity availability of SRP is assumed to be constant, but an yearly increase of 1, 4% was included in the model parameters. This was due to the expected increase of the SRP installed power (Direcção Geral da Energia e Geologia, 2012). Table 19 presents the assumed values for SRP production between 2014 and 202

Table 19 - Assumed SRP production 2014-2023 (MWh) (REN, 2012)

Year	Production
2014	551 750
2015	559 475
2016	567 307
2017	575 249
2018	583 303
2019	591 469
2020	599 750
2021	608 146
2022	616 660
2023	616 660

The model implies the definition of a set of scalars describing the technical conditions or other fixed parameters of the system. These scalars include: the minimum share of electricity production from RES, interest rate, energy potential, pumping reserve, maximum reservoir of pumping power plants, initial reservoir level of hydro power plants.

The minimum share of electricity production from RES will be defined according to each scenario under analysis.

The power potential for each RES technology for Portugal was obtained from the literature. The values were established as limits to the maximum installed power of these plants in the future. Table 20, describes the assumed values.

Table 20 - Installed power potential for RES power plants (MW) (Krajacˇic, Duic, & Carvalho, 2011) (Fernandes L. , 2012)

Energy	Potential
Onshore	4429
Offshore	1100
Solar	4500
SHP	750
Biomass	750

For hydro power plants, it was necessary to establish a maximum reservoir level corresponding to the maximum storage capacity of the dams. This value was set as 3500000 MWh. The model required also, as a starting point the definition of the initial reserve conditions set as 1200000 MWh. Finally, the maximum and minimum value for hydro pumping reserve were also established corresponding to 1000000 (maximum) and 240000 (minimum) MWh (Pereira, Ferreira, & Vaz, 2011).

III.2.3.2- Results

This section describes the results of the model implementation for the four scenarios previously presented.

The first scenario is assumed to be the reference, departing from 2012 data and presenting future electricity scenarios non constrained by RES share.

In 2012, electricity production from renewable sources supplied already 37% of consumption (REN, 2012).

Table 21 presents the results of the cost optimization procedure, including also the corresponding CO_2 emissions, for a 10 years planning period.

Table 21 - Optimal solutions for scenario 1

	Value
Optimal cost solution	12 140 M€
Optimal Emissions Solution	274 580 Mt CO_2

To able to respond to the growing demand for electricity, it is necessary to install new power plants, in a way over the years. So, from 2014 to 2023, according to the previous restrictions and impositions, the optimal cost solution points to the addition of the following power plants.

Table 22 - Installed power of new units for scenario 1 (MW)

Year/Energy	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Coal a	1800			200	300			500		
Coal b								800		
Coal c	750									
Hydro pump.	141									
Run of river	90									
Biomass						199		196	103	110

The distribution of the electricity production for different technologies was obtained for the 10 years period. For the sake of simplicity, the analysis will focus only on the last year of the planning period - 2023. As such, table 23 describes the forecasted monthly electricity production for each technology in 2023.

Table 23 – 2023 Electricity production for scenario 1 (MWh)

Month/Energy	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Coal a	3312	3312	3312	3312	3312	3312	3312	3312	3312	3312	3312	3312
Coal b	736	736	736	736	736	736	736	736	736	736	736	736
Coal c	664	690	363	690	690	690	257	367	690	690	690	690
Coal (e)		131		578	567	578			134	578	578	578
Ccgt												44
Wind (e)	1132	1803	1468	1007	1132	881	923	839	629	1132	1803	1971

Hydro						632						
Hydro (e)				546						2412	1611	961
Hydro – pump	18	18	18		18		18	18	18	12		
Hydro – pump (e)	139	139	139		139		139	139	139			
Run of river	10	8	12	11	15	12	7	7	6		23	21
Run of river (e)	296	227	337	309	451	358	213	206	166	343	661	610
Sun (e)	28	40	39	32	44	50	58	55	47	39	26	26
SHP (e)	142	75	54	142	321	113	50	33	29	67	204	371
Biomass	328	328	328	358	358	358	352	352	352	346	346	346
Biomass (e)	57	57	57	62	62	62	61	61	61	59	60	60

(e) means production from already existing power plants.

For Scenario 2, the minimum contribution of renewable energies for electricity production was increased to 50%.

Table 24 presents the results of the cost optimization procedure, including also the corresponding CO_2 emissions for Scenario 2, for a 10 years planning period.

Table 24 - Optimal solutions for scenario 2

	Value
Optimal cost solution	13 640 M€
Optimal Emissions Solution	226 300 $MtCO_2$

The optimal cost solution points to the addition of the following power plants, from 2014 to 2023 under Scenario 2 conditions.

Table 25 - Installed power of new units for scenario 2 (MW)

Year/Energy	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Coal a	300				300			900		300
Coal b	800							400		
Coal c	750									
Hydro	174	1104	379	308		705	111			
Hydro - pump	141									
Run of river	201	706	242	197		450	71			
SHP								334	306	
Biomass	750									

Table 26 describes the forecasted monthly electricity production for each technology in 2023.

Table 26 - Electricity production for scenario 2 in 2023 (MWh)

Month/Energy	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Coal a	1656	1656	1656	1656	1656	1656	1656	1656	1656	1656	1656	1656
Coal b	1104	1104	1104	1104	1104	1104	1104	1104	1104	1104	1104	1104
Coal c	690	690	690	690	690	690	690	690	690	690	690	674
Coal (e)	578	578	570	578	59	578	550	570	578	578	578	
Wind (e)	1132	1803	1468	1007	1132	881	923	1468	629	1132	1803	1971
Hydro										945		
Hydro (e)	187	494		1477	907	1575			603	2492	2208	1974
Hydro – pump	18	18	18	18	18	18	18	18	18	18	18	18
Hydro – pump (e)	139	139	139	139	139	139	139	139	139	139	139	139

Run of river	214	163	243	223	325	258	153	243	119	248	477	440
Run of river (e)	296	227	337	309	451	358	213	337	166	343	661	610
Sun (e)	28	40	39	32	44	50	58	39	47	39	24	26
SHP	142	115	83	218	493	173	77	83	45	102	314	570
SHP (e)	218	75	54	142	321	113	50	54	29	67	204	371
Biomass	405	405	405	443	443	443	405	405	435	428	428	428
Biomass (e)	57	57	57	62	62	62	57	57	60	60	60	60

(e) Means production from already existing power plants..

For Scenario 3, the minimum contribution of renewable energies for electricity production was increased to 75%.

Table 27 presents the results of the cost optimization procedure, including also the corresponding CO_2 emissions for Scenario 3, for a 10 years planning period.

Table 27 - Optimal solutions for scenario 3

	Value
Optimal cost solution	19 200 M€
Optimal Emissions Solution	12 280 $MtCO_2$

The optimal cost solution points to the addition of the following power plants, from 2014 to 2023 under Scenario 3 conditions.

Table 28 - Installed power of new units for scenario 3 (MW)

Year/Energy	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**
Coal a			300				300	900		
Coal b				400						
Wind onshore	3189	740	500				354			
Wind offshore						746				

Hydro	2163										
Hydro - pump	1051	212	143			214	101				
Run of river	2056	135	292								
Sun											1000
SHP	750										
Biomass	750										

Table 29 describes the forecasted monthly electricity production for each technology in 2023.

Table 29 - Electricity production for scenario 3 in 2023 (MWh)

Month/Energy	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Coal a	1380	1380	1380	1380	1380	1380	1380	1380	1380	1380	1380	1380
Coal b	368	368	368	368	368	368	368	368	368	368	368	368
Coal (e)			101		578	578	578	458	578	578	566	
Wind onshore	1195	1904	1550	1063	1196	930	974	886	664	1196	1904	2082
Wind offshore	297	473	385	264	297	231	242	220	165	297	473	517
Wind (e)	1132	1803	1468	1007	1132	881	923	839	629	1132	1803	1971
Hydro										1085		
Hydro (e)	509	347	172	2380	411	1980	337	728	1421	2491	1420	1907
Hydro – pump	225	225	225	225	225	225	225	225	225	225	225	225
Hydro – pump (e)	139	139	139	139	139	139	139	139	139	139	139	139
Run of river	284	217	323	296	451	343	204	198	159	329	634	585
Run of river (e)	296	227	337	309	432	358	213	206	166	343	661	610
Sun	128	183	177	145	201	227	263	250	215	177	120	116
Sun (e)	28	40	39	32	44	50	58	55	47	39	26	25
SHP	255	135	98	255	578	203	90	60	53	120	368	668

SHP (e)	141	75	54	142	321	113	50	33	29	67	204	371
Biomass	405	405	405	443	443	443	435	435	435	428	428	428
Biomass (e)	57	57	57	62	62	62	61	61	61	60	60	60

(e) Means production from already existing power plants.

For Scenario 4, the contribution of renewable energies for electricity production was increased to 88%.The limit was established according to the estimated maximum potential for each RES and respecting the same reserve levels assumed for the other scenarios.

Table 30 presents the results of the cost optimization procedure, including also the corresponding CO_2 emissions for Scenario 4, for a 10 years planning period.

Table 30 - Optimal solutions for scenario 4

	Value
Optimal cost solution	31 110 M€
Optimal Emissions Solution	7 706 $MtCO_2$

The optimal cost solution points to the addition of the power plants described in Table, from 2014 to 2023 under Scenario 4 conditions.

Table 31 - Installed power of new units for scenario 4 (MW)

Year/Energy	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**
Coal a								300		
Coal b								400		
Coal c								750		
Onshore	4429									
Offshore	1100									

Hydro	233						
Hydro pump.	1720					4586	362
Run of river	4413						
Sun	272	1371	734	790	1333		
SHP	750						
Biomass	750						

Table 32 describes the forecasted monthly electricity production for each technology in 2023 under Scenario 4 conditions.

Table 32 - Electricity production for scenario 4 in 2023 (MWh)

Month/Energy	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Coal a	180	276	276	276	276	276	276	276	276	276	276	276
Coal b		368	368	368	368	368	368	368	368	368	368	368
Coal c		690	305	690	690	690	690	690	690	690	690	103
Coal (e)				578	212	578	578	510	578	578	578	
Ccgt										1053		
Wind onshore	1196	1904	1550	1063	1196	930	974	886	664	1196	1904	2082
Wind offshore	297	473	385	264	297	231	242	220	164	297	473	517
Wind (e)	1132	1803	1468	1007	1132	881	923	839	629	1032	1803	1971
Hydro										219		
Hydro (e)	2492	599	849	2127	800	1982	320	708	1607	2492	1557	1699
Hydro – pump	874	874	874	874	874	874	874	874	874	874	874	874
Hydro – pump (e)	139	139	139	139	139	139	139	139	139	139	139	139

Run of river	505	386	574	527	769	610	363	351	282	586	1127	1040
Run of river (e)	296	227	337	309	451	358	213	206	166	343	661	610
Sun	576	824	797	653	905	1022	1184	1125	968	798	540	522
Sun (e)	28	40	29	32	44	50	58	55	47	39	26	26
SHP	255	135	98	255	578	203	90	60	53	120	368	668
SHP (e)	142	75	54	142	321	113	50	33	29	67	204	371
Biomass	405	405	405	443	443	443	435	435	435	428	258	428
Biomass (e)	57	57	57	62	62	62	61	61	61	60	60	60

(e) Means production from already existing power plants.

III.2.3.3- Results analysis

As described previously, the electricity power planning software simulated the model with data obtained in 2012, the last year with complete information available. The first scenario was used as groundwork for other alternative based on estimated values for the years till 2023, and simulating different scenarios. The last scenario corresponds to simulation of the model with the higher RES percentage estimated as possible for the Portuguese system.

Analyzing the cost on the first place, it is possible to notice that the total cost of the system increases with the increasing amount of renewable energies, as demonstrated in Fig. 15.

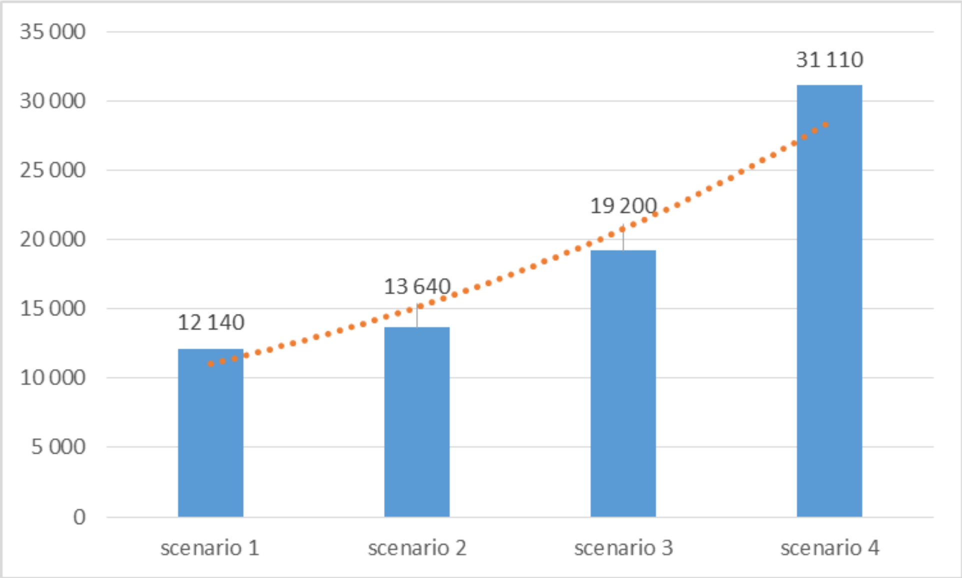


Fig. 15 - Cost evolution for different scenarios

The orange line represents the trend line for costs as it moves forward with the increasing share of RES in the system.

These cost values include new power plant investment cost (€/MW), O&M fixed cost of the type of power plant (€/MW), variable O&M costs for each type of power plant (€/MWh), the cost of pumping for each type of power plant (€/MWh), the fuel cost for each type of power plant (€/MWh) and CO_2 emission allowance cost (€/ton) assuming an annual discount rate of 5% and taking into account the new power plant lifetime.

Cost values present a large increase for high RES scenarios due to the need to install new power units. Installation costs are one of the major limitations of the implementation of RES power plants, which may, however, be compensated due to the long term life time and the benefits associated with these technologies.

On the opposite, CO_2 emissions present a decreasing trend line, with the increase of RES share, as described in Figure 16.

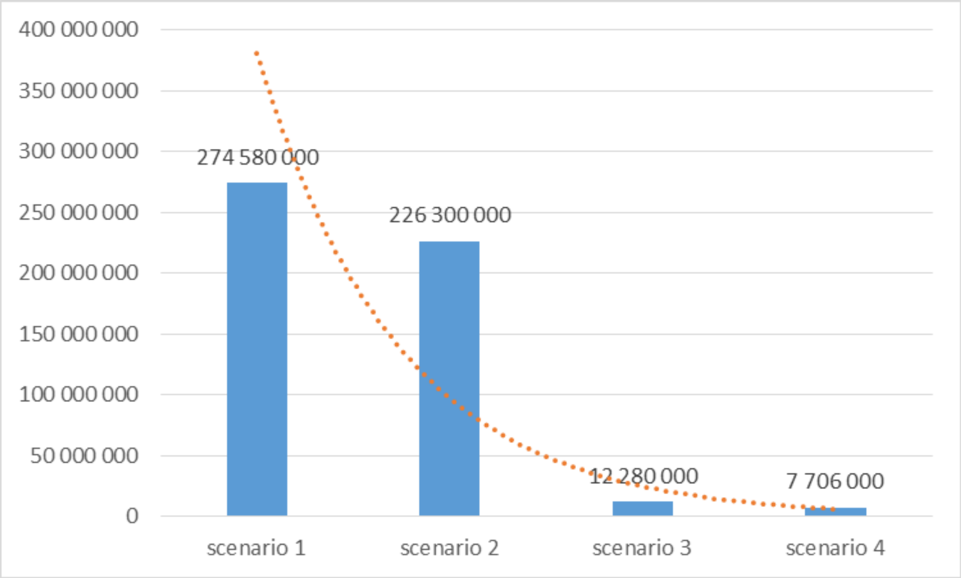


Fig. 16 - Emissions evolution for different scenarios

The emission value corresponds to the sum of the total CO_2 emissions released from all power plants during the entire planning period.

With the raise of the required percentage of RES, the total installed power shows a significant increase. It is possible to agree that the higher is the percentage of required RES, the highest is the total installed capacity of the system.

Table 33 presents the evolution of the new installed power for the four scenarios added to the system, demonstrating that scenarios 3 and 4 present much higher values for the total installed power.

Table 33 – New installed power added per year and per scenario

Scenario		2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
	RES	231	0	0	0	0	199	0	196	103	110
Scenario 1	NON-RES	2550	0	0	200	300	0	0	1300	0	0
	TOTAL	**2781**	**0**	**0**	**200**	**300**	**199**	**0**	**1496**	**103**	**110**
	RES	1266	1810	621	505	0	1155	182	334	306	0
Scenario 2	NON-RES	1850	0	0	0	300	0	0	1300	0	300
	TOTAL	**3116**	**1810**	**621**	**505**	**300**	**1155**	**182**	**1634**	**306**	**300**
	RES	9959	1087	935	0	0	960	455	0	0	1000
Scenario 3	NON-RES	0	0	300	400	0	0	300	900	0	0
	TOTAL	**9959**	**1087**	**1235**	**400**	**0**	**960**	**755**	**900**	**0**	**1000**
	RES	13667	1371	734	790	1333	4586	0	362	0	0
Scenario 4	NON-RES	0	0	0	0	0	0	0	1450	0	0
	TOTAL	**13667**	**1371**	**734**	**790**	**1333**	**4586**	**0**	**1812**	**0**	**0**

As a result of the increase of the total installed power, the electricity production from RES also increases and evidently, at the same time that non-RES production decreases. In 2023, the last year of analysis, it is possible to predict the following production according to the 4 scenarios:

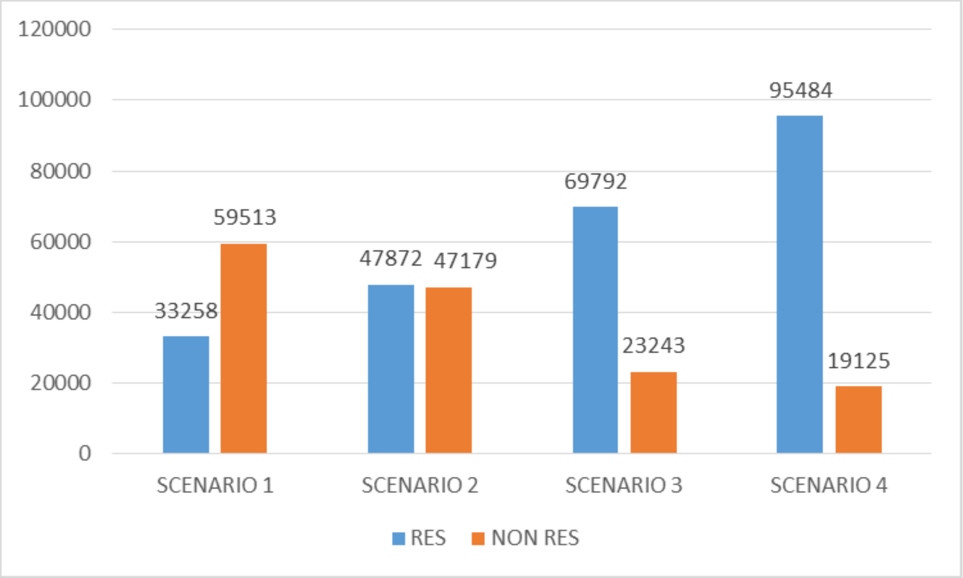


Fig. 17 - Electricity production for the different scenarios in 2023 (MWh)

Figure 17 also clearly shows that the increasing of RES power in the systems leads to an increase of non-usable electricity production, demonstrating the importance of proceeding to a strongly interconnected system allowing to include the importation and exportation possibilities on systems with high share of RES.

Regarding the distribution of RES for electricity production, these values change between the scenarios under consideration.

For scenario 1, with 37% share of RES, among these the highest percentage belongs to wind power with 44% that corresponds to 14 720 MWh in 2023. The second most relevant RES power producer is hydropower with a 19% share, corresponding to 6 162 MWh. The less used RES is solar power, with only 1% of the total electricity produced, corresponding to 484 MWh. Hydro power pumping corresponds to 3% of total electricity production.

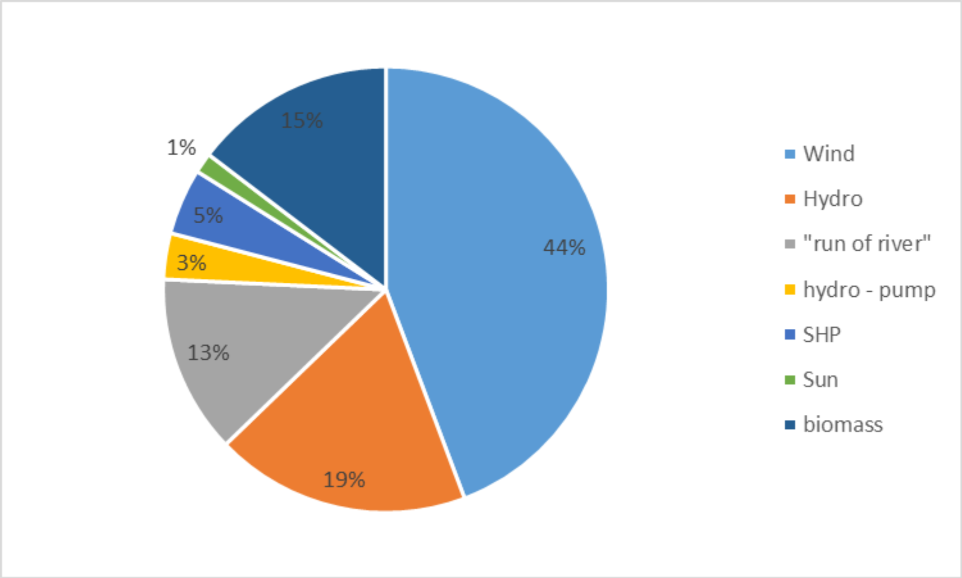


Fig. 18 - Distribution of RES for electricity production for scenario 1 in 2023

For scenario 2, wind power production decreases to 32%, while hydropower production share increases to 27%, corresponding to 15 394 and 12 862 MWh respectively.

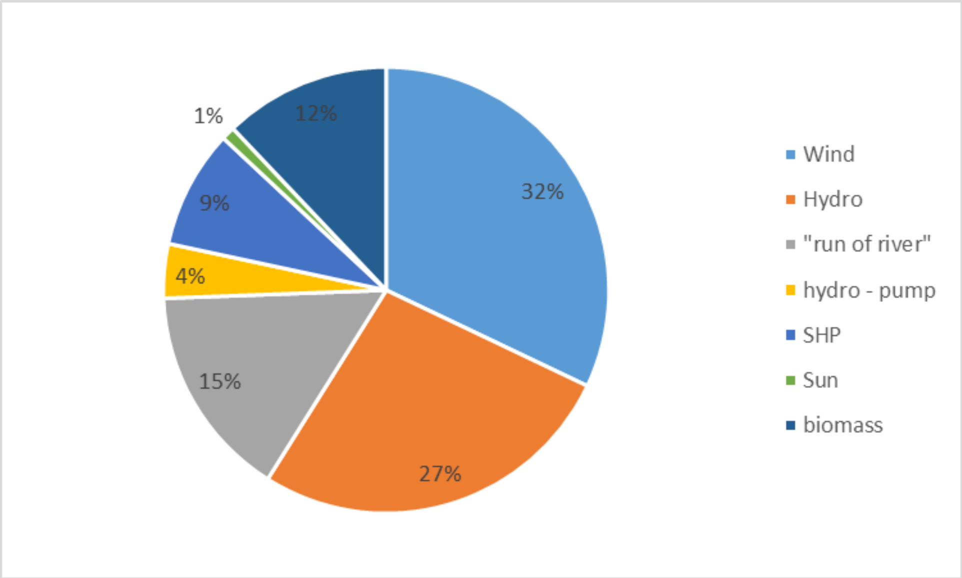


Fig. 19 - Distribution of RES for electricity production for scenario 2 in 2023

For scenario 3, the share of wind power production reaches 45% corresponding to 31 501 MWh. Following wind, the share of hydropower is 21% and with 14 679 MWh. For this scenario solar, small-hydro and have the lowest share of production with

3 and 6% respectively. Hydro power pumping corresponds to 6% of total electricity production.

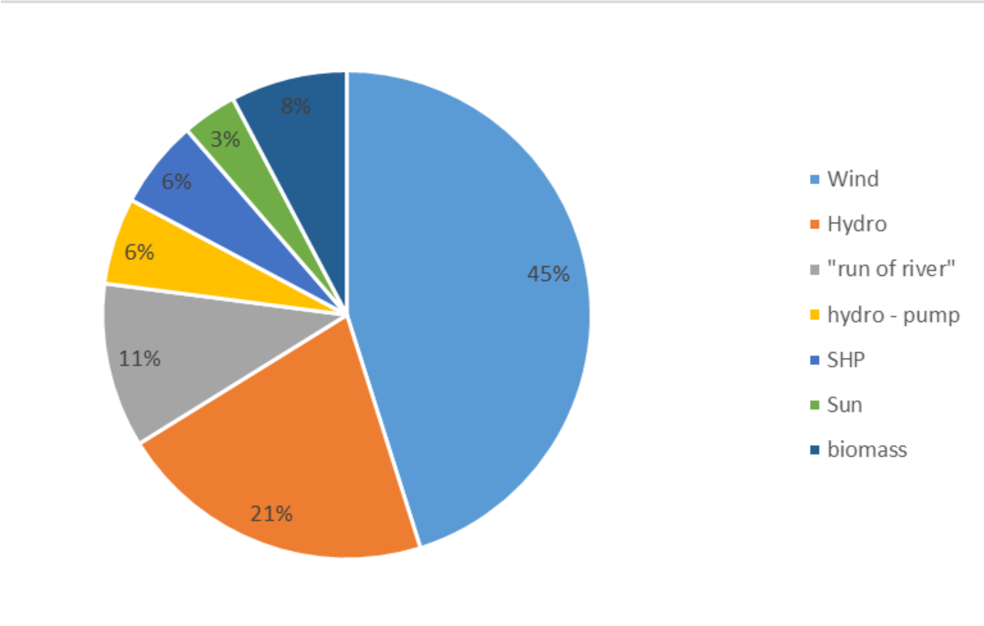


Fig. 20-Distribution of RES for electricity production for scenario 3 in 2023

For scenario 4, wind and hydro power still have the highest percentage of RES electricity production but, in this case, it is possible to see a significant increase in solar power reaching a share of 11%, corresponding to 10 338 MWh, leaving small hydro in the last position with 5%, 4 484 MWh.

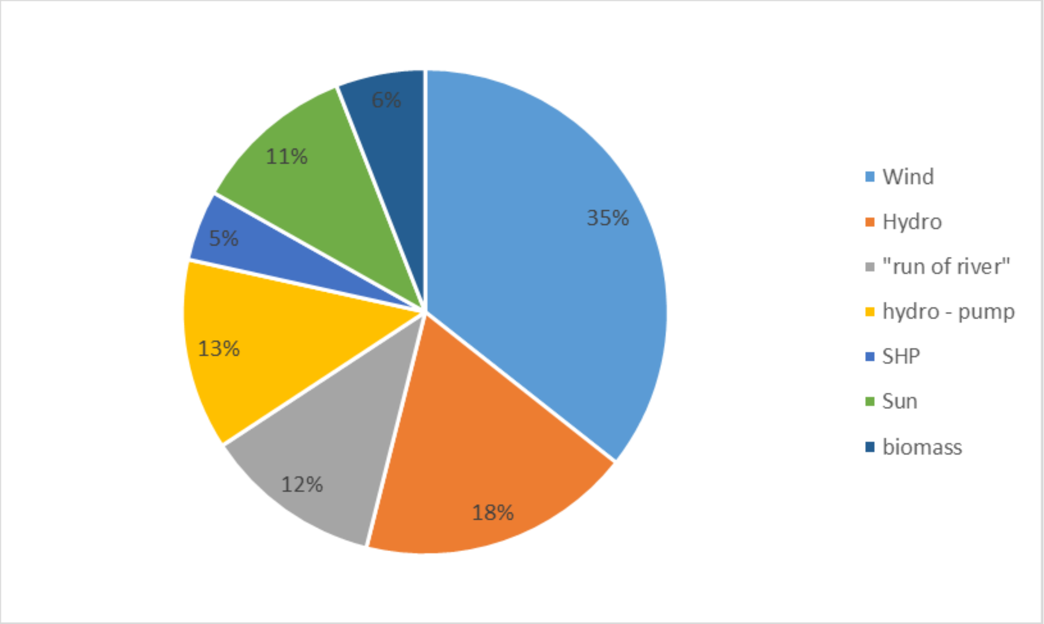


Fig. 21 - Distribution of RES for electricity production for scenario 4 in 2023

In summary, for all four scenarios wind power dominates the RES electricity production closely followed by hydro power.

By analyzing energy production per month and per scenario it is possible to observe the seasonality of RES power production. Figure 22 describes the monthly RES power output for scenario 1 for year in scenario 1.

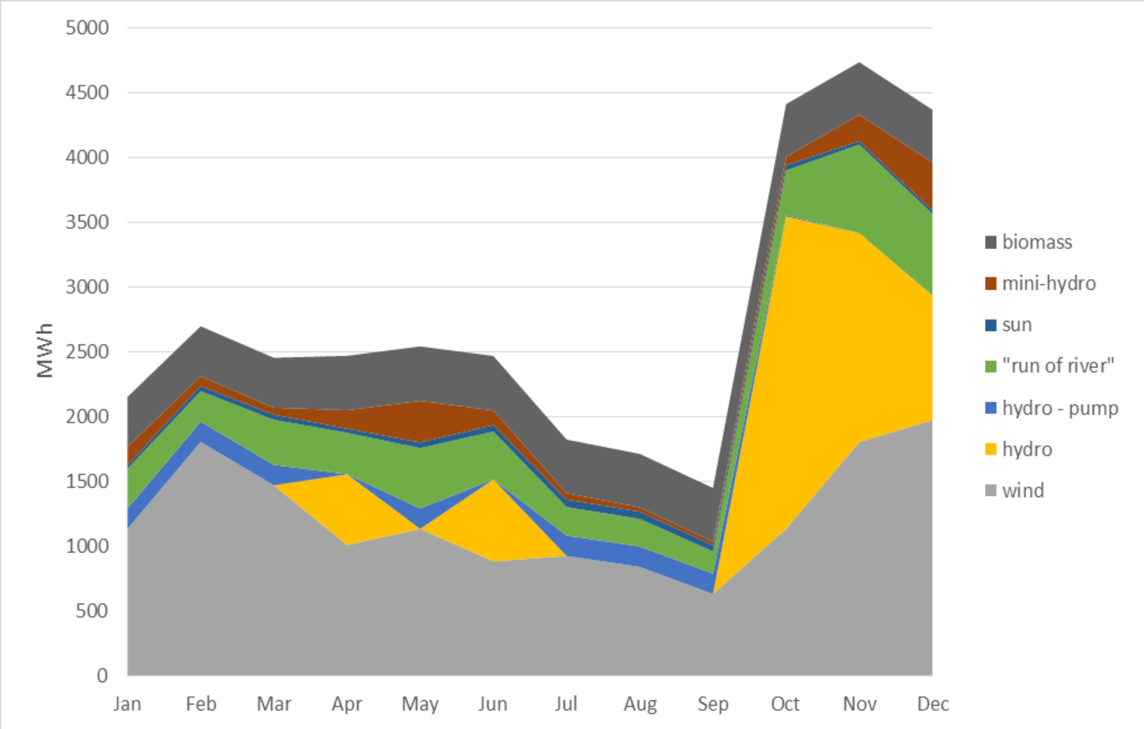


Fig. 22 - Monthly RES electricity production for scenario 1 in 2023

Some RES technologies such as hydro and wind present a high variation in different months, related to the seasonality of the resources. For example, hydro power, in October, produces 2 412 MWh while in August does not produce at all.

On the other hand, biomass is very stable, presenting only a variation of 28 MWh through the year.

Analyzing now scenario 4, with the highest percentage of renewable energies, the outcomes are showed in fig. 23:

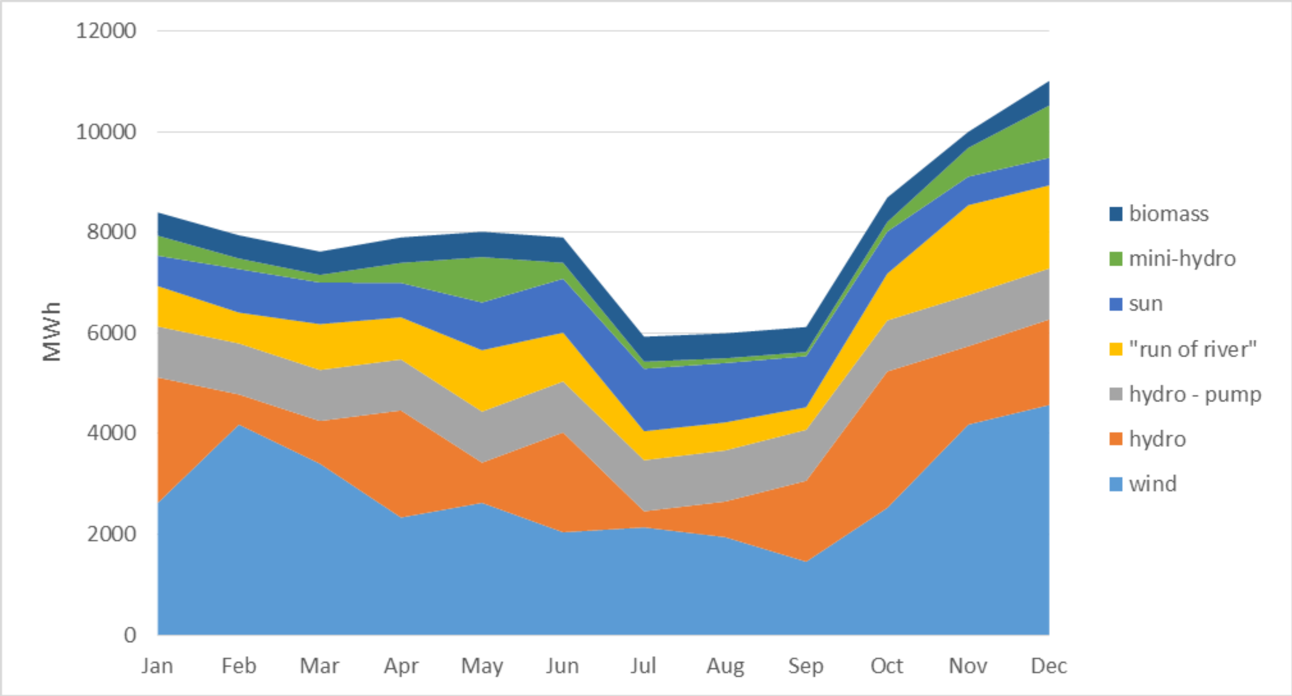


Fig. 23 - Monthly production for scenario 4 (MWh)

With the chart demonstrated previously, it is clear the variability of RES. Confirming wind and hydro power as the less regular ones and confirming also biomass as the most stable and more prone to the yearly seasonality. The figure demonstrates also the importance of hydro with pumping, as a stabilization measure of the system allowing to deal with the increasing share of RES of variable output.

Part IV – CONCLUSIONS AND FUTURE WORK

IV.1 - Final Considerations

IV.2 - Proposals for future work

PARTE IV – CONCLUSIONS AND FUTURE WORK

IV.1 - Final Considerations

Upon completion of all studies required to design the project, it can be concluded that the purpose of the work was reached, as described throughout this report.

Fossil fuel resources are limited. It is crucial to develop a solution to replace oil, coal and natural gas with renewable energy resources. However, renewable energy generation is more unpredictable than conventional energy sources in normal operational conditions. It is then fundamental that energy demand, harvesting and storage are well integrated.

Portugal is a country with scarce energy resources like those that ensure the generality of the energy needs of most developed countries (such as oil, coal and gas).This scarcity of fossil resources leads to a high dependence on foreign energy, especially of primary of fossil origin. To increase the contribution of RES such as hydro, wind, solar, geothermal, biomass is a very important step to the economy and to the sustainable development of Portugal, not forgetting the environmental advantages of RES.

This work aimed to approach the possible development of an electrical system based on 100% renewable production in Portugal. Methodologies to analyze the construction of future scenarios were selected, taking into consideration the objectives of minimizing costs and prospects for future development of technologies for generating electricity. The work required the adaptation of the SEPP model for the construction and analysis of future scenarios. The scenarios obtained were analyzed taking into account the expected costs of electricity generation and CO_2 emissions.

This dissertation presents the results of the modelling of four electricity production scenarios for the Portuguese power system. The first one represents a reference scenario using the data of the last complete year, 2012. The other three scenarios differ in the share of renewable energy production. Scenario 1 assumes a percentage of 37% of electricity production from RES, representing the share of electricity production from RES in year of 2012. Scenario 2 increases this percentage to 50%, scenario 3 to 75% and the last scenario presents the maximum renewable energy percentage for Portugal under the assumed restrictions of the model – 86%. To compare all three scenarios, year 2023, the last year of the simulation, was taken in consideration.

Regarding SEPP modeling, this study focuses solely on a cost optimization applied to all scenarios, minimizing total cost for scenario. Results obtained by cost minimization permitted to apprehend that with the increase of both demand and share of RES, cost increases from scenario to scenario due to the imposition of higher RES share resulting in an increase of the total installed power. The investment cost lead to an increase of the total cost of the system.

The CO_2 emissions were analyzed too, and it is possible to verify that as expected with the increase of RES in the system, CO_2 emissions reduce visibly.

For all scenarios wind and hydro power are the main RES contributors to the electricity production with the highest share. Solar power contribution starts to be small but in the last scenario, new solar power plants are installed and their share increase from 1 in scenario to 6%. Biomass is a very stable electricity production option with reduced on even no impact from seasonality and from scenario 1 to scenario 4 it is produced the same amount of electricity from biomass according to the installed capacity. All other RES technologies raised their production through all four scenarios.

Analyzing monthly production, it was also possible to verify energies' seasonality. Biomass is the more stable one against wind and hydro energy. This monthly analysis clearly demonstrated the seasonality of the RES resources, which can be a major source of concern for high RES scenarios. In fact, the possibility of reaching a 100% renewable scenario in the model was undermined by the difficulty of ensuring the production and demand match for periods of low RES availability and also by the need to guarantee the stabilization of the system defined according to the minimum reserve margin. The possibility of interconnection with Spain should be considered in future versions of model, as a viable stabilization measure.

In conclusion, by itself, under the assumed models conditions the maximum percentage that could be implemented was 86%. To reach a 100% RES electricity model for Portugal real possible cooperation with Spain should be included in the model. Cooperation mechanisms permit countries with limited or expensive RES potential partially fulfil their RES target by purchasing or jointly developing RES energy. This would both increase the efficiency of the system and reduce the intermittency problems.

Finally, it should be stresses that throughout this paper, the existence of obstacles was verified especially with data collection and its application on software. Although it has sought to select the data approached to the reality of the country, it was necessary to use select data obtained from studies produced for other countries, especially for cost data.

IV.2 - Proposals for future work

Energy sector, in the past years, has become the focus of great interest of world politics and, with the increasing demand, it is important to have a good strategic planning in all countries. This study represents a possible approach to the design of renewable energy systems in Portugal, but it is recognized that further analysis on the topic is required.

To be able to achieve a 100% renewable electricity system it would be important to study cooperation with other countries. Due to the location of Portugal, cooperation with Spain would be an important study and a possible solution to reach the main goal. The main question to be answered is would this cooperation be sufficient to realize the required competitiveness and pricing optimization? This implies major changes to the model, namely the conversation of what it is now a technical optimization model to an economic optimization model taking into account the Iberian market operating conditions.

Also, the study should proceed further with a risk and uncertainty analysis recognizing the variability of the RES resources and of the demand in the next years and integrating these aspects in the scenario creation, under sensitivity and probabilistic analysis.

In summary, this paper aims to stimulate further studies in this area that still has a lot to explore, always looking towards a more efficient electricity generation systems, sustainable and innovative.

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