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Impact of Climate Change on Electricity Planning – The Portuguese Case

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IMPACT OF CLIMATE CHANGE ON ELECTRICITY PLANNING – THE PORTUGUESE CASE

Abstract

Climate change (CC) is increasingly recognized as a fundamental issue for the 21st century and it is expected to have a significant impact on energy systems, especially on renewable energy. Information on the impacts of CC on the availability of renewable energy sources (RES) is essential for investment decision making and for strategic energy planning. Also, the formulation of adaptation policies is a vital strategy to reduce the vulnerability of the energy system to the CC impacts.

The effects of CC can be highly relevant in the southern Europe and particularly in Portugal. As such, the general objective of this study is to analyze the impact of CC scenarios in electricity production from hydro, wind and solar power in Portugal, evaluating also strategic power scenarios for a 10 years planning period.

According to the reviewed projections, until 2023 a decrease of precipitation and wind speed availability can be expected in Portugal. CC can lead to a reduction of 7,7% and 15% in precipitation and wind speed, respectively. On the contrary, the solar radiation is expected to increase and may reach an increase of 1%.

Twelve different strategic scenarios were simulated for the Portuguese electricity system in 2023, resourcing to the SEPP (*Sustainable Electricity Power Planning*) model. This allowed to evaluate the impact of CC on each one of these scenarios, addressing the installed power, electricity production, cost, emissions and renewables share. The results indicate that CC affects very slightly the optimal installed capacity in 2023, resulting in a marginal increase of the total installed power just enough to compensate for the RES power output reduction. Under CC scenarios electricity production from hydro, wind and small hydro is reduced comparatively to scenarios without CC, reaching a reduction of 4,4%, 5% and 0,3%, respectively in 2023. The solar power output is always higher in CC scenarios and a 4,6% increase can be achieved in the most extreme scenario. CC also has an impact on the costs of the electricity system leading to higher values.

Keywords: Climate change; Electricity planning; Renewable energy sources.

IMPACTO DAS ALTERAÇÕES CLIMÁTICAS NO PLANEAMENTO ELÉTRICO – O CASO PORTUGUÊS

Resumo

A alteração climática (AC) é cada vez mais reconhecida como uma questão fundamental para o século 21 e espera-se que tenha um impacto significativo nos sistemas de energia, especialmente nas energias renováveis. Informação sobre os impactos das AC na disponibilidade de fontes de energia renováveis (FER) é essencial para a tomada de decisão de investimento e de planeamento energético estratégico. Além disso, a formulação de políticas de adaptação é uma estratégia vital para reduzir a vulnerabilidade do sistema de energia para os impactos das AC.

Os efeitos das AC podem ser altamente relevantes no Sul da Europa e particularmente em Portugal. Como tal, o objetivo geral deste estudo é analisar o impacto de cenários de AC na produção de eletricidade a partir de energia hídrica, eólica e solar, em Portugal, avaliando também cenários estratégicos para o setor elétrico para um período de planeamento de 10 anos.

De acordo com as projeções verificadas, até 2023 pode ser esperada em Portugal uma diminuição na disponibilidade da precipitação e da velocidade do vento. As AC podem levar a uma redução de 7,7% e 15% na precipitação e na velocidade do vento, respetivamente. Pelo contrário, a radiação solar deverá aumentar e pode chegar a um aumento de 1%.

Doze cenários estratégicos diferentes foram simulados para o sistema elétrico português em 2023, recorrendo ao modelo SEPP (*Sustainable Electricity Power Planning*). Isto permitiu avaliar o impacto das AC em cada um desses cenários, abordando a potência instalada, a produção de eletricidade, o custo, as emissões e a quota de energias renováveis. Os resultados indicam que as AC afetam ligeiramente a capacidade instalada ótima em 2023, resultando num ligeiro aumento da potência total instalada apenas o suficiente para compensar a redução de potência FER. Sob cenários de AC a eletricidade produzida a partir da energia hídrica, eólica e pequena hídrica apresenta uma menor disponibilidade face aos cenários que não consideram as AC, atingindo uma redução de 4,4%, 5% e 0,3%, respetivamente em 2023. A produção de energia solar é sempre mais alta em cenários considerando as AC, e um aumento de 4,6% pode ser mesmo alcançado no cenário mais extremo. As AC têm também um impacto nos custos do sistema elétrico levando a um aumento destes.

Palavras-chave: Alterações climáticas; Planeamento elétrico, Fontes de energia renováveis.

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Abbreviations and Nomenclature

APA	Agência Portuguesa do Ambiente (Portuguese Agency Environment)
CC	Climate Change
CO_2	Carbon Dioxide Emissions
CCGT	Combined Cycle Gas Turbine – Natural Gas
CHP	Combined Heat and Power
DGEG	Direção Geral de Energia e Geologia (Directorate General for Geology and Energy)
EEA	European Environment Agency
EFOM	Energy Flow Optimisation Model
EPA	US Environmental Protection Agency
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
GAMS	General Algebraic Modeling System
GCM	Global Climate Model
GHGs	Greenhouse Gases
GWh	Gigawatt-hour
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
ICEM	Integrated Community Scale Energy Model
IIASA	International Institute for Applied Systems Analysis
IPCC	Intergovernmental Panel on Climate Change
JRC-P	Joint Research Centre Peseta
LNEC	Laboratório Nacional de Engenharia Civil (National Laboratory of Civil Engineering)
MAED	Model for Analysis of Energy Demand
MESSAGE	Model of Energy Supply Systems and their General Environmental Impacts

MGME	Multi Global Model Ensemble
MILP	Mixed Integer Linear Programming
MTOE	Million Tonnes Oil Equivalent
MW	Megawatt
MWh	Megawatt-hour
OECC	Oficina Española de Cambio Climático (Spanish Office of Climate Change)
OECD	Organisation for Economic Co-operation and Development
PDIRT	Plano de Desenvolvimento e Investimento da Rede de Transporte de Eletricidade
PNAEE	National Action Plan for Energy Efficiency
PNAER	National Action Plan for Renewable Energy
RCM	Regional Climate Model
RCP	Representative Concentration Pathays
REN	Redes Energéticas Nacionais
RES	Renewable Energy Sources
RNBC	Roteiro Nacional de Baixo Carbono (National Low Carbon Roadmap)
SIAM	Scenarios, Impacts and Adaptation Measures
SEPP	Sustainable Electricity Power Planning
SRES	Special Report on Emissions Scenarios
SRP	Special Regime Producers
TIMES	Integrated MARKAL-EFOM System
TWh	Terawatt-hour
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
WEM	World Energy Model
WEO	World Energy Outlook

WMO World Meteorological Organization

WWF World Wide Fund for Nature

1. Introduction

1.1. Scope

According to the World Wide Fund for Nature (WWF)[1], climate change (CC) is the greatest environmental threat of the 21st century, with serious consequences and transverse areas of society: economic, social and environmental. In the last century, the CC has suffered a strong acceleration and if measures are not taken, the tendency is that this problematic worsens increasingly throughout the present century.

The Intergovernmental Panel on Climate Change (IPCC) is the leading international body for the assessment of CC and it was established by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) in 1988. Its role is to provide an assessment of the understanding of all aspects of CC by carrying out at regular intervals assessment reports of the state of knowledge on CC (IPCC)[2].

According to WMO[3], CC occurs when there is a statistically significant variation on the means that characterize the weather and / or its variability for a period sufficiently large (decades). The largest known phenomenon caused by CC is the increased temperature. Factors such as the amount of greenhouse gases (GHGs) and aerosols in the atmosphere (from, e.g. volcanic activity and the burning of fossil fuels), the amount of energy from the sun or the properties of the land surface affect the Earth´s climate. Changes in these factors will cause changes in Earth's climate.

Global awareness of the problem of the CC is increasing and several actions are being developed and implemented to try and tackle the underlying causes, both at national and international levels (OECD/IEA, 2013). Hereupon, the energy sector has a vital role to play in tackling CC and is a key sector to limiting it (OECD/IEA, 2013).This sector must take responsibility on to arresting and reversing the growth of GHGs, otherwise will be increasingly affected by CC consequences in all world. Almost everywhere in world, CC will affect energy services and resources, either directly or indirectly. Energy demand and supply will be affected, increasing variability and inter-annual variations in

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[1] Website page consulted on May 2013: http://www.wwf.pt/o_nosso_planeta/alteracoes_climaticas/

[2] Website page consulted on May 2013: http://www.ipcc.ch/organization/organization.shtml#.UjxZRD8QMvZ

[3] Website page consulted on May 2013: http://www.wmo.int/pages/prog/wcp/ccl/faqs.html

climate parameters and increasing the probability of occurrence of extremes (Ebinger and Vergara, 2011).

Energy is essential to all human activities. Indeed, is crucial to social, environmental and economic development. Thus, energy decisions play a major role in reaching sustainable development and consequently on the economic, environmental and social welfare of future generations.

In fact, energy resources are required to supply the basic human needs of food, water, health and shelter and to improve the quality of life. Given that the energy system is currently based on large fossil fuels burning dependence, WWF[4] support that it is imperative to progressively eliminate the massive use of fossil fuels, replacing them by RES and encouraging energy savings and energy efficiency.

RES are a then a key strategy to meet energy needs in the world and to limit the increase of CC. Until 2035, it is expected that RES represent one-third of total electricity production (OECD/IEA, 2013).

According to various studies, such as IPCC and World Bank, it is correct to say that the temperatures are increasing, sea levels are rising, glaciers are melting and precipitation patterns are changing. Extreme weather events are becoming more intense and frequent. Certain guidelines predict a rise in temperature and a decrease in annual precipitation (less water available) particularly in south Europe and consequently in Iberian Peninsula (Portugal and Spain) (IPCC, 2007b and Ebinger and Vergara, 2011).

These changes will have a strong impact in energy services and resources. For example, changes in rainfall can lead to a reduction of water available affecting hydro production. Also, extreme events can disrupt production and effect structural integrity. RES availability and potential will be seriously affected because they depend primarily on weather conditions (temperature, solar radiation, wind speed, precipitation) (Ebinger and Vergara, 2011 and OECD/IEA, 2013).

Electricity planning has been limited by government regulations and policies for the energy sector, so various policies must be taken into consideration in energy planning. Kyoto Protocol is an international treaty intended to bring countries together to reduce global warming and to cope with the effects of temperature increases. According to

[4] Website page consulted on May 2013: http://www.wwf.pt/o_nosso_planeta/alteracoes_climaticas/

Portuguese Government Resolution 20/2013, PNAEE (National Action Plan for Energy Efficiency) and PNAER (National Action Plan for Renewable Energy) are energetic planning instruments that establish how to achieve the goals and commitments assumed by Portugal in energy efficiency and utilization of energy from renewable sources, ensuring a sustainable society for future generations.

The vulnerability and impacts of CC scenarios in the energy sector are important information that should support energy electricity planning decisions in the future. Strategic electricity planning should learn from past development but must also adapt historic data to future projections. This requires studying the present resources and planning for the addition of new power plants according to the forecasted demand requirements, the technical restrictions and possible environmental commitments. To support planning decisions the use of models frequently translated in software tools is required. These models can be particularly helpful for the simulation of different scenarios analyzing the impacts that projections in external factors such as CC have on the electricity system design and overall performance.

1.2. Objectives of the research and methodological approach

The increasing importance that has been given to the CC theme is evident. This work envisages now looking at it from the perspective of strategic planning of an electricity system with a strong renewable component, being the Portuguese case an important example to explore.

The main objective of this study is to investigate the impacts of CC on the design of strategic power scenarios, resourcing to the sustainable electricity planning model (SEPP) departing from Pereira et al. (2011) proposed model and adapting it to this research requirements. The particular case of Portugal will be analyzed aiming to build future scenarios for the electricity sector, taking into consideration the forecasts for the sector constrained by CC projections. For this study, a period of 10 years was considered, from 2014 to 2023. The specific objectives can be summarised as follows:

1 - Assessing the impact of CC on the availability of RES.

2 - Construction and scenarios analysis of electricity production in Portugal considering the impact of CC.

During the research, to form the theoretical basis of the work, a literature review on the impact of CC on energy systems was undertaken. For this, scientific publications, reports of international organizations and international projects that address the issues were used as sources of information.

The work also included an extensive data collection, which focused mainly on the Portuguese electricity sector and for the years under study. Information on the CC impacts for the Portuguese case, namely addressing, hydro, wind, sun and temperature projected variation, was collected. These projections were mainly based on IPCC studies.

On a later stage, a study and adaptation of the model SEPP (Pereira et al., 2011) was conducted for the construction of future scenarios for Portugal, taking into account the information collected in previous phases.

Lastly, a critical analysis of the scenarios presented was performed comparing the differences between scenarios constrained by CC and non-constrained scenarios. This analysis allows evaluating how these CC can affect the choice of technologies for electricity production, the cost and emissions of the system.

1.3. Organization of the thesis

The work was conducted according to the objectives outlined, being organized as follows:

Chapter 2 begins with a presentation of the concept of electricity planning and its importance for the energy sector decision making. A brief description of energy models is provided reviewing some studies that used models of electricity planning, describing the main purpose of their use and their main characteristics.

Chapter 3 describes the main impacts of CC in the energy system, and presents the CC forecasts, particularly for temperature, solar radiation, rainfall, river flow, wind speed and energy demand, to southern Europe, Mediterranean and consequently for Portugal.

Chapter 4 gives a brief description of the Portuguese energy system. The external energy dependence is demonstrated. The main energy sources that contribute to electricity production and the installed capacity of the system are described.

Chapter 5 presents a brief description of the electricity planning model used (SEPP) and the adjustments required for this work. The results of the model implementation are then presented, describing each scenario obtained with the simulation of Portuguese electricity system in cost optimization approach.

Chapter 6 draws the main conclusions of this work, presenting also some perspectives for further work.

2. Electricity planning

2.1. Introduction

The increasing demand for electricity in the world has led to increased burning of fossil fuels which may create havoc for our climate (Hill, 1995). The producing electricity using fossil fuels contributed significantly to the release of GHGs (primarily CO_2 - carbon dioxide). This fossil fuel increasing reliance and its consequences represent a particularly relevant global problem that has been catching government's attention for more than a decade. GHGs are having a significant effect on the Earth´s climate causing an increasing rate of warming (Nolan et al., 2011).

The carbon emissions grew fastest in developing countries than in the developed countries over the past two decades, because of high growth rates in electricity production (Hill, 1995). The energetic dependence on fossil resources turns to be a problem too when these natural resources run out or start to be scarce. Inappropriate exploitation of energy sources can have devastating effects on the natural systems that support life on this planet. Environmental impacts of electricity generation activities become then increasingly critical. The solution may be to use RES as a way to reduce CO_2 emissions to minimize CC and to reduce energetic dependence on fossil resources (OECD/IEA, 2013).

Krajačić et al. (2011) assumed that sustainability is increasingly the main objective in many communities and to reach it is necessary to ensure adequate energy for local development. Fossil fuels are progressively more expensive due to limited resources and over last decades the population has increased and consequently the energy consumption too. In this situation, these authors also claim that the RES utilization appears to be a promising sustainable solution.

Choices about how energy is produced and used will determined the sustainability of the future energy system and therefore, of socioeconomic progress. Energy plans is an essential tool for the development of energy policies in the medium and long term. Security of supply, energy dependence and diversification, but especially environmental considerations are concerns that today are the guidelines for the development of any energy plan.

Electricity power planning is, according to Hobbs (1995), “the selection of power generation and energy efficiency resources to meet customer demands for electricity over a multi-decade time horizon”. This author classified energy planning according to the time length and objectives, including for example resource planning, long range fuel planning, maintenance, unit commitment and dispatching. Hobbs (1995) presents reasons for the increased complexity of this process, such as the increasing number of options, the great uncertainty in load growth, fuel markets, technological development and government regulation, and the inclusion of new objectives other than cost.

Electricity generation expansion planning allows to identify which technologies and energy sources are most efficient and rational to use for meeting the demands of society (Pereira and Saraiva, 2010). In line with this, Meza et al. (2009) underlined that generation expansion planning aims to satisfy the expected electricity demand taking into account that the smallest error in defining the best location for building power plants will result in significant loss of money and also loss of society welfare. This would result on the increase of social costs for not meeting the energy demand of future generations.

According to Tekiner et al. (2009), the biggest problem for the electricity generation expansion planning studies is to find the least cost expansion plan. These authors refer also that environmental impact, reliability, imported fuel, safety and so on, are various conflicting objectives in the generation expansion planning problem.

Electricity planning is particularly challenging under sustainable development requirements. These planning tools must now recognize the underlying principles of sustainable development, clearly interconnected with the increasing reliance on RES. An effective use of these tools can contribute to prevent the degradation of non-RES and present its substitution with cleaner alternative energy sources, thus responding to the demand for energy in a positive way and ensuring the sustainable development of society. In fact, the increasing acceptance of the principle of sustainable development has been a major driving force towards new approaches to energy planning (Ferreira et al., 2010).

There exists a strong link between energy, environment and sustainable development (Ferreira et al., 2010). According to Brutdtland Report (World Commission on Environment and Development, 1987), the sustainable development is “development that meets the needs of the present without compromising the ability of future generations to meet their own needs". The satisfaction of human needs and aspirations are included the major objective of development.

Ferreira et al. (2010) consider that inclusion of environmental dimension in the electricity planning process is essential. Therefore requiring the full evaluation of the environmental characteristics of each electricity generation technology is fundamental. Cost minimization is also an undeniable essential criteria to ensure the competitiveness if the economy and the society access to electricity at reasonable prices.

Energy planning is a complex process involving multiple and conflicting objectives, in which many agents were able to influence decisions (Ferreira et al., 2010). Besides general trends, intra- and inter-annual climate variations are important for the strategic energy planning and operational decision making (Ebinger and Vergara, 2011). In other words, strategic energy planning is the process of developing long-range policies to help guide the future of a local, national, regional or even the global energy system.

Over recent years has been a growing awareness that energy planning is increasingly important in the regulatory framework of a country. This increased concern is due mainly to the impact of the energy sector on the environment and consequently the threat of CC. However, it is also important to understand the potential vulnerabilities of energy services to CC.

Ilic et al. (2011) states that sustainable energy system is characterized by five several attributes: ability for supply and demand to match during normal conditions (viability); ability for supply and demand to match during abnormal conditions (reliability); short and long-term efficient energy utilization (efficiency); low pollution (environmental sustainability); impacts on technology providers and consumers (business sustainability and well-being).

The creation of energy strategies is an important step in the development of an energy policy of a country. In addition, the countries, to achieve economic, social and environmental welfare, must cope with considerable challenges in energy namely, it is growing dependence on imports, CC and increasing demand.

The regulation of the power systems are highly conditioned by the general energy strategies and policies. For example, many countries and states have been adopting targets for emissions of CO_2 and other GHGs giving particular attention to the electricity sector. The electricity planning will then become increasingly constrained.

According to Ferreira (2008) this planning requires also a vast knowledge of the existing electricity system and a preliminary study of possible new plants in the future. However, it must be underlined that fuel prices are changed frequently, technological innovation potential is very high, the rate of demand is difficult to predict and government regulations and policies for the sector change frequently, so the planning process is thus based on uncertain forecasts.

Energy planning should aim at a transversal approach to all energy sector, in order to contribute to the conception, promotion and evaluation of policies relating to energy, with the objectives of policies integration, such as, environment and sustainable development, security of supply, competitiveness, implementation and development of new technologies (more efficient and cleaner). This process should envisage also monitoring and controlling the supply and demand of energy matching supply growth with the needs of demand and designing more efficient system. This requires to follow regularly the evolution of the respective sectors and markets. It is important also to control the security of supply and to monitor and to evaluate results of the implementation of policies and measures formulated in plans, programs and strategies (by indicators of energy consumption and supply).

According to the Portuguese document Energy 2020 (Portuguese Government Resolution 29/2010), energy strategic planning must take into consideration three points: sustainability, to actively combat CC by promoting RES and energy efficiency; to increase competitiveness improving the effectiveness of the European network through the completion of the internal energy market; and to ensure security of supply better coordinating supply and demand energy. The reduction of the energy dependence without compromising the security of supply is also a major objective of the Portuguese energy policy.

Today's challenges impose that the energy system be viewed as a whole, from a perspective of integration and complementarity of the various vectors that compose the energy system.

The energy planning is an important tool to define how best to achieve the goals that are imposed on the energy sector in the short, medium and long term, in an integrated way, aimed at safeguarding the sustainability and security of supply.

2.2. Electricity planning models

Energy planning models are direct to a series of energy issues and provide a consistent framework for developing and evaluating alternative paths for the energy system in a country. These models should take into account expected changes in demography and life-styles, technological development and innovations, economic competitiveness, environmental regulations, market restructuring, and global and regional developments. The models have the added advantage of being extremely flexible and can be readily adapted to the often very different national and regional energy system structure, constraints, needs and uses in different countries (IAEA, 2009).

According to Foley et al. (2010) electricity systems models are software tools used to manage electricity demand and the electricity systems, to trade electricity and for generation expansion planning purposes. These authors refer that since 1950 the companies began electricity modeling using linear programming techniques to plan new generators to meet increased electricity and mostly to resolve capacity expansion problem.

The energy system is described by mathematical functions that are developed in a computational formulation in the form of software, a tool that together with other factors will assess the sustainability of projects to produce electricity. The aim is to find the best solutions according to the objective functions and limitations, relying on single or multiple objective optimisation procedures (Ferreira, 2008).

Through models, data mathematically described can be understood and interpreted and processing updating them practically. Scenarios are then built through the development of mathematical models. These scenarios aim to support decision making on policy and on business development plans in electricity systems in order to choose the best advice for governments and industry on the least cost economic and environmental approach to electricity supply, ensuring a quality supply to the entire society and reducing external energy dependency (Mäkelä, 2000).

These models are a simplified representation or interpretation of reality because the real systems are normally far too complicated to be perfectly represented in a model (Mäkelä, 2000). This author says that one should have a good understanding about the model and the data used in order that these simplifications, uncertainties, possible mistakes and many other things do not make model results untrustworthy. As such, models can be considered rather as a way of gaining insight of complex systems than providing direct answers for decision making.

According to Suganthi and Samuel (2012), energy models can be developed for sustainable development of any country and as already mentioned earlier is increasingly important to reduce energy costs and GHGs emissions to meet sustainable energy system planning, thus energy models are created in order to meet these objectives.

To Mäkelä (2000) the complexity of energy system and negative consequences derived of unfavorable decision making has been motivations for increasing development of various energy systems models.

There are a various methods and models that will give a broad overview of the planning models tools most frequently used. Energy models can be supported on optimization, simulation or equilibrium tools.

Cai et al. (2012) developed an integrated community scale energy model (ICEM) of long-term to support renewable energy management systems planning taking into account CC. This model aimed to reduce energy-shortage risks under CC conditions for a multi-period, thus conducting energy planning minimizing system cost, maximizing system reliability and maximizing energy security always.

In 2008, Cleto et al. (2008) had already studied two water availability scenarios caused by CC on the Portuguese energy system up to 2050 based on a linear optimization model – TIMES. This model was used to evaluate the impacts on the power sector in Portugal. TIMES is generally used to assess impacts of energy and environment policies such as building codes, energy or emission taxes, investment subsidies, emission intensity standards and regulations, and to perform technological assessments. The satisfaction of the demand for energy services at a minimum system cost is the intended purpose.

Harrison and Whittington (2002) used WatBal model to study the vulnerability of hydropower projects to CC on a large potential scheme in Africa for the 2080 period. WatBal model is an integrated water balance model developed for assessing the impact of CC on river basin runoff. This model was described to evaluate the relationship between CC, hydropower production and financial performance.

Cormio et al. (2003) used EFOM-based optimization model to support planning policies for promoting the use of RES, applied in southern Italy (Apulia). This model aimed to reduce environmental impact and economic efforts taking into account the possible installation of combined cycle power plants, wind power, solid-waste and biomass exploitation together with industrial combined heat and power (CHP) systems.

The International Energy Agency (IEA)[5] uses the World Energy Model (WEM) for the World Energy Outlook (WEO) scenarios. Based on medium to long term, prospect this model is used to analyze global and regional energy, environmental impact of energy use, effects of police actions and technological changes and investment in the energy sector. MAED model has been used by the International Atomic Energy Agency (IAEA) to evaluate future energy demand based on medium- to long-term scenarios of socioeconomic, technological and demographic development (IAEA, 2006). MESSAGE is a model for medium-long term to energy system planning, energy policy analysis, and scenario development. This model has been used by major international assessments and scenarios studies, e.g. the IPCC and the Global Energy Council (IIASA, 2013).

According to Connolly et al. (2010) the EnergyPlan is a model for energy systems analysis based on inputs and outputs and is used to assist the design of national energy planning strategies on the basis of technical and economic analyses of the consequences of different national energy systems and investments. This model emphasizes the analysis of the interaction between the use of CHP production and use of RES.

Pereira et al. (2011) developed a SEPP model that takes into account both the economic and environmental impacts. This optimization model was built for the analysis of a mixed hydro-wind-thermal power system. The Portuguese electricity system was analyzed with this model, aiming to minimize total generation costs and environmental

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[5] Website page consulted on May 2013: http://www.worldenergyoutlook.org/weomodel/

impacts. The results obtained were possible strategic scenarios for a 10 years horizon, described by a set of technical, economic and environmental characteristics.

Jebaraj and Iniyan (2006) underlines that a formulation of an energy model will help in the proper allocation of widely available RES and not only in meeting the future energy demand of the respective country. The energy models will then help the energy planners, researchers and policy makers widely. The models should be seen as valuable tools contributing to promote discussion and formulation of policies, which are appropriate to each situation and system under study.

3. CC impact on energy systems

Although the weather has been stable for several years, there are now clear signs that the climate is changing (EEA, 2010).

Climate change in IPCC can be defined as a change in the state of the climate that can be identified (e.g. using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Refers to any change in climate over time, whether due to natural variability or as a result of human activity. Also, the United Nations Framework Convention on CC (UNFCCC) defines CC as a change that which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods (IPCC, 2007a).

CC have been observed in continents, regions and oceans. From observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level, so it is possible to conclude that warming of the climate system is unequivocal. Changes in temperature, in amount of precipitation, in ocean salinity, in wind speed and extreme weather events (droughts, heavy precipitation, heat waves, cold waves and intensity of tropical cyclones) will be trends likely to happen in the future (IPCC, 2007b).

To EEA (2012) *climate change impacts* refer to the observed or projected effects of CC on natural and human systems. In the case of projected effects, these projections often refer to 'potential impacts', which are those impacts that may occur given a projected change in climate, without considering adaptation.

According to the study of World Bank (Ebinger and Vergara, 2011), the impacts of global CC may become evident on the energy sector, in general but specially in renewable energy, because of the RES dependency on climate conditions makes it also susceptible climate. According to the same study, CC will increasingly affect the energy sector and these impacts can have direct and indirect effects on energy services. Changes in temperature, precipitation, storms, and sea level are likely to have direct effects on energy production and use; but CC can affect also other economy sectors. Wilbanks et al. (2008) said that indirect effects could have higher impacts, positives or negatives, in some cases (institutions or locations). The possible indirect effects of CC on energy systems can be felt on energy planning and investments, on technology, on energy supply institutions, on energy aspects of regional economies, on energy prices, on energy security, on environmental emissions from energy production/use and on energy technology /service exports.

Gruenspecht (2011) underlines that the assessment and valuation of the impacts of CC on energy systems, including both effects on energy demand and effects on energy supply systems, have received considerable attention over the past 25 years. This author asserts that effects of CC on energy demand are through the energy consumption for heating or cooling. According to the Joint Research Centre Peseta II project (JRC-P II, 2013), CC is expected to lead to reduced demand for heating in winter, and increased demand for cooling in summer due to expected generalized warmer climate. This trend is particularly evident for southern Europe. In what concerns energy supply, CC can have significant impacts on the access to traditional energy resources. For example, hydroelectricity is an important renewable source for electricity production that is extremely sensitive to changes of precipitation and consequently on changes of river flows (Gruenspecht, 2011). According to Ebinger and Vergara (2011) changing climate conditions can affect the operation of existing hydropower systems and might even compromise the viability of new investments. The same way, changes in the wind speed could affect power availability from natural resource and solar energy can be affected by extreme events and increased air temperature.

Weather has the largest impact on electricity production and CC has been identified as one of the biggest environmental, social and economic threats that planet and humanity faces today (APA)[6].

Energy services are a necessary input for development and growth of a country, mainly developing countries, and are indispensable from a globally sustainable prosperity. The countries, through energy services increase productivity, enhance competitiveness and promote economic growth, thereby improving the quality of life of citizens.

It becomes then imperative to understand the potential vulnerabilities of energy services to CC (Ebinger and Vergara, 2011). Cai et al. (2012) assumed energy production from a

[6] Website page consulted on May 2013: http://www.apambiente.pt/index.php?ref=16&subref=81

number of RES such as geothermal, hydro, solar and wind energies could significantly be affected by CC.

The generation potential impacts will however depend on the plant location and the type of RES under consideration (Ebinger and Vergara, 2011).

Increasing temperatures can lead to an increasing use of electricity for air conditioning and less natural gas, oil, and wood for heating. These changes in energy demand could require investments in new energy infrastructures, for example increasing the need for additional electricity generating capacity, or lead to reliability problems (EPA)[7], 2013 and Ebinger and Vergara, 2011).

Energy and water systems are closely related. Hydroelectricity (electricity produced by running water) is an important energy source and cooling water is needed to run many today´s power plants (Ebinger and Vergara, 2011). As such, CC could affect the amount of water available to produce electricity (EPA)[8]. Wilbanks et al. (2008) state that hydropower operations are affected when precipitation, air temperatures, solar radiation, humidity, evaporation or wind patterns are affected by CC.

According to Ebinger and Vergara (2011) an increase in precipitation generally increases water availability for cooling purposes as well as for hydropower production, but also dams may have to be modified to prevent downstream flooding. More regular and severe heat waves will probably increase the demand for electricity, and a decrease of precipitation combined with an increase of temperature, solar radiation and evaporation could stress water resources, leading to increased competition for water between energy production and other uses in areas where the availability of water is already scarce, for example, for agriculture (irrigation). This may increase the need for energy-intensive methods of providing drinking and irrigation water. For example, desalinization plants can convert salt water into freshwater, but consume a lot of energy. CC may also require irrigation water to be pumped over longer distances, particularly in dry regions. Gruenspecht (2011) also underlines that hydroelectric dams are directly dependent on water flows and almost all existing generating facilities require access to cooling water for the correct operation. Ebinger and Vergara (2011) concluded that highly variable water supply due to flooding or drought may have severe implications

[7/8] Website page consulted on May 2013: http://www.epa.gov/climatechange/impacts-adaptation/energy.html on the plant infrastructure itself, including water regulation (storage), safeguarding, and maintenance - in addition to the issues related to energy demand and supply.

The increased solar radiation results in higher temperature (Tham, 2011). Changes in solar radiation are of crucial importance for the conditions of solar energy production (Ruosteenoja and Räisänen, 2009). So, an increase in solar radiation will affect positively the solar energy because there will be a greater production potential. The increasing air temperature will not directly influence the production of solar energy but can modify the efficiency of equipment that is not prepared for high temperatures and by this reduce electricity generation (Wilbanks et al., 2008). Then, it will be necessary to maintain the performance of the solar equipment for higher temperatures.

CC can have significant positive or negative impacts in wind speed (Ebinger and Vergara, 2011 and Wilbanks et al., 2008). However, storms may bring increased wind speeds at times, both at sea and over land and the tolerance of wind platforms and wave and tidal generators could be at risk.

In general, extreme events (hurricanes, flooding sea level rise, storm) can disrupt production and damage structural integrity of infrastructures energy. For example, in areas sensitive to sea level rise and storm surge could endanger energy production and delivery by damaging electricity infrastructure, fuel delivery infrastructure and equipment, power plants, or storage facilities. Changes in weather variability and frequency of extreme events would affect required stocks of fuels and or installed nominal generation capacities, which will cause increasing operational and maintenance costs (EPA[9] and Ebinger and Vergara, 2011).

Energy planners, regulators, and industry of each country need to develop possible adaptation actions for the energy sector under the CC perspective. Energy planning, decision making, and investment are three very important points for development goals and climate actions adaptation actions. Cross-sector and regional coordination is also fundamental to integrate considerations and solutions that span energy, water, agriculture, and hydro-meteorological services or cross traditional boundaries (Ebinger and Vergara, 2011).

[9] Website page consulted on May 2013: http://www.epa.gov/climatechange/impacts-adaptation/energy.html

According to European Environment Agency (EEA) (2010) “adaptation” is defined as the adjustment of natural or human systems to actual or expected CC or its effects in order to moderate harm or exploit beneficial opportunities. Adaptation is then a first step towards an adaptation strategy to reduce vulnerability to the impacts of CC, and complements actions at national, regional and even local levels.

Ebinger and Vergara (2011) suggested as example of possible adaptation actions increasing regional electricity power generation capacity, plan for and implement enhanced delivery capacity and when planning new plants take into account changing patterns of demand (summer – winter, wet – dry season, north – south) – to be applied by national government and private sector. National government should invest in research and development centers to make space cooling and building enclosure more efficient and affordable and ensure partnership with these centers. Government agencies can weatherize buildings and improve efficiency energy use to reduce cooling demand.

According to Ebinger and Vergara (2011) local governments should ensure energy requirements to populations, mainly during heat waves periods. Wilbanks et al. (2008) believe that planning at the local and regional level to anticipate drought impacts is vital. National government and private sector must improve efficiency of power generation/distribution. Also, incentives to study the issue of whether decentralized power production reduces risk should be implemented (Ebinger and Vergara, 2011). Wilbanks et al. (2008) suggests development of technologies that minimize the impact of the temperature increase on the power plant equipment.

For changes in precipitation and water availability, Wilbanks et al. (2008) propose technologies that conserve water use for power plant cooling processes. Ebinger and Vergara (2011) support that the national government and private sector should develop less-water intensive electricity power generation strategies, ensuring also contingency plans for possible reduction of the hydropower generation, accelerate development of low-energy desalination technologies, diversify energy sources to provide a more robust portfolio of options and establish incentives for water conservation in energy systems, including technology development and for integrated water and energy conservation planning.

Wilbanks et al. (2008) recall the importance of planning at the local and regional level to anticipate extreme weather events impacts. Ebinger and Vergara (2011) also recommend stronger infrastructures to support increased flood, wind, lightning, and other storm-related stress, including reinforcement of walls and roofs or structural improvements to transmission assets and call attention to the need to consider relocation of infrastructures to less vulnerable regions in longer term. However, relocating or protecting energy infrastructure and increase resilience to energy interruptions and other threats have high costs (Wilbanks et al., 2008) – increasing electricity transmission capacity and storage capacity. National/local governments and private sector should be prepared for supply interruptions, for example investing in backup systems for emergencies facilities, schools, etc. (Ebinger and Vergara, 2011).

RES are particularly vulnerable to damage from extreme weather events. Wilbanks et al. (2008) propose an improved projecting of the impacts of global warming on RES at regional and local levels, and development/implementation action plans and policies that conserve both energy and water.

Options and CC preventing measures can be difficult to implement in developing countries with varying degrees of exposure to CC and with large energy needs and supply options are not possible. For example, for countries where hydropower is prevalent, impacts from changes in rainfall cycles must be assessed. As for regions with coastal assets, reducing vulnerability to weather extremes and sea level rise is fundamental. The increased probability of extreme weather events implies that contingency plans are required, increasing firm energy availability, extending backup power capacity, and extending disaster protection and recovery plans (Ebinger and Vergara, 2011).

To develop adaptation strategies is important to have easy access to primary information, genuine, authentic and updated. According to Ebinger and Vergara (2011) the availability of such information raises a further challenge. The exact vulnerability to weather variations is not well mapped for most countries. Changes in vulnerability would generally increase operation and maintenance costs of energy delivering systems. Occurrence of extreme events and climates trends will require changes and thorough rethinking of energy planning, construction, operations, and maintenance to better identify and manage climate risks now and in the future.

As seen above, the literature revised strongly support that the energy sector is susceptible to climate change consequences. For this reason is vital to consider these vulnerabilities for the formulation of adaptation policies taking into account the characteristics of the system under analysis and its location.

3.1. CC forecasts

CC is a serious subject and these changes are expected to have a big impact around the world. As such, this problem has been an important topic in international events and legislative and policy options in last times.

Until 2007, the global mean temperature increased by about 1,2°C since pre - industrial times (Römisch, 2009) and scientists considered extremely likely this increase in global average temperature, i.e., an overall warming of the Earth´s climate, is primarily caused by increasing concentrations of GHGs produced by human activities such as the burning of fossil fuels and deforestation. A continuous increase in GHGs is projected to happen during the 21st century (IPCC, 2007b).

The latest IPCC report was published in 2007 (IPCC fourth assessment report: CC 2007) and this report summarized information on climate projections based on the IPCC emission scenarios. Also concludes with strong confidence that human activities have contributed to the warming of the global climate since at least 1750 (IPCC, 2007b).

According to WMO[10], climate projection is normally a report about the likelihood that something will happen in future if certain conditions maintain as an increase in GHGs concentration, which might influence the future climate. The projections are conditional expectations (if this happens, then that is what is expected) about the future. Then, scenarios are developed using global climate models (GCM) and regional climate models (RCM) taking into account several assumptions and judgments about emissions, CO_2 concentrations and others GHGs emissions.

All projections about temperature tend to have a higher level of confidence than projections about precipitation. Projected changes to the wind speeds and solar radiation are particularly uncertain. To Römisch (2009) most European regions are considered to be low vulnerable to CC, and with some adaptation/adjustments the potential impacts should be controllable. To IPCC (2007b) southern Europe will be more severely affected than northern Europe, prevailing hot and dry conditions.

[10] Website page consulted on May 2013: http://www.wmo.int/pages/themes/climate/climate_projections.php

The projections found are estimates that were produced by running different GCM at different GHGs scenarios. Different emission scenarios give a range of several predictions about variables of CC. Almost all predictions are based in IPCC scenarios from latest IPCC report, published in 2007.

3.1.1. Temperature

To IPCC Special Report on Emission Scenarios (SRES: B1, A1B andA2) (including only anthropogenic forcing) global warming averaged for 2011 to 2030 compared to 1980 to 1999 is between +0,64°C and +0,69°C, with a range of only 0,05°C, for early 21^{st} century (IPCC, 2007a).

According to third assessment report by IPCC, the average annual surface temperature increased by about 0,8ºC in most of Europe, during 20^{th} century. And the climate models results indicated a trend an increase in annual temperature in Europe about 0,1ºC to 0,4ºC/decade over the 21^{st} century. Annual mean temperatures in Europe are likely to increase more than the global mean temperatures and model projections suggest that warming in northern Europe is likely to be greatest in winter and southern Europe in summer (IPCC, 2007b).

The IPCC (2007b), in its fourth assessment report developed several emissions scenarios taking into account the 21^{st} century, SRES - modeling results are for the period 2070-2099, using as baseline period 1961-1990. Concerns about sustainability and the levels of GHGs emissions are the main assumptions for the scenarios development.The A1 scenario is characterized by rapid economic growth, a global population that reaches 9 billion in 2050 and then gradually declines the rapid introduction of new and more efficient technologies. This scenario includes three more scenarios: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B). The A2 scenario is characterized by a world of independently operating, self-reliant nations, continuous increasing population and regionally oriented economic development. The B1 scenario is ecologically friendly and is characterized by rapid economic growth as in A1, but with rapid changes towards a service and information economy, population rising to 9 billion in 2050 and then declining as in A1, reductions in material intensity and the introduction of clean and resource efficient technologies, an emphasis on global solutions to economic, social and environmental stability. The B2 scenario is more ecologically friendly and is characterized by continuously increasing population, but at a slower rate than in A2, emphasis on local rather than global solutions to economic, social and environmental stability, intermediate levels of economic development and less rapid and more fragmented technological change than in A1 and B1. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels. This intergovernmental body indicates which climate initiatives such as UNFCC or the emissions targets of the Kyoto Protocol were not taken into account in SRES.

For period 2090-2099 the best estimate for the temperature increase under the low scenario (B1) is 1,8°C (likely range is 1,1°C to 2,9°C), and the best estimate for the high scenario (A1FI) is 4,0°C (likely range is 2,4°C to 6,4°C) (IPCC, 2007a).

In short, for the scenario A1T and B2 the best estimate for the expected temperature rise is 2,4°C with a likely range of 1,4ºC to 3,8°C. For scenario A1B the best estimate temperature rise is 2,8°C with a likely range of 1,7ºC to 4,4°C. For scenario A2 the best estimate temperature rise is 3,4°C with a likely range of 2,0ºC to 5,4°C (IPCC, 2007a).

To IPCC (2007a) the same A1B scenario project that annual mean warming from 1980 to 1999 to 2080 to 2099 can change from 2,2°C to 5,1°C in southern Europe and Mediterranean.

For the period 2070-2099, the climate projections show that during the 21st century a relatively uniform increase of the temperature in Iberian Peninsula is expected. This increase can be about 0,4ºC/decade in winter and 0,7ºC/decade in summer for the low favorable scenario (A2 IPCC) and 0,4ºC to 0,6ºC/decade, respectively, for the more favorable scenario (B2 IPCC). On the inland Peninsula the temperature increase in relation to the present climate in A2 scenario (IPCC) can reach values between 5ºC to 7ºC in summer and 3ºC to 4ºC in winter. The B2 scenario (IPCC) is similar to that of A2 scenario, but generally less intense, with a temperature increase of about 1ºC. On the coast of the Peninsula the projected temperature increase is around 2ºC less than that on the inland Peninsula in all the seasons of the year (OECC, 2005).

The Climate Cost project has considered three scenarios, but A1B scenario is the one that reflects a medium-to-high emission and has been largely used in recent European regional climate modeling studies, for example, in the ensembles study. This project shows that global average temperatures could rise by between 1,6°C and 2,3°C by 2041-

2070, and 2,4°C and 3,4°C by 2071-2100, relatively to the modelled baseline period used in the project of 1961-1990. The Iberian Peninsula has a mean projected temperature increase of up to 5°C by 2071-2100 (Christensen O. et al., 2011).

According to study Regions 2020 (European Commission, 2009) A2 scenario is another scenario that is used by most European research projects because it is characterized by moderately free trading world with a regional focus and some sustainability objectives, and contrasts it with B2. A2 scenario is characterized by few environmental concerns and high emissions of GHGs, and B2 scenario presents a higher environmental concern and consequently lower GHGs emissions. A2 is presented as the worst scenario to Europe and B2 as the better, taking into account their characteristics.

Climate projections from models with different sensitivity to GHGs concentrations and economic focus indicated that until the year 2100 the average annual temperature in Europe is projected to increase by 2,5ºC to 5,5°C for the A2 scenario, and 1ºC to 4°C for the B2 scenario (IPCC, 2007b).

For the same period (2070-2099) the worst scenario (A2) projections showed that in some regions of Europe increase temperature may be as low 2ºC or even higher than 7ºC. Southern Europe will be most affected, with consistent temperature increases between 3°C and more than 7°C, with warming even greater in the summer (IPCC, 2007b). The largest warming is projected to occur in the Mediterranean region in summer temperatures. It´s expected summer temperatures higher than 6ºC in parts of France and Iberian Peninsula (Christensen and Christensen, 2006).

According to EEA (2012) four representative concentration pathways (RCPs) with projections until 2100 have been developed recently to succeed the IPCC SRES emissions scenarios in IPCC fifth assessment report. These projections showed a potential increase in global mean temperature by 2100, relative to pre-industrial levels (1850–1900), of 1,5ºC – 2,3°C for the lowest RCP to 4,5ºC – 5,8°C for the highest RCP.

According to the results from the ensembles project, the annual temperature for Europe is projected to increase by 1,0°C to 2,5°C (between periods 2021–2050) and 2,5°C to 4,0°C (between periods 2071–2100) (EEA, 2012).

Cleto et al. (2008) report an increase in temperature in northern of the Mediterranean (Portugal, Spain, Greece, etc.). To Giorgi and Lionello (2008) in the Mediterranean region the mean temperature will steadily increase throughout the century, being maximum in summer (1,2ºC in 2001–2020 to 4,6ºC in 2081–2100) and minimum in winter (0,7ºC to 3,1°C), based on the most recent ensembles of global and regional climates simulations completed a part of international collaborative projects. The changes are large predominantly in the summer, above 4°C to 5ºC warming, for the A1B and A2 scenarios. This study clearly shows that summer is the most responsive season to GHGs forcing over the Mediterranean and consequently the Mediterranean might be an especially vulnerable region to global change. According to SIAM II (2006), since 1970 the mean temperature increased in all the regions of Portugal, about 0,5ºC/decade, more than twice the observed changes and projections for global mean temperature. In Portugal a significant increase in annual average temperatures is projected for all regions. An increase of the maximum summer temperature, between 3ºC – 7ºC, is also expected for mainland Portugal, until 2100.

To Aguiar (2010) the information obtained from scenarios supported by scenarios SRES (IPCC) indicate that during this century the region of Cascais (Portugal) will warm up. The annual mean temperature will increase about 1,7ºC – 3,2ºC in mid-century. The expected increase in the summer temperature can be about 2,8ºC – 5,0ºC and in the winter can be about 0,9ºC – 1,8ºC. Until 2100, is projected an increase in average annual temperatures between 3,4ºC and 6,5ºC.

3.1.2. Solar radiation

Difficulties were encountered during the data collection period about the evolution of the solar radiation, because the investigation of the impacts of CC on solar technology is still very poor.

According to Tham (2011) there is a considerable amount of information available on mathematical models that relate solar radiation to other climate parameters such as temperature and rain amount. However, the most notable parameter is the temperature, because the temperature is closely related to solar radiation. Sunshine duration is the main variable that is used to generate solar radiation. To the same author, more solar radiation results in higher temperature. A small increase in solar radiation can cause a dramatic change in temperature on Earth. Then, as is expected to increase in temperature is also very likely that there is an increase in solar radiation and consequently more solar hours.

Sanchez-Lorenzo et al. (2013) support that since 1980s in many regions of the world, especially in the industrialized nations an overall increase in global solar radiation have been detected. According to author, an increase of the solar radiance of about 2,3% per decade was estimated in Spain.

Ruosteenoja and Räisänen (2013) studied future seasonal changes in surface incident solar radiation and relative humidity over Europe and concluded that is projected an increase by 5% – 10% in summer solar radiation in central and southern Europe, by 2070-2099. In winter, radiation can decrease in most of northern and eastern Europe by 5% – 15%. These projections have emphasized about a drier and sunnier climate in the south Europe.

IPCC (2007b) refers that in Mediterranean region more energy solar until 2100 will be available. Aguiar (2010) projects an increase in solar radiation of about 1% - 3% by 2050 and 2% - 7% in 2100 to Portugal. This will be due to an increase on the number of days with clear skies resulting in more sun hours.

The projection of temperature and solar radiation imply a change in the potential of solar power output. Although the high temperature negatively affects the performance of solar technologies, the increased availability of radiation in summer, in Portugal, will result in positive effects on the solar power (SIAM I, 2002).

3.1.3. Precipitation

Christensen and Christensen (2006) in their study about prudence model projections in Europe assumes precipitation changes with positive changes in the north and negative changes in the south of Europe by the end of this century (until 2100).

According to IPCC (2007b), trends in the 20th century showed a decrease in some regions in southern Europe by up 20% in average annual precipitation. CC scenarios show that annual average precipitation will increase in northern and central Europe, while it will decrease further in southern Europe, during 21st century. The decrease in annual average precipitation in southern and central Europe can be as high as 30 - 45%, and as high as 70% in the summer in some regions, for the period 2070-2099. Small precipitation changes are foreseen for spring and autumn.

Cleto et al. (2008) forecast a decrease the in rainfall rates in northern of Mediterranean and an increase in the expected aridity conditions. To Giorgi and Lionello (2008) Mediterranean region exhibit a general reduction in precipitation as obtained from the MGME models, A1B scenario, for the period 2071-2100. During the summer season climate conditions will be more aggressive. Summer shows the highest rainfall decrease, from about −7% in 2001–2020 to −28% in 2081–2100. In the other seasons the decrease are −2 to −8% in December to February, −2 to −14% in March to May and −3 to −15% in September to November. For the A1B and A2 scenarios, the changes are particularly relevant in the summer, over −25% to –30% precipitation reduction. However, there are some a few exceptions namely, a small increase in winter precipitation (December to February) in north/center of Iberian Peninsula for the B1 scenario and in north of Portugal for the A2 scenario. However, the expected increase in winter precipitation should not exceed 10%. These projections were based on the most recent ensembles of global and regional climates simulations.

For the same period, Rowell and Jones (2006) have claimed that in the Mediterranean region annual precipitation will decrease about 20%, between 2070-2100.

According to Costa et al. (2012), between 2071-2100, an overall decrease in the annual precipitation under the A1B and B1 scenarios from ensembles is projected for Portugal. In autumn in the northwestern and southern regions of Portugal, this decrease in precipitation results can be more significant. Northwestern Portugal is projected to experience the most remarkable rainfall decrease. However, there are some few exceptions, as the expected increase in winter precipitation over northeastern Portugal.

According to the authors of SIAM II (2006), precipitation scenarios are more uncertain than temperature scenarios. But, for mainland Portugal is expected in almost all scenarios a reduction in precipitation during spring, summer and autumn. The latest of regional model projections predict changes between -20% and -40% for different scenarios of its present values in mainland Portugal, where the highest losses happening in south. The greatest losses in precipitation, about 60%, are projected for Baixo Alentejo. Most of the models expect a small increase in winter precipitation in mainland Portugal, especially in north region, not exceeding 10%. The A2 scenario indicate decreases in precipitation until 2100, being higher than -30% in south, -40% in Algarve, and between -10% and -30% in north and center. The B2 scenario presents a uniform decrease in annual precipitation, between -10% and -30%, being the greatest losses in south of mainland Portugal. It is clear that almost all scenarios show a significant reduction in the expected annual precipitation to end 21st century.

To Aguiar (2010) precipitation will reduce significantly in the Cascais region (Portugal). The expected cumulative annual value will decrease about 10% in mid-century, and about 20% in the end of century. These significant reductions include the months April to May, and October to December. June to September will be increasingly dry.

3.1.4. River flow

There is an obvious correlation between precipitation and river flow. So is evident that a change in the amount of precipitation will affect the amount of water in a river. More rainfall more river flow, lower rainfall lower river flow.

According Alcamo et al. (2007) annual river flow is projected to decrease in southern and south-eastern Europe and increase in northern and north-eastern Europe. Winter and spring river flows are projected to further increase in most parts of Europe, except for the most southern and south-eastern regions. In summer and autumn, river flows are projected to decrease in most of Europe, except for northern and north-eastern regions where they are projected to increase. The principal cause of decreasing river flows is the lesser availability of water due to decreased annual precipitation related to CC in southern Europe.

Runoff is originated primarily in rainfall, and precipitation is expected to decrease in southern Europe, as already stated. As such, runoff can decrease by 0 to 23% up to the 2020s, by 20% - 30% to 2030 and by 6 to 36% up to the 2070s for the SRES A2 and B2 scenarios, according to IPCC (2007b). This same study also indicates that during summer, low flow may decrease by up to 50% in central Europe and by up to 80% in some rivers in southern Europe. Changes in the water cycle are probable leading to the intensification of the risk of floods and droughts. Projections indicate that the risk of drought can increase mainly in southern Europe. The most susceptible regions to an increase in drought risk are the Mediterranean (Portugal, Spain) and some parts of central and eastern Europe, where the highest increase in irrigation water demand is projected. An increasing water stress is projected mainly in southeastern Europe (IPCC, 2007b).

Global warming and its associated reduction in precipitation are expected to reduce surface runoff and water yields in the Mediterranean region (Römisch et al., 2009).

Lehner et al. (2001) support that since 1970s annual energy production from hydropower systems in Europe has declined, in particular in Portugal, Spain and other southern European countries. The same authors attributed this reduction to CC cause in average discharge, such as a change in river flow. According to projections, hydropower potential production in Europe in the 2070s will be about 4% lower than in 2001. Trends in future precipitation, change of temperature and evapotranspiration rates will have significant effects in river flows. Portugal receives substantial discharge inflows from Spain, so impacts to river flows in Spain have will be felt in Portugal. Taking into account the results of Lehner et al. (2001) study to 2070s in southern Europe, the maximum decrease in discharge volumes can reach more than 25%. In Portugal the decrease in hydropower potential will be about 5% for runoff generated within Portugal. Reductions of about 20% can happen for inflows from Spain.

To IPCC (2007b) by the 2070s hydropower potential for the whole of Europe is expected to decline by 6%, translated into a 20 to 50% decrease around the Mediterranean, a 15 to 30% increase in northern and eastern Europe and a stable hydropower pattern for western and central Europe.

OECC (2005) states that in Spain with an increase of temperature and a decrease of precipitation a reduction in water resources should be expected. The most sensitive regions are semi-arid areas and a reduction of about 50% in water resources can happen. According to scenarios of OECC project, by 2030, projections of temperature increase of about 1ºC and reductions of precipitation of about 5% could cause a decrease between 5% and 14% in water resources of Spain. By 2060, projections of temperature increase of about 2,5ºC and reductions of precipitation about 8% could cause a decrease in global mean water resources around 17%. Until 2100, these reductions could reach 20% - 22% to Spain.

According to SIAM II (2006) all scenarios present a reduction of the runoff during the autumn, spring and summer. The worse scenario predicts a decrease in annual runoff about 10% and 50%, respectively north and south of Portugal. Magnitude of impacts increases from north to south. This trend becomes stronger in 2100 and the decrease could reach 80% in south. The decrease in precipitation will lead to reduced runoff expected both Spain and Portugal, which will accentuate the decrease of water availability expected in Portugal by trans-boundary rivers, to energy production from hydropower stations.

Analyzing these studies a reduction of water availability in Iberian Peninsula is expected with increased drought, and reduced hydropower production. This will result in increased competition for available resources.

3.1.5. Wind speed

To IPCC (2007a) confidence in future changes in wind speed in Europe is relatively low. According to this study, there are several model studies that have projected increased average wind speeds in north and central Europe, but others studies state exactly the opposite. Trends to reduce windiness in the Mediterranean area are predicted taking into account the northward shift in cyclone activity. Simulations with little change in the pressure pattern tend to show only small changes in mean wind speed. Mean annual wind speed could increase over northern Europe by about 8% and decrease over Mediterranean Europe, taking into account studies of Räisänen et al. (2004) and Pryor et al. (2005), from regional simulations (IPCC, 2007b).

Zhao et al. (2011) assume that the declining of wind speed trends in central Asia, east Asia, southeast-south Asia, Europe, and north America is obvious. During the last 30 years, the surface wind speeds have decayed by about 5% - 15% with a high confidence.

Hennemuth et al. (2008) studied different realizations of regional climate models scenarios of ensembles for the end of 21st century in Europe, taking into account the last period 1961-1990. Average wind speed changes in Europe are expected to be small under future scenario conditions. Their projections show slight decrease for southern Europe wind speed of about (-0,1m/s to -0,2m/s), between 2021-2100. To Spain projected an increase of low wind speed and a decrease of wind speed, over 5 m/s until 2100.

According to Kjellström et al. (2011) resourced to an ensemble of RCM simulations and concluded that wind speed can decrease in many areas with exceptions in the northern seas and in parts of the Mediterranean in summer, during 21st century. In most simulations, a reduction in wind speed during winter in the Mediterranean area is foreseen.

3.1.6. Energy demand

One of the factors that will influence the energy consumption is the evolution of energy demand.

Ebinger and Vergara (2011) state that energy demand is expected to increase considerably in the coming years mostly driven by population growth and economic development, but the most direct causes relate will be CC – higher temperatures. As already mentioned an increase in temperatures will reduce heating demands but will increase cooling demands (air conditioning), so energy demand for cooling is projected to increase quickly until 2100. According to this study, global energy demand for cooling will rise by 72% until the end of century. The climate impacts will vary across regions, for example south Europe will experience energy consumption for cooling due to projected increases in temperatures, but from a global perspective, increased cooling tends to be higher. It should also be emphasized that light vehicles will likely be affected by changes in temperature, altering fuel consumption due the use air conditioning that reduce the efficiency at highway speeds. According to a study mentioned in World Bank 2011 (Ebinger and Vergara, 2011) for five countries in Europe an increase of electricity demand of about 2,5% - 4% by 2050 compared with 2007 is projected.

According to Rede Energética Nacional (REN) - PDIRT (2011) for the scenario EU 2020 the annual increase rate of demand forecast is higher than or equal to 1,3% in Portugal between 2011 and 2020. For the scenario B this annual rate is between 1,3% and 2,7% to the same period. In accordance with REN – PDIRT (2011) the annual rate of demand for electricity in Portugal between 2011 and 2022 varies between 1,3% and 2,3%. This document also indicates that is more appropriate to take into account rates closer to the extreme.

Food and Agriculture Organization of the United Nations (FAO) (2008) also assumes that between 2004 and 2030 developing countries will have a large increase in global energy consumption reaching about 46% - 58%. On average an annual increase rate of about 3% is expected from 2004 to 2020. To ENERDATA (2007) global energy consumption will rise by 30% until 2020 and the European energy consumption should increase about 12% between 2005 and 2020.

4. Electricity sector in Portugal

The Portuguese economy is characterized by a high energy intensity, high carbon intensity and very high external dependence with regard to primary energy consumption. The world population has doubled in the second half of 21st century, and the world consumption of primary energy grew by 50% between 1980 and 2005. The response to this increased consumption was mainly based on coal, natural gas and oil (LNEC, 2009). But, Portugal is a country with limited indigenous energy resources, in particular, those that ensure the generality of the energy needs of most developed countries (oil, coal and natural gas). Due to the lack of fossil resources, Portugal is strongly dependent on imports of primary energy, essentially fossil fuel. In 2012, 79,8% of the energy consumed came from imports. This percentage is expected to decrease over time due to its impact on CO_2 emissions for electricity production. The major national resources come from RES, especially the hydro sector for electricity production (DGEG, 2012).

Despite the external energy dependency has been declining 9% since 2005 (see Figure 4.1), there was an increase of 3,7% between 2010 and 2012, mainly due to the increased electricity production from coal consumption to compensate the reduction of hydro power production (DGEG, 2012). A sharp decline on importations from 2009 to 2010 was promoted by renewable energies, particularly hydro and wind power, and also to energy efficiency measures. A continuous reduction from 2012 to 2020 remains expected under the current energy policies (Portuguese Government Resolution 20/2013).

In fact, Energy 2020 (Portuguese Government Resolution 29/2010) established as objective a reduction of the external energy dependency of the country to 74% in 2020 and underlines the importance of Portugal being recognized as a leading country in renewable energy in the international context.

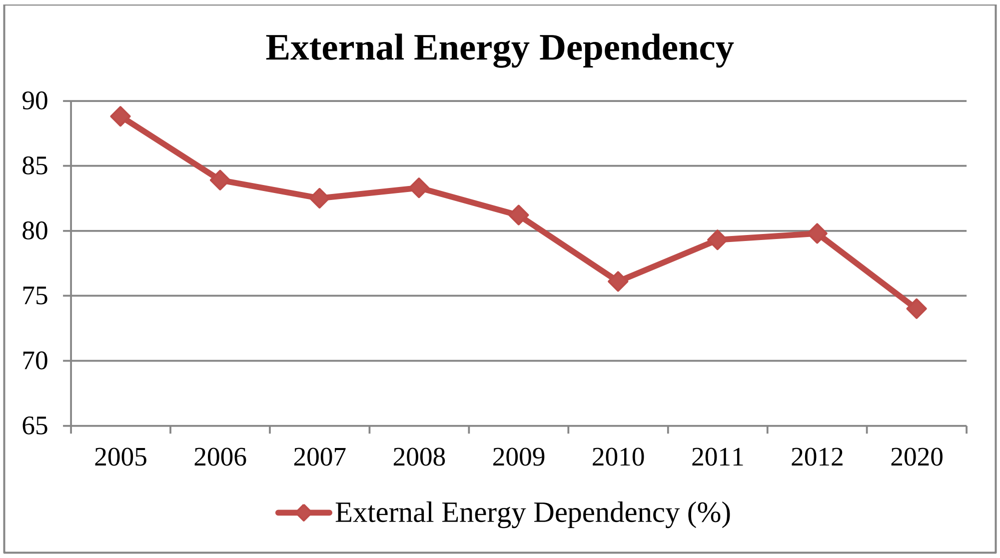

Figure 4. 1 - Index of external energy dependency of Portugal, in %, between 2005 and 2020 (Source: Own elaboration (DGEG, 2012 and Portuguese Government Resolution 29/2010))

According to Portuguese Government Resolution 20/2013, in order to reduce external energy dependency, Portugal should both increase energy efficiency, reducing this way energy consumption and the contribution of renewables endogenous (hydro, wind, solar, geothermal, biomass) under the economic rationality context. RES are the important contributions for the reduction of the external energy dependency, reducing also emissions of GHGs, increasing the security supply and increasing diversification of primary energy sources (APA and DGEG, 2012).

Figure 4.2 demonstrates that the lack of endogenous energy resources led to a high dependence on external energy in terms of primary energy, but a strong expansion of energy production from renewable sources (mainly hydro and wind) caused a continuous decrease in primary energy consumption since 2005.

The EU's 20-20-20 goals, established as target achieving a 20% reduction primary energy consumption by 2020, compared to projections made in 2007. The Portuguese document PNAEE indicates the consumption of primary energy should reach about 24Mtoe in 2020, not thereby undermining the goals imposed by EU. Until 2020 an increase in the consumption of natural gas and renewables sources and a decrease in the consumption of oil and coal is to be expected (Portuguese Government Resolution 20/2013).

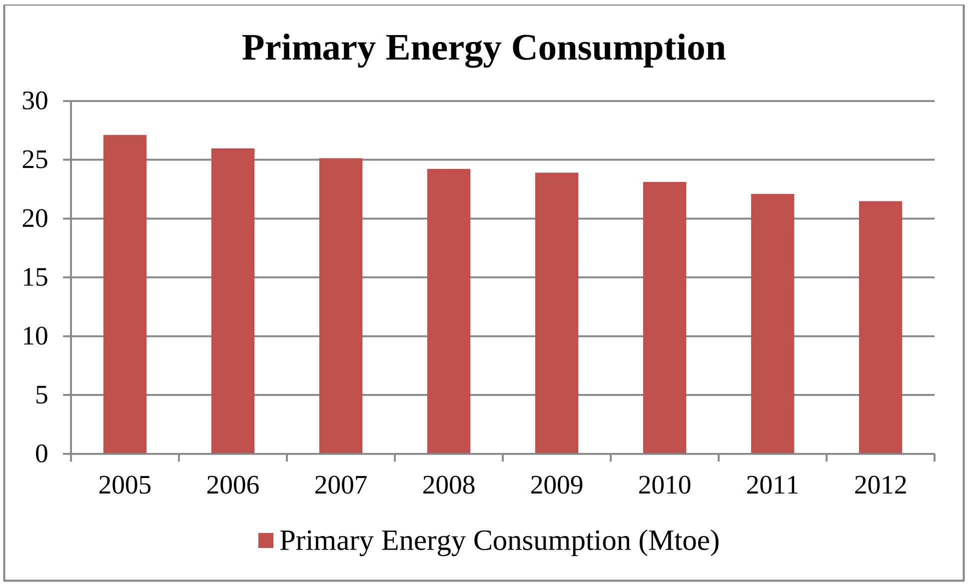

Figure 4. 2 - Evolution of primary energy consumption in Portugal, in Mtoe, between 2005 and 2012 (Source: Own elaboration (DGEG, 2012))

The excessive release of CO_2 emissions and other GHGs is a major consequence of the lack of efficiency in the consumption of energy obtained from burning fossil fuels. Portugal efforts to reduce CO_2 emissions have however had little success. Continued divergence from Kyoto targets will entail addition to the environmental damage, considerable economic losses to Portugal. It takes a lot of efforts on the most ambitious and dynamic energy efficiency in all sectors of Portuguese society.

The current energy policy in Portugal aims to strengthen the competitiveness of the sector, development a better equilibrium between the three pillars of sustainability: economy, environment and social (APA, 2012). There must be an increase in connectivity between the energy and politics.

According to Portuguese Government Resolution 20/2013, PNAEE and PNAER are instruments that establish the energy planning defining strategies aiming to achieve the goals and international commitments made by Portugal in energy efficiency and use of energy from RES. In addition to the definition of targets, these plans also identify existing barriers as well as the potential for improvement in energy efficiency and incorporation of RES in multiple industries, with a view of establishing programs and measures best suited to the aforesaid commitments, taking into account the national reality. The objectives of PNAEE and PNAER aim to:

a) Comply with all commitments made by Portugal under economically rational;

b) Significantly reduce emissions of GHGs within a framework of sustainability;
c) Strengthen the diversification of primary energy sources, contributing to structurally increase supply security of the country;
d) Increasing the energy efficiency of the economy, particularly in the state sector, contributing to the reduction of public expenditure and efficient use of resources;
e) Contribute to increasing the competitiveness of the economy, by reducing consumption and costs associated with the operation of enterprises and the management of the domestic economy, freeing up resources to boost domestic demand and new investments.

A general goal of reduction of the primary energy consumption by 25% in 2020 was established for Portugal, comparatively to 2005. Also, a specific goal of reducing the consumption of primary energy by 30% for public administration was set. Portugal, under the guidelines of the EU, is committed to increasing the share of renewables from 20,5% in 2005 to 31% in 2020. According to Portuguese Government Resolution 20/2013, an increase of the RES share is expected, reaching 60% of the final consumption of electricity to by 2020. The targets for each of the renewable energy technologies are defined in PNAER.

RES have an important role in the achievement of a sustainable development contributing to reducing the environmental impact of the energy sector and reducing external energy dependence of the countries or regions. RES also are inexhaustible resources, allowing for decentralized production and contributing to the creation of new business opportunities for countries investors. Being independent of the price of fossil fuel they can turn the energy sector much less sensitive to variation of these commodity prices, reducing then de investment risk.

The electricity in Portugal is produced mainly from coal, natural gas, cogeneration, hydro energy, wind energy, biomass and others renewables in a much less extent.

Portugal was, in 2011, the third country of the European Union (EU15) with greater incorporation of renewable energy with a weight of 45,6% of electricity production from renewable energy (DGEG, 2013).

Historical development of electricity produced by RES in Portugal is illustrated in Figure 4.3.

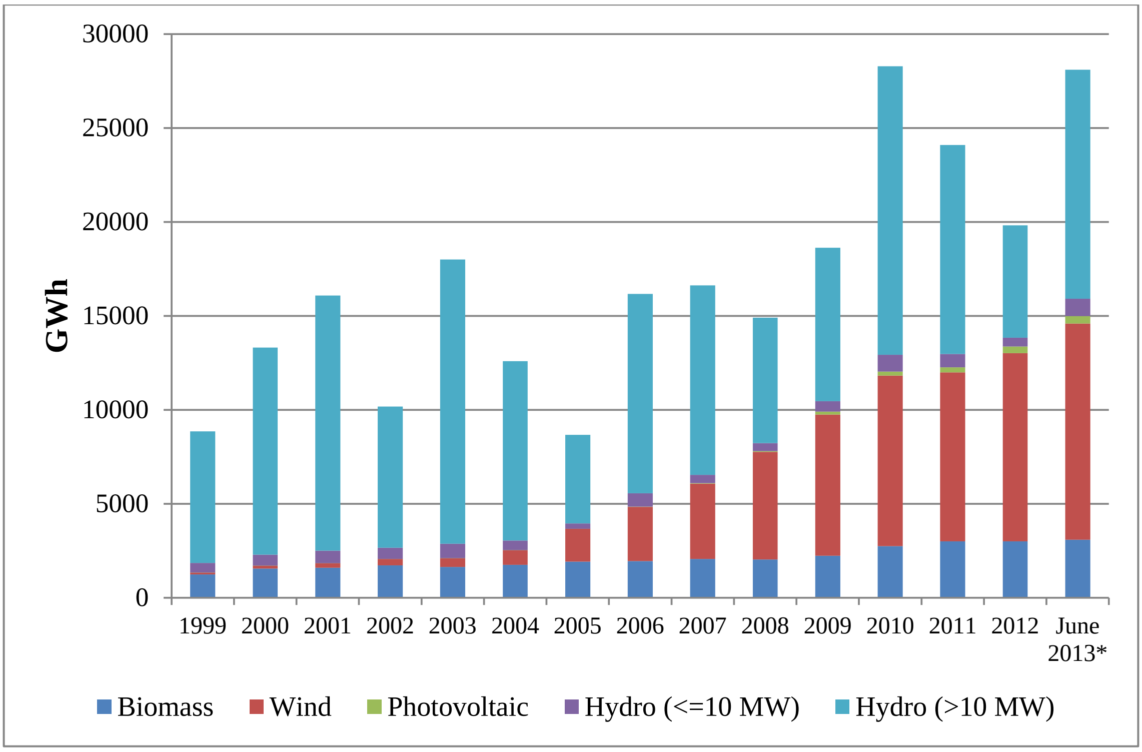

Figure 4. 3 - RES in Portugal, in GWh (Source: Own elaboration (DGEG, 2013))

Observing Figure 4.3, the increase of electricity produced by wind power is notorious, especially since 2005. Between 2005 and June 2013 wind power output increase by 9763 GWh. There was a significantly decrease in hydro power production between 2010 and 2012, less 9364 GWh, reflecting the dry period of 2011 and 2012 and the wet year in 2010. Summarizing, the present mix of renewables is mainly based on the production of hydro and wind. In the future, a new development planned in Energy 2020 (Portuguese Government Resolution 29/2010) will pass for investment in other RES and in particular in solar energy.

According to REN (2013) the electricity consumption in 2012 was 49,1 TWh whereas in the previous year had been 50,5 TWh, thus recording a fall of 2,9%. The production from RES supplied 37% of consumption, being lower than the 46% recorded in 2011 (see Figure 4.4).

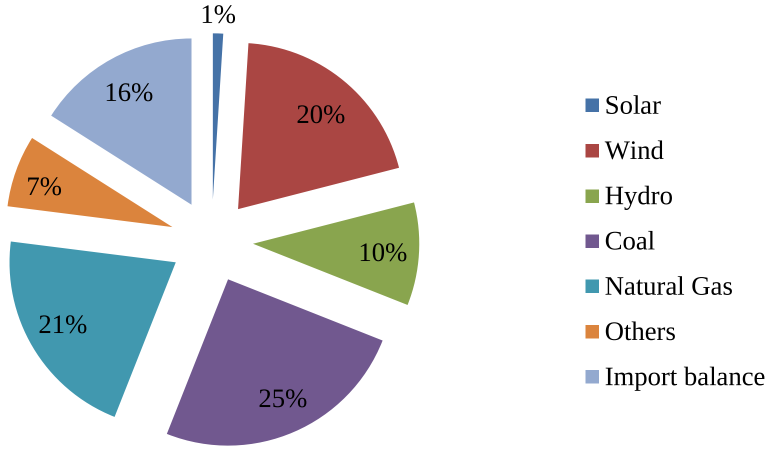

Figure 4. 4 - Electricity production (%) by energy source in 2012 (adapted REN, 2013)

In 2012, the RES installed power was 10689 MW, representing 58% of the total installed power. In Portugal, hydropower represents approximately 31% of the total installed power (5656 MW), of which 7% (417 MW) relate to mini-hydro plants. The wind energy has had a significant increase in Portugal, reaching in 2012, 23% (4194 MW) of the total installed power. The solar energy presented also a slight increase, although its capacity remained still low, representing about 1% of the total installed power (220 MW). Natural gas power plants presents 25,6% (4739 MW) and coal 9,5% (1756 MW) of the total installed capacity of the electricity sector (REN, 2013).

For the year 2020, according to PNAER (Portuguese Government Resolution 20/2013), hydro power is expected to reach 8440 MW of installed power, remaining as the RES with higher share in Portugal. Small hydro should reach a total installed power of 500 MW in 2020. As for wind power, in 2020 it is expected to reach 5300 MW. Solar energy will have a significant increase, reaching 720 MW of installed power. The PNAER document does not provide projections for 2020 on the installed power for coal and natural gas.

5. Electricity planning in Portugal

The main objective of this work is to evaluate the impact of CC scenarios in the Portuguese electricity system, especially on the potential change of RES (hydroelectric power, wind and solar), for a 10 years planning period from 2014 to 2023. The methodology focused largely on the information extracted from studies of the projections of CC during the 21st century in Europe and Portugal.

Thereafter, projections were made about the possible trajectories of the Portuguese energy system considering different scenarios, using the SEPP model (Pereira et al., 2011) translated in a general algebraic modeling system code (GAMS). GAMS is a high-level modeling system for mathematical programming and optimization tailored for complex, large scale modeling applications (GAMS, 2011). The simulation exercise allowed obtaining values of CO_2, costs, electricity productions and installed electrical power for twelve scenarios for the period 2014-2023, for the minimum cost objective function.

5.1. The SEPP model

The SEPP model described in Pereira et al. (2011) aims to develop new optimization models for electricity power planning, supporting the strategic long term investment decision. In the model, economic and environmental criteria are included in the objective functions, aiming to minimize total generation costs and environmental impacts. Economic aspects comprise investment and operation costs of power generation units, while environmental ones comprise the GHGs emissions, specifically CO_2. As such, the proposed model formulation takes into account both the economic and environmental cost and is defined by a set variables, parameters, equations and constraints. These equations represent a mix integer linear optimization problem (MILP) to be used for the analysis of energy system taking into account all the electricity power generation technologies relevant for the system under analysis. For this particular problem the technologies included were large hydro power (dams and run of river), pumping hydro, small hydro power, wind power, solar power, coal and natural gas power.

5.1.1. Model adjustment

Although the work departed from the existing SEPP model proposed by Pereira et al. (2011), the model and optimization model had to be adjusted and for the particular problem under study. The following adjustments were made:

- Two new types of technologies were added to the model, namely small hydro and solar power.

- Data were collected and settled in order to be based on year 2011 but adjusted to represent a typical year. Input data included the monthly availability factor of wind, hydro, small hydro and solar power plants, monthly water inflows to dams and installed power of existing units. This information was obtained from the Portuguese grid operator website and reports (REN, 2011).

- According REN - PDIRT (2011), until 2022 the annual increase rate of the electricity demand in Portugal is expected to range between 1,3% and 2,3%. Data on the electricity demand projects was also based on 2011 information assuming a yearly increase rate of 2,3%.

- Taking into account PNAER 2020 (Portuguese Government Resolution 20/2013), an average annual growth rate of about 4,9% for the electricity production from other special regime producers (SRP) until 2020 and an average annual growth rate of about 5% for SRP installed power until 2020 were assumed.

- A lifetime of 50 years was assumed for small hydro power plants (Madlener and Stagl, 2005) and 25 years for solar power plants (Micali, 2011). This data is relevant for the computation of the annualized investment costs of these plants.

- The variable and fixed costs of units for small hydro and solar power plants were obtained from consultation of private companies operating in the sector and Fernandes (2011). The investments costs were obtained from IEA (2010) for the same technologies.

- Values for the CO_2 emissions limits were obtained from APA - RNBC 2050 (2012).

- Maximum values for installed power of RES power plants were defined according REN - PDIRT (2011).

5.2. Scenarios analyzed

The analysis of different scenarios should allow observing the behavior of the energy system to changes in the availability of RES.

Figure 5.1 shows the scenarios analyzed in this study for the year 2023. The analysis departs from the reference case scenario (base scenario) where no CC impacts are considered and the cost minimization model is not constrained by CO_2 maximum limits. Other base case scenarios are defined, defining maximum CO_2 limits for the 10 years planning period and imposing also the inclusion of new wind and solar power in the system. The scenarios with CC start from the same assumptions as the respective reference scenarios, but with different projections of CC: Low CC impact, Medium CC impact and Extreme CC impact (see Figure 5.1). In summary, the reference scenarios and CC scenarios represent how the Portuguese energy system will evolve, not taking into account CC and taking into account CC.

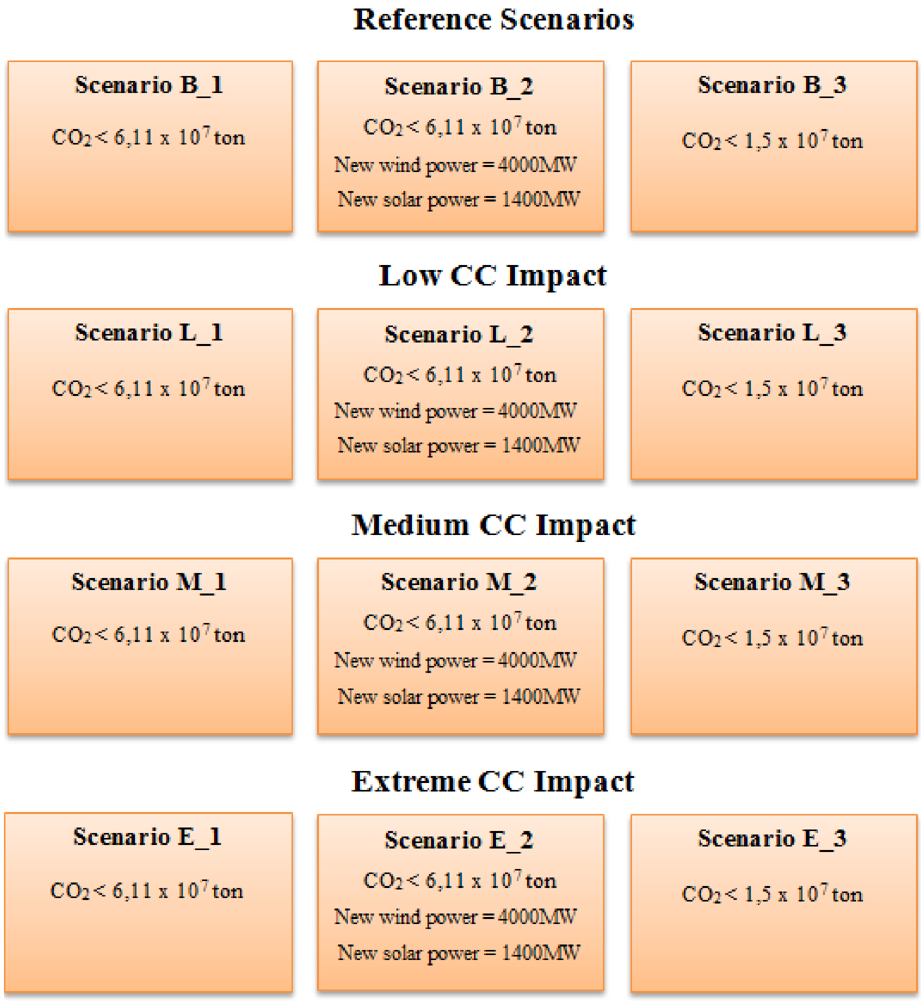

Figure 5. 1 - Scenarios for the evolution of the Portuguese electricity system in 2023

Based on all literature review about future projections of CC impact on the electricity system, with particular focus on Portugal, a summary-table was created describing the assumed data for the scenarios (Table 5.1). Mean values were computed between the various projections found and a linear projection then was assumed to calculate the values to take into account for the study period (2014 -2023).

It is important to note that the projections about temperature were not used in the model and no assumptions were made regarding the possible loss of efficiency of solar power plants. As said above, the temperature increase is assumed to lead to a greater number of days of clear skies, increasing the amount of energy coming from the sun, solar radiation.

The projections of variable river flow were also not used in the production of scenarios, since the variable precipitation is the main factor to take into account the variation of hydropower production.

The variables used were the amount of precipitation for hydro power and small hydro power, wind speed for wind power and amount of solar radiation for solar power.

Table 5. 1 - Summary-table of scenarios for the 10 years planning period

Types of energy	**Variable**	**Scenarios**				**Sources**
		Reference Scenarios	**Low CC Impact**	**Medium CC Impact**	**Extreme CC Impact**	
Hydro and Small Hydro	Precipitation	Without CC	- 3,3%	- 5%	- 7,7%	IPCC (2007b) Giorgi and Lionello (2008) SIAM II (2006)
Wind	Wind speed	Without CC	- 5%	- 10%	- 15%	Hennemuth et al. (2008) Zhao et al. (2011) Castro (2003)
Solar	Solar Radiation	Without CC	+ 0,6%	+ 0,8%	+ 1%	Ruosteenoja and Räisänen (2013) Aguiar (2010)

The values indicated in the Table 5.1, put in evidence a significant decrease in the amount of precipitation that can be foreseen to Portugal. Wind power presents also a decrease in its production potential for the incoming years. It should be noted that the electricity power output is proportional to the cube of the wind speed, Castro (2003). Meaning that if the wind speed drops 5% the power output is reduced by 15%, thus revealing that the electricity production is strongly dependent on the wind speed. These wind speed forecast were derived from projections for Europe in general, but were assumed to be replicable for Portugal, in line with various studies referring a slight decrease of the potential resource in the south of Europe.

Unlike these, the percentages set for solar power are expected to increase, since the solar radiation should also increase. These values also correspond to Europe in general and were also assumed to be valid for Portugal. So, CC scenarios considered in the model will affect hydro, small hydro, wind and solar power output. To analyze the differences that occur between the energy systems scenarios with and without CC, also taking into account CO_2 emissions and minimum installed power, scenarios will be compared as follows:

- The scenario B_1 against scenarios L_1, M_1 and E_1.
- The scenario B_2 against scenarios L_2, M_2 and E_2.
- The scenario B_3 against scenarios L_3, M_3 and E_3.

The objective of performing these comparisons for the installed capacity, electricity production, costs and CO_2 emissions is to assess how CC may negatively influence or benefit the production of electricity from RES, how the energy system compensates these CC driven losses and gains over the period under study, which technologies will increase their electricity output and which ones will reduce their contribution. The main goal is to understand whether CC will impose big changes in the electricity system planning.

5.3. Presentation and analysis of results of the evolution Portuguese energy system

The integration of RES on the Portuguese system was already the focus of several studies (Fernandes, 2012 and Krajačić et al., 2011) but these studies do not usually consider the potential impacts of CC. However, in view of this dissertation and considering the evidences presented before, it can be seen that the projections indicate that hydro energy, wind energy and solar energy are likely to undergo significant changes in the future.

This section, presents the results of each scenario obtained by simulation of the Portuguese electricity system resourcing to the model SEPP, for the cost minimization. Reference scenarios are critical to understand and interpret the evolution and behavior of the energy system over the years under study. In this section we present the results of the simulations conducted, resulting on the description of the installed power, the electricity produced, the costs and values of CO_2 emissions for each scenario in 2023, showing the best investment decisions under CC variations.

5.3.1. Reference scenario B_1 and CC scenarios

5.3.1.1. Installed power

The installed electricity capacity was analyzed according to the technology used. The results of the CC scenarios were compared to the reference scenario, with no CC considerations. Differences occurred for all scenarios, as can be seen in Table 5.2.

Table 5. 2 - Installed power (MW) in 2023 for scenario B_1, scenario L_1, scenario M_1 and scenario E_1, according to the technology used

	Scenario 2011	**Scenario without CC**	**Scenarios with CC impact**		
		Scenario B_1 2023	**Scenario L_1 2023**	**Scenario M_1 2023**	**Scenario E_1 2023**
Coal power	1756	1756	1756	1756	1756
CCGT power	3829	4839	4839	5182	5344
Wind power	4081	4081	4081	4081	4081
Hydro power	6023	10778	10778	10778	10778
Solar power	155	155	155	155	155
Small hydro power	412	792	792	792	792

For scenario L_1 (low CC impact) it is verified that there has been no change in the installed electricity capacity until 2023, compared with the scenario B_1 (reference scenario). The only type of technology that changes its installed capacity is natural gas (CCGT) for scenario M_1 and scenario E_1, scenarios with medium and extreme projections of CC, respectively. There is an increase of 343 MW in scenario M_1 compared scenario B_1, and an increase of 505 MW compared scenario E_1. This difference occurs because the model implementation results in an increase in investment on fossil energy, in this case natural gas, due to the impact of CC on RES. As such natural gas is used to compensate the RES reduction potential ensuring to meet the demand for electricity. The technologies that contribute to the increase in installed power comparatively to 2011 are natural gas, hydro and small hydro. The hydro and small power plants capacity increase remain constant whether there is an impact of CC or not. It can be seen that for this scenario CC will not significantly affect the optimal power capacity installed in Portugal and in this case will not also modify the energy source used.

5.3.1.2. Electricity production

The amount of electricity produced was analyzed according to the technology used. Figure 5.2 demonstrates the amount of electricity produced by the power source in 2023, for scenario B_1.

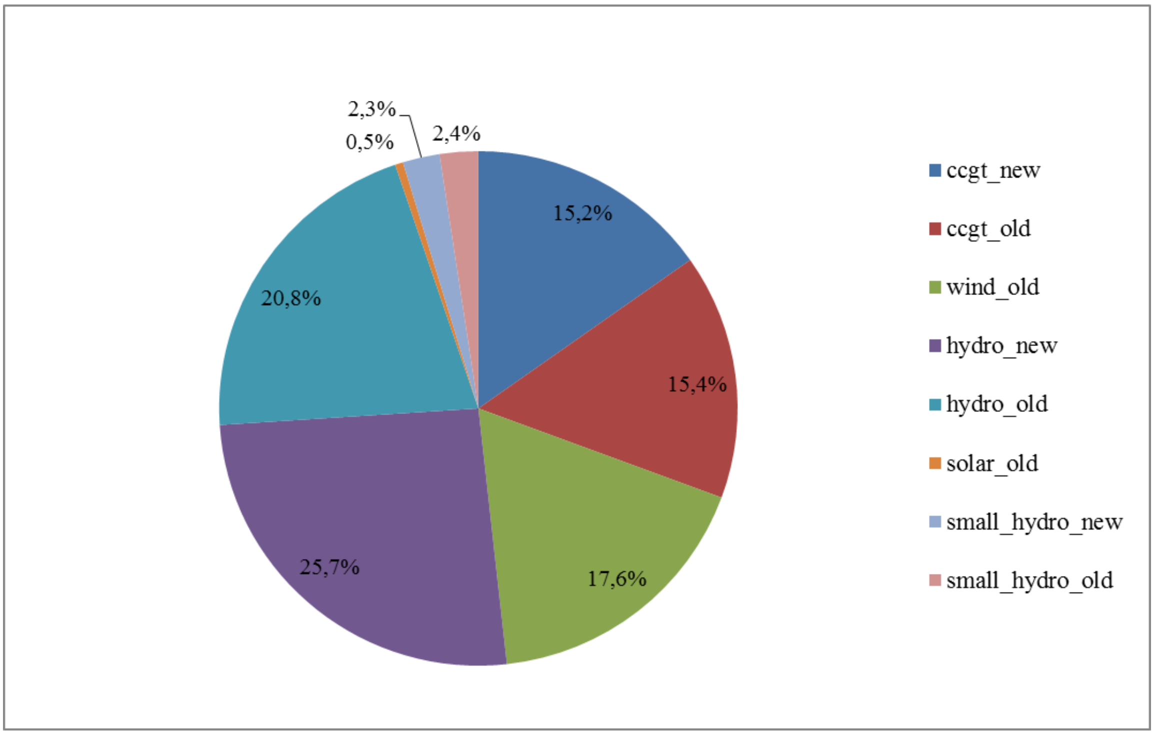

Figure 5. 2 - Electricity produced in % in 2023 for scenario B_1

For the analysis of Figure 5.2, it can be seen that in the scenario B_1 in 2023, without CC impact, hydro power plants (hydro_new and hydro_old) contribute with the higher share for electricity production with 46,5%, followed by natural gas with 30,6%. Then, with 17,6% is located wind energy. The small hydro contributes with 4,7% and solar energy contributes only 0,5%. In this case, the RES amount to 69,3% against 30,6% of the fossil energy.

Figure 5.3 demonstrates the amount of electricity produced by the power source to 2023, for scenario L_1.

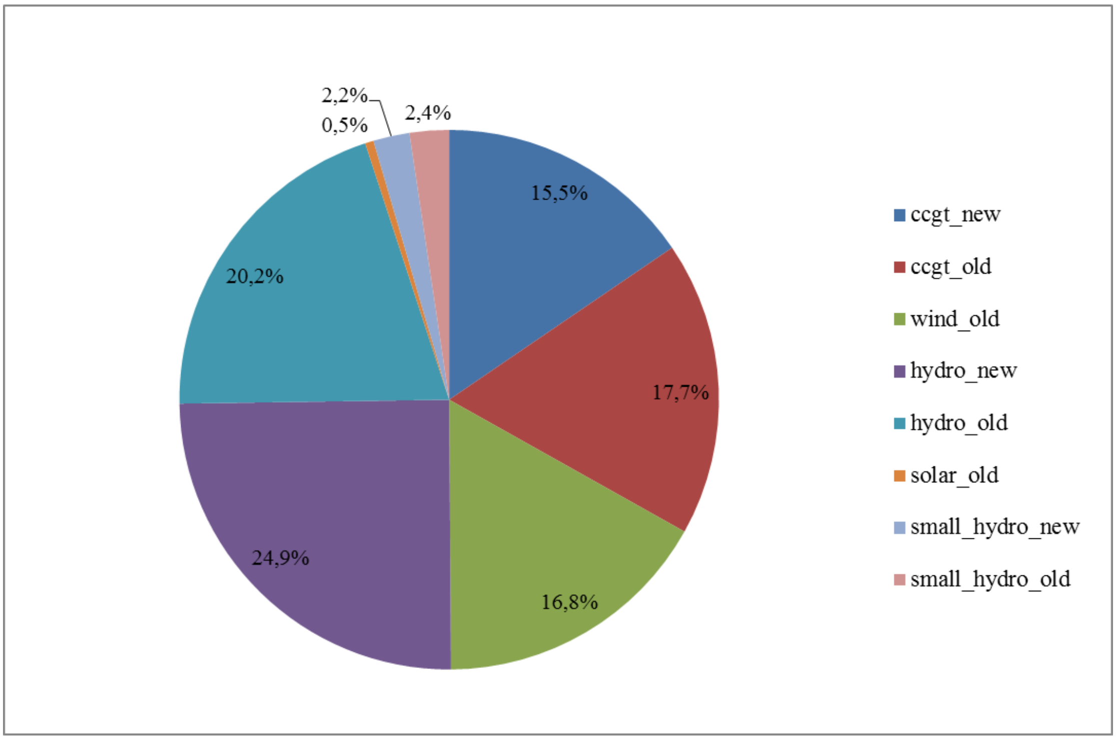

Figure 5. 3 - Electricity produced in % in 2023 for scenario L_1

As can be observed by Figure 5.3, in 2023, in the scenario L_1 (low CC impact) hydro power remains the largest contributor (45,1%) although there was a slight decrease in the production of hydro, about – 1,4% compared to the scenario B_1 (reference scenario). On the contrary, there was a small increase on the electricity production from natural gas (33,2%) in relation to the scenario B_1 (30,6%). As for wind power production there was also a slight decrease to 16,8% compared with 17,6% of the scenario B_1. Small hydro suffered a slight reduction about 0,1% and solar energy had a mild increase of about 0,01%. In this scenario, RES represent 67% of energy produced.

Figure 5.4 presents the amount of electricity produced by each power source in 2023, for scenario M_1.

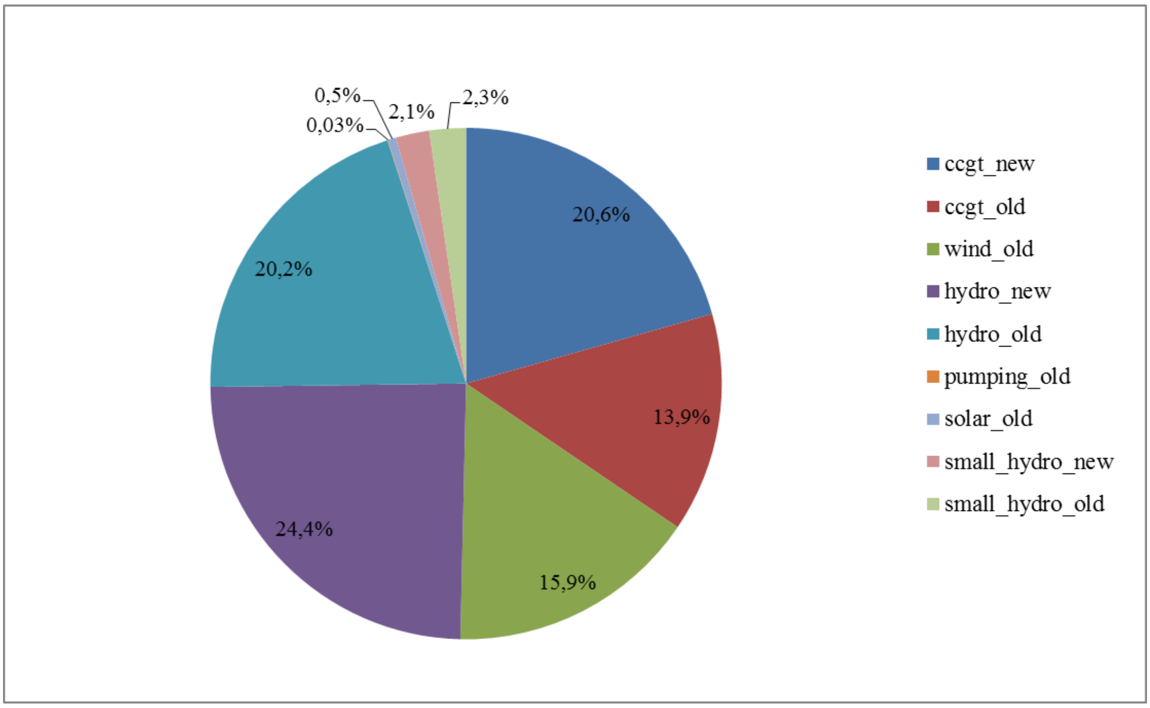

Figure 5. 4 - Electricity produced in % in 2023 for scenario M_1

Analyzing Figure 5.4 it is possible to verify that hydro power remains leading although having fallen to a production of 44,6% (included the 0,03% of the pumping hydro). The electricity production from this technology fell about 2%.The production from natural gas increased to 34,5%, more 4% than scenario B_1. The wind production fell about 1,7% compared to the scenario B_1. Small hydro represents 4,4% of total production, less 0,3%. There is a slight increase in solar electricity, about more 0,01% than in scenario B_1. The RES amount to 65,4% against 34,5% of the fossil energy.

Figure 5.5 shows the amount of electricity produced by each power source in 2023, for scenario E_1.

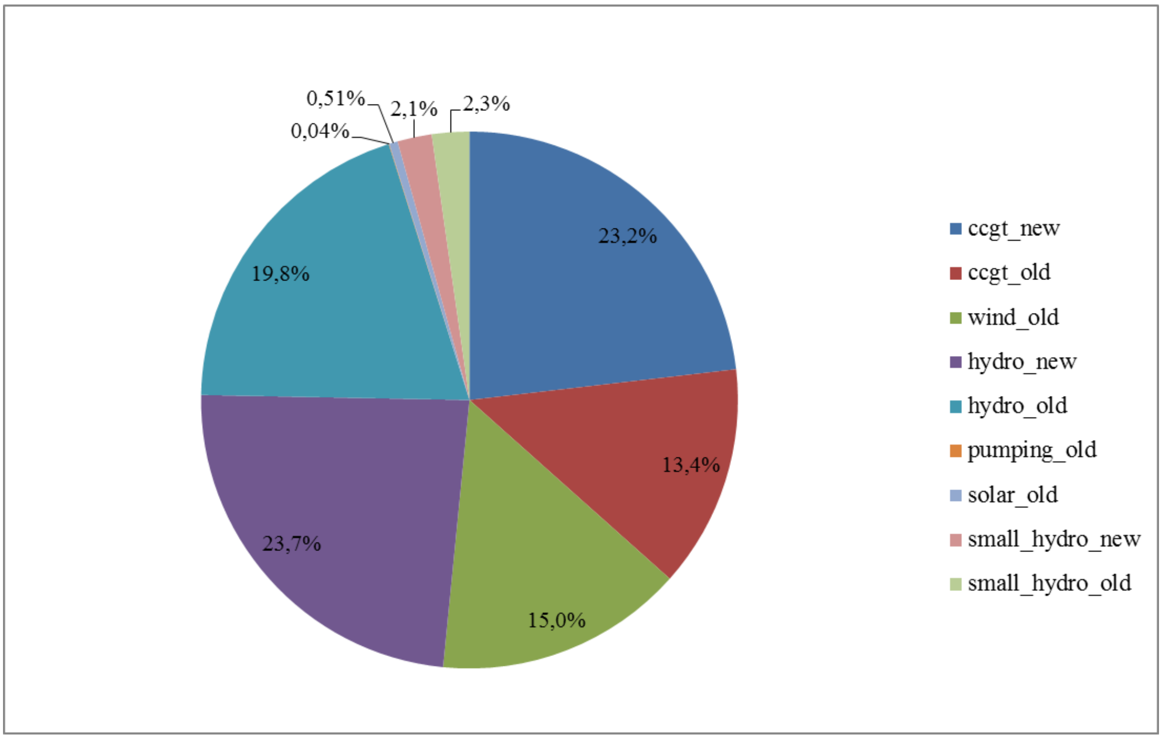

Figure 5. 5 - Electricity produced in % in 2023 for scenario E_1

As can be observed by Figure 5.5, hydro power represents 43,5% (included the 0,04% of pumping hydro) of total production. This energy source had a reduction of about 3% compared to the scenario without CC (B_1). There is an increase in the electricity production from natural gas, about 6% (36,6%). The wind electricity production represents 15% of the total production. Comparing with the scenario B_1, this technology output can fell by 2,6%. The small hydro contributes with 4,4%, less 0,3% than scenario B_1. The solar electricity increased about 0,01% (+2640 MW). RES share represent 63,4% of energy produced, almost 6% less than for the reference scenario.

5.3.1.3. Costs and CO_2 emissions

Table 5.3 shows the obtained costs and CO_2 emissions for each scenario analyzed above.

Table 5. 3 - Costs and CO_2 emissions for each scenario analyzed

	Costs	CO_2 emissions
Scenario B_1	15.7 €/MWh	0.102 ton/MWh
Scenario L_1	16.8 €/MWh	0.102 ton/MWh
Scenario M_1	17.5 €/MWh	0.102 ton/MWh
Scenario E_1	18.5 €/MWh	0.102 ton/MWh

Analyzing Table 5.3, it is found that there are increased energy costs of the system for all scenarios relative to the reference scenario (scenario B_1). Note that the greater the impact of CC the higher the cost of the electricity system, because it new investments in non-RES are required to offset the losses of renewable electricity production due to the negative impacts of CC. The CO_2 emissions remain constant comparatively to the reference scenario, as maximum amount was established in a restriction of the model.

5.3.2. Reference scenario B_2 and CC scenarios

5.3.2.1. Installed power

The installed electricity capacity was analyzed according to the technology used. The greatest changes occurred in the medium and extreme scenarios of CC, with the introduction of new coal in the system, as can be seen in Table 5.4.

Table 5. 4 - Installed power (MW) in 2023 for scenario B_2, scenario L_2, scenario M_2 and scenario E_2, according to the technology used

	Scenario 2011	Scenario without CC	Scenarios with CC impact		
		Scenario B_2 2023	Scenario L_2 2023	Scenario M_2 2023	Scenario E_2 2023
Coal power	1756	1756	1756	2056	2156
CCGT power	3829	3829	3829	3829	3829
Wind power	4081	8081	8081	8081	8081
Hydro power	6023	11921	11921	11921	11921
Solar power	155	1555	1555	1555	1555
Small hydro power	412	412	412	412	412

Looking at the Table 5.4 it is clear that there is an increase in the installed power for most of the scenarios compared to the 2011 situation, except for natural gas and small hydro power. This happens, because these scenarios assumed as restriction a minimum increase on amount of wind power in the system (4000 MW) and a minimum increase on the amount for solar power (1400 MW), for the year 2023. For scenario L_2 (low CC impact) it is verified that there has been no change in the installed electricity capacity in 2023, compared with the scenario B_2 (reference scenario). But for the medium and extreme scenarios new coal power plants are added to the system. Coal power increases 300 MW in scenario M_2 and 400 MW in scenario E_2, compared to scenario B_2. These results also demonstrate that, according to these projections, CC will not significantly affect the total installed electricity capacity in Portugal, but will modify the energy source used.

5.3.2.2. Electricity production

The amount of electricity production was analyzed according to the form of energy used. The Figure 5.6 demonstrates the amount of electricity produced by the power source in 2023, for scenario B_2.

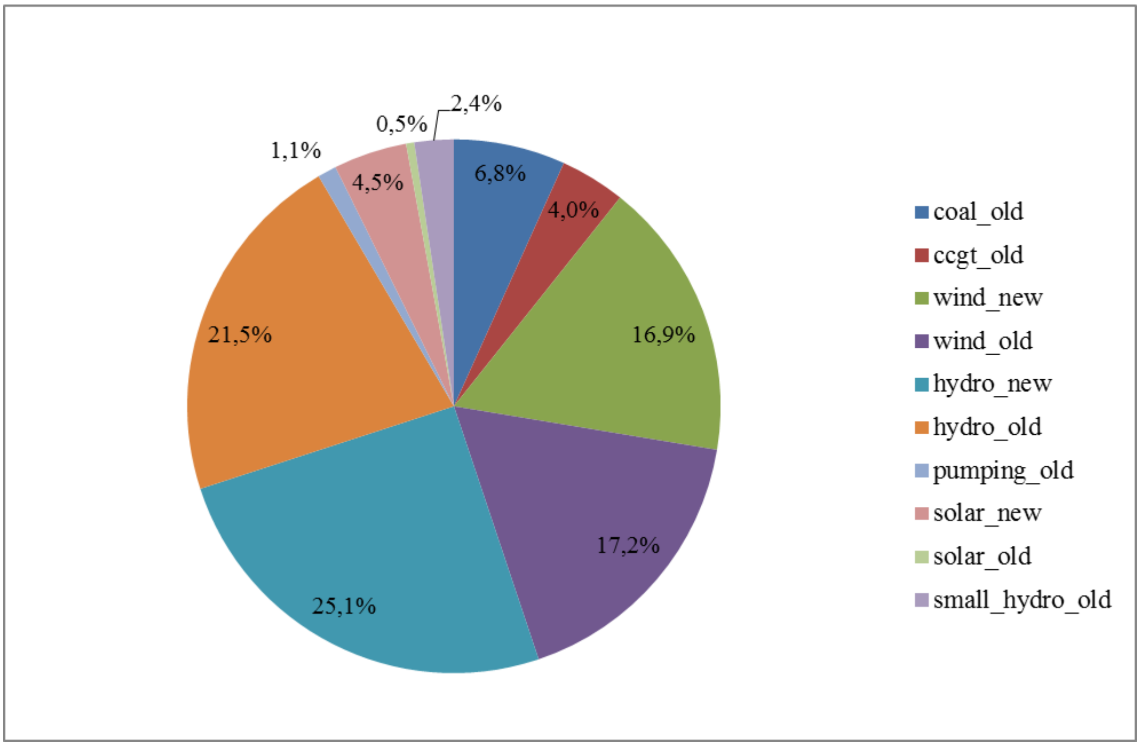

Figure 5. 6 - Electricity produced in % in 2023 for scenario B_2

For the analysis of Figure 5.6, it can be seen that in scenario B_2 in 2023, without CC, hydro power plants contribute with the higher share for electricity production (hydro_new, hydro_old and pumping_old) with 47,7%, followed by wind power with 34,1%. Then, coal electricity production represents 6,8% and solar power reaches 5%. The share of electricity production from natural gas is 4% and the small hydro share is

2,4%. In this scenario (B_2), the share of wind and solar electricity is much higher than in scenario B_1 due to the minimum installed capacity that was imposed for this scenario. The RES share represent almost 90% of the electricity produced in this reference scenario.

Figure 5.7 demonstrates the amount of electricity produced by the power source in 2023, for scenario L_2.

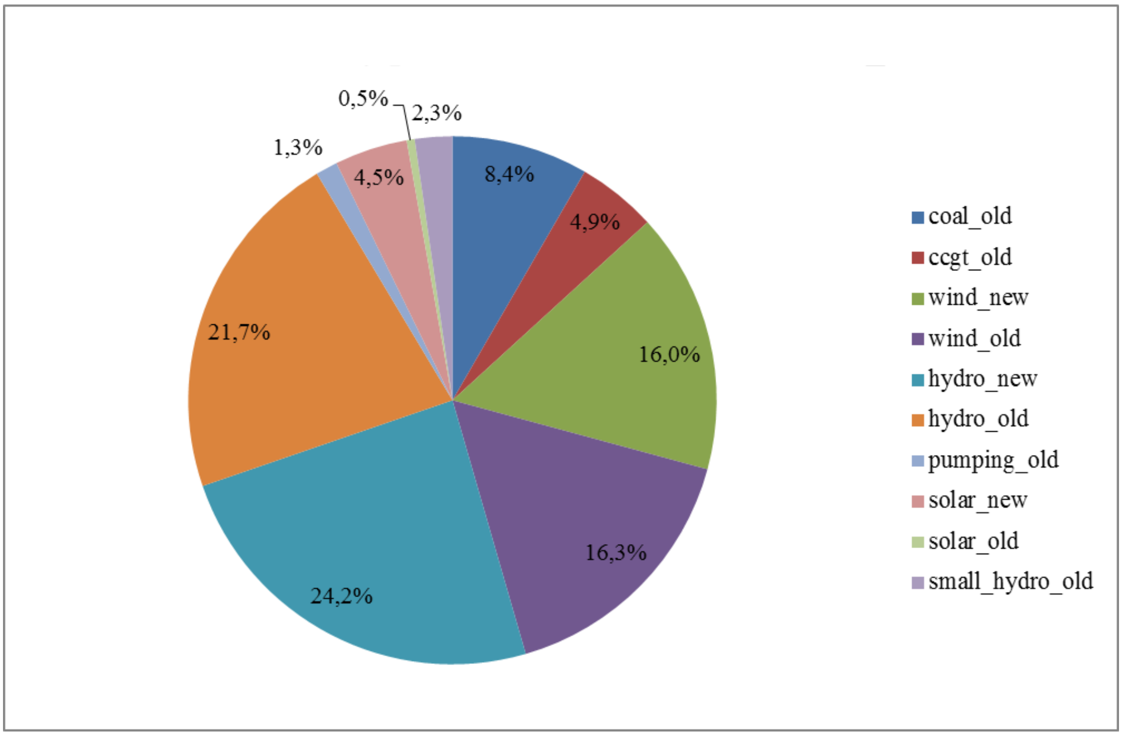

Figure 5. 7 - Electricity produced in % in 2023 for scenario L_2

As can be observed in Figure 5.7, compared to scenario B_2 (reference scenario), in 2023, hydro power output is reduced by about 1,8%, thus representing 45,9% of total production. However, power production of the pumping hydro plants ends up offsetting this decline. The wind electricity production also decreased to 32,3%, less 1,8% than in scenario B_2. On other hand, there was an increase in production from coal to 8,4% and in production from natural gas to 4,9%. Solar electricity increased about 0,01% (+15892 MW) comparatively to scenario B_2 and small hydro decreased about 0,1%. The RES amount to 86,8% of the electricity produced in this reference scenario.

The Figures 5.8 demonstrates the amount of electricity produced by the power source in 2023, for scenario M_2.

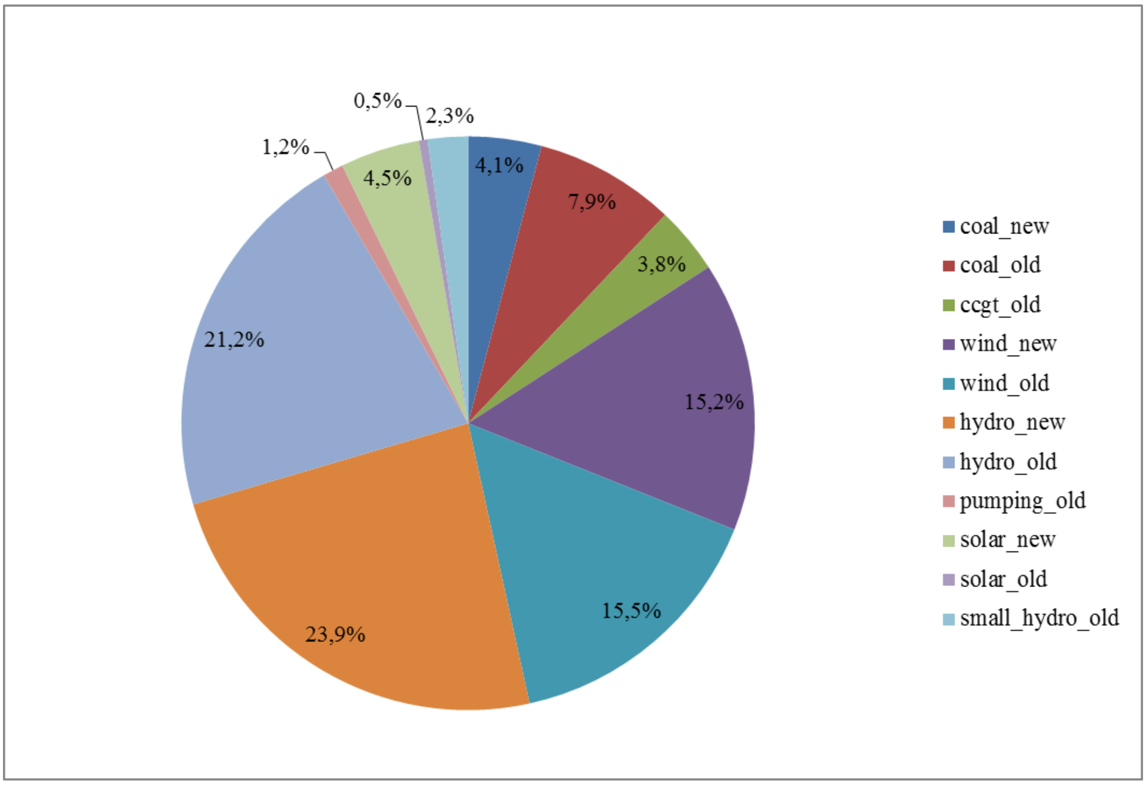

Figure 5. 8 - Electricity produced in % in 2023 for scenario M_2

Observing Figure 5.8, for the year 2023, it is possible to say that major portion of electricity produced came from hydro power, with a share of 46,3% (included the 1,2% of pumping hydro). There was however a decrease of hydroelectricity about 1,4% in relation to the scenario B_2 (reference scenario). The wind electricity represents 30,7% of the total electricity produced, less 3,4% than in the scenario without CC impact (B_2). On the other hand, there was an increase of coal electricity production, with more 5,2% than in scenario B_2, presenting now 12% of the total electricity produced. The production from natural gas reached 3,8% and small hydroelectricity decreased 0,1% compared to scenario B_2, thus representing 2,3% of total production. The share of solar electricity increased about 0,03% (+21189 MW). The RES share represent 84,3% of the electricity produced.

Figure 5.9 shows the amount of electricity produced by the power source in 2023, for scenario E_2.

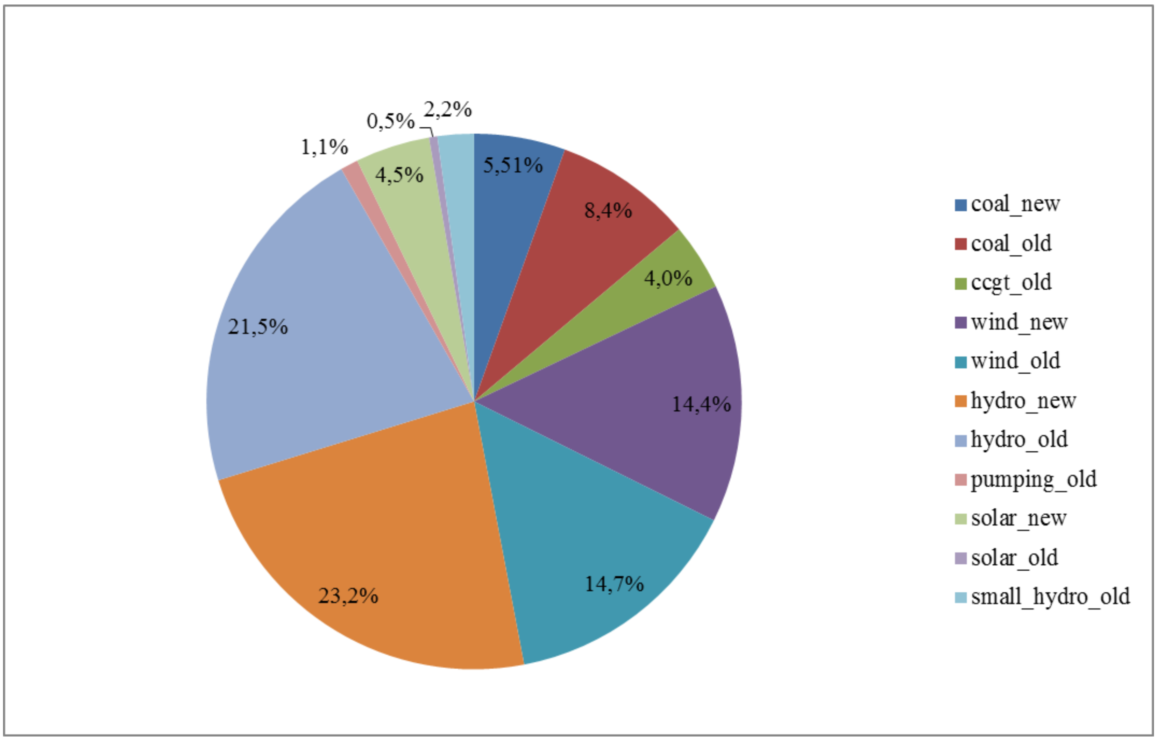

Figure 5. 9 - Electricity produced in % in 2023 for scenario E_2

From the analysis of Figure 5.9, it can be seen that in the scenario E_2 (extreme CC impact) in 2023, hydro power plants remains as the technology with higher electricity supplying levels, representing 45,8% of the total production (included pumping hydro), presenting however a 2% decrease compared to the scenario B_2 (reference scenario). It is followed by the wind power with 29,1%, thus showing a decrease of 5% compared to the reference scenario. The share of electricity production from coal is 13,9%, indicating here an increase of 7,1% compared to the scenario B_2. The natural gas contributes to the electricity system with 4% and small hydro contributes only with 2,2%, less 0,2% than reference scenario. The solar power output presents an increase of about 0,06%, more 26486 MW than in scenario B_2. Under this scenario RES would represent about 82,7% of the electricity produced in Portugal. Note that it is less almost 8% than reference scenario (B_2).

5.3.2.3. Costs and CO_2 emissions

Table 5.5 shows the obtained costs and CO_2 emissions for each scenario analyzed above.

Table 5. 5 - Costs and CO_2 emissions for each scenario analyzed

	Costs	**CO_2 emissions**
Scenario B_2	24.9 €/MWh	0.102 ton/MWh
Scenario L_2	25.5 €/MWh	0.102 ton/MWh
Scenario M_2	26.1 €/MWh	0.102 ton/MWh
Scenario E_2	26.8 €/MWh	0.102 ton/MWh

Analyzing Table 5.5 is possible to see the increasing trend of the total costs of the electricity for the more restricted CC scenarios. CC impacts mainly affect RES power output and although a small increase in solar power output is foreseen it cannot offset the reduction of both wind and hydro power production. This will result in an increase of fossil fuel requirements increasing both the investment and fuel costs for the system. Also here, the CO_2 emissions remain constant comparatively to the reference scenario, as maximum amount was established in a restriction of the model.

5.3.3. Reference scenario B_3 and CC scenarios

5.3.3.1. Installed power

The installed electricity capacity was analyzed according to the technology used. The greatest variations comparatively to the scenario 2011 occurred in the medium and extreme CC scenarios, as can be seen in Table 5.6.

Table 5. 6 - Installed power (MW) in 2023 for scenario B_3, scenario L_3, scenario M_3 and scenario E_3, according to the technology used

	Scenario 2011	Scenario without CC	Scenarios with CC impact		
		Scenario B_3 2023	Scenario L_3 2023	Scenario M_3 2023	Scenario E_3 2023
Coal power	1756	1756	1756	1756	1756
CCGT power	3829	4839	5344	4839	5344
Wind power	4081	8907	9181	9181	9181
Hydro power	6023	12157	12235	12235	12235
Solar power	155	155	155	1555	1555
Small hydro power	412	792	792	792	792

Looking at the Table 5.6 it is clear that there is an increase of the installed power for all scenarios for natural gas, wind, hydro and small hydro compared to the 2011 situation. The installed capacity of solar power remains unchanged in both scenarios B_3 and L_3. As for medium and extreme scenarios, solar power increases by 1400 MW. For scenario L_3 an increase in the installed electricity capacity in 2023 is obtained for natural gas, wind and hydro power comparatively to scenario B_3. In scenario M_3 the installed power of natural gas technologies remains equal to scenario B_3, due to the increase of solar power. Scenario E_3 presents an increase for all technologies, excluding coal. These results also show that, according to these projections, CC will not significantly affect the installed electricity capacity in Portugal, but it will modify the energy source used depending on the extension of the impact on RES.

5.3.3.2. Electricity production

The electricity production was analyzed according to the power technology. Figure 5.10 demonstrates the amount of electricity produced by the power source in 2023, for scenario B_3.

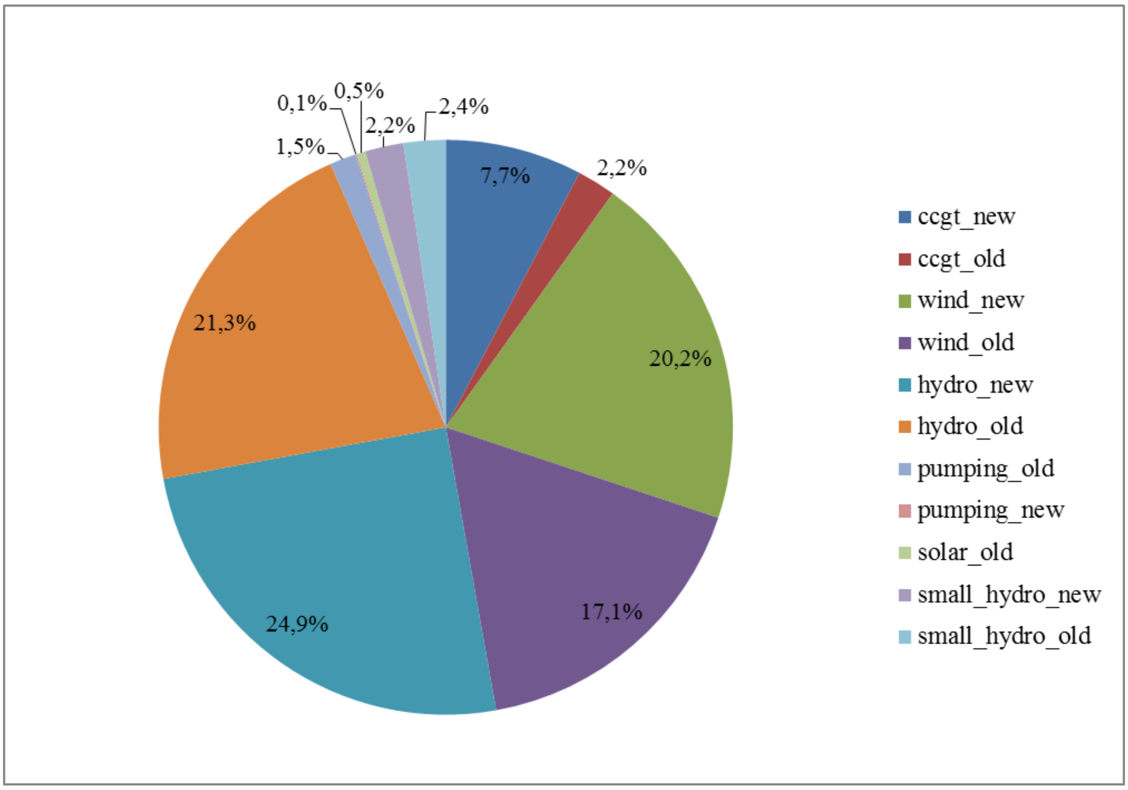

Figure 5. 10 - Electricity produced in % in 2023 for scenario B_3

From the analysis of Figure 5.10, it can be seen that for scenario B_3 in 2023, without CC impact, hydro power plants (hydro and pumping hydro) remains the most important technology in the system contributing with 47,8% of the electricity production. It is followed by wind power with 37,3%, natural gas with 9,9% and 4,6% for small hydro. The solar power contribution is 0,5% and coal would be no longer producing electricity. There is a big contribution of hydro and wind energy in this reference scenario (B_3). RES power represent more than 90% of the electricity production in this scenario.

Figure 5.11 shows the amount of electricity produced by the power source in 2023, for scenario L_3.

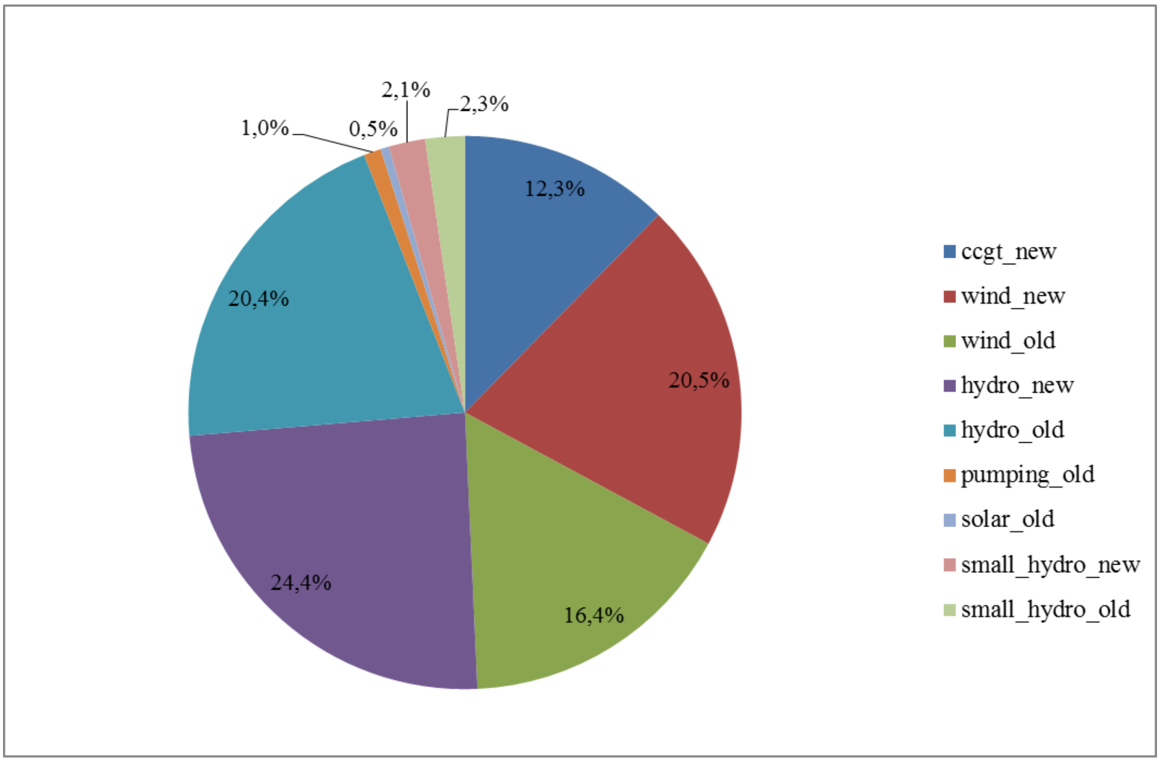

Figure 5. 11 - Electricity produced in % in 2023 for scenario L_3

As can be observed by Figure 5.11, in 2023, for scenario L_3 (low CC impact) hydro power remains the largest contributor (45,8%) although there was a decrease on the hydropower output comparative to the base scenario (B_3). The same goes to wind power production with a slight decrease to 36,9% comparatively to 37,3% of scenario B_3. On the contrary, a small increase in the electricity production from natural gas comparatively to scenario B_3 is obtained. In fact, natural gas would be compensating the reduction of both hydro and wind power production. Also, small hydro output presents a reduction of about 0,2% but solar power had a mild increase of about 0,01%. For this scenario, RES represent 87,7% of electricity produced against 12,3% from fossil fuels.

Figure 5.12 indicates the amount of electricity produced by the power source in 2023, for scenario M_3.

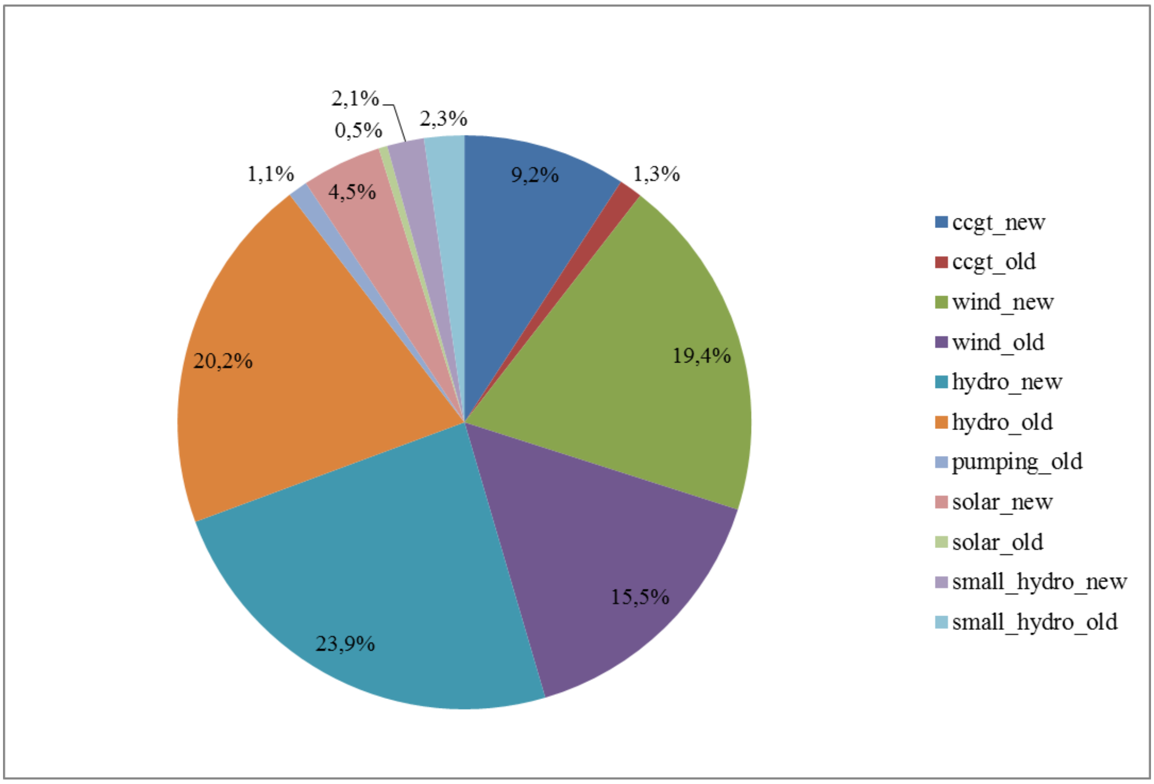

Figure 5. 12 - Electricity produced in % in 2023 for scenario M_3

For the analysis of Figure 5.12, it can be seen that in the scenario M_3 (medium CC impact) in 2023, once more hydro power is leading electricity production contributing with 45,2% (included pumping hydro) of the total electricity production, although with a decrease of 2,6 % comparatively to scenario B_3 (reference scenario). Wind power follows hydro power with a share of 34,9%, thus showing a decrease of 2,4% compared to the reference scenario (B_3). The share of electricity from natural gas is 10,5%, revealing here a small increase of 0,6% compared to scenario B_3. The small hydro contributes with 4,4%, less 0,2% than in base scenario. The solar power output presents an increase of about 4,5% than in the reference scenario (B_3) to the increased installed power, due of new solar production. The RES share represent 89,5% of the electricity produced in this scenario.

Figure 5.13 demonstrates the amount of electricity produced by the power source in 2023, for scenario E_3.

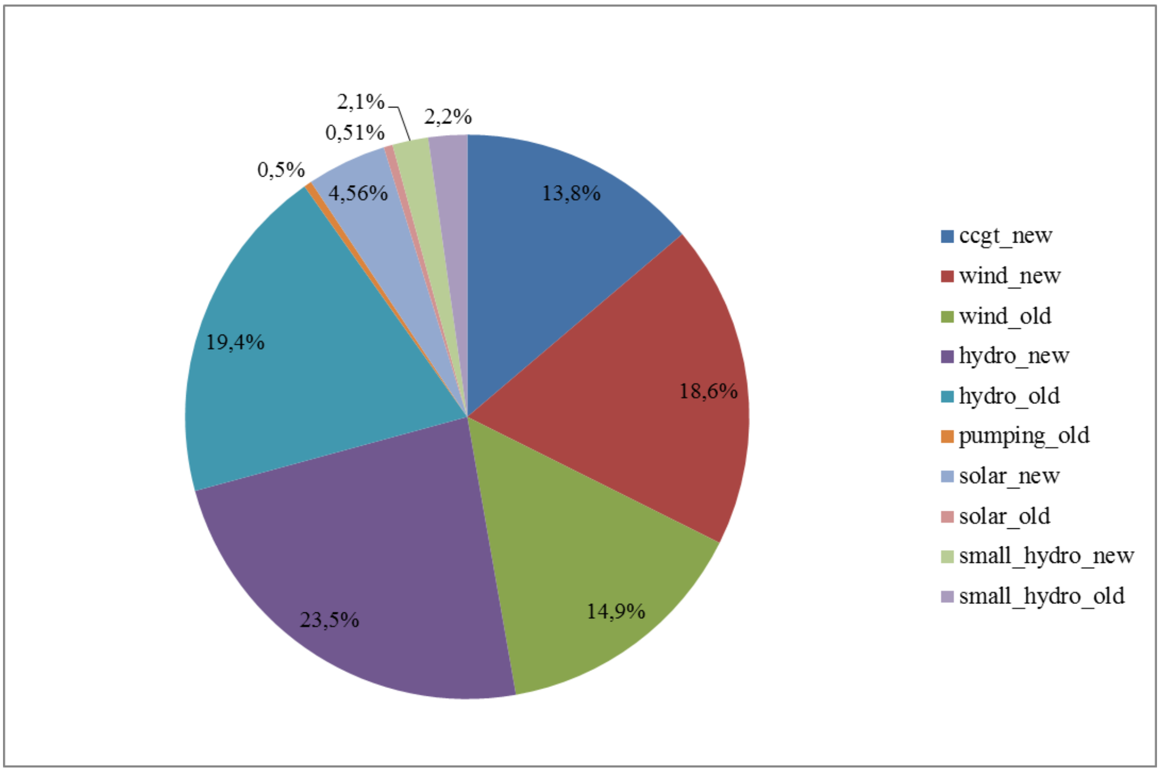

Figure 5. 13 - Electricity produced in % in 2023 for scenario E_3

As can be observed by Figure 5.13, hydro power represents 43,4% of the total electricity production. This hydro power production is however reduced by 4,4% comparatively to the reference scenario (B_3). Also, wind power contribution is reduced by 3,8% compared to the scenario B_3 representing now 33,5%. There is an increase in the production electricity from natural gas of about 3,9%, thus presenting 13,8% of total production. Small hydro power contributes with 4,3%, less 0,3% than in scenario B_3. Also, the solar power electricity production increased about 4,6% compared with reference scenario. The RES share represent 86,2% of the electricity produced against 13,8% from fossil fuels. Note that is less 4% than reference scenario (B_3).

5.3.3.3. Costs and CO_2 emissions

Table 5.7 shows the obtained costs and CO_2 emissions for each scenario analyzed above.

Table 5. 7 - Costs and CO_2 emissions for each scenario analyzed

	Costs	**CO_2 emissions**
Scenario B_3	20.9 €/MWh	0.025 ton/MWh
Scenario L_3	23.5 €/MWh	0.025 ton/MWh
Scenario M_3	26.2 €/MWh	0.025 ton/MWh
Scenario E_3	30.1 €/MWh	0.025 ton/MWh

Analyzing Table 5.7 is possible to see an increase of the energy costs of the system for all scenarios relative to the reference scenario B_3. The greater the impact of these CC will be the highest cost to the electricity system is obtained. According to the results, CC cause an economic impact in the electricity system, leading to need to be remodeled and consequently increasing costs related to additional investments and fossil fuel. The CO_2 emissions remain constant comparatively to the reference scenario, as maximum amount was established as a constraint in the model.

The effects of CC on electricity produced in Portugal are mainly caused by the decrease in hydro and wind power potential and by the increase in solar power potential. Thus, it can be stated that as expected and as can be seen above, the hydro power output is always reduced under CC scenarios. The wind power also shows a reduction in the production of electricity in all CC scenarios compared to the respective reference scenarios (without CC impact). The solar power shows a slight increase in the electricity production compared for CC scenarios comparatively to the reference scenarios. However, solar power contribution is quite reduced in all cases and in most cases natural gas plants are required to compensate the loss of hydro and wind power potential.

The cost of the system is a good indicator for assessing the impact of CC in the electricity system. Observing system costs associated with CC scenarios and without CC scenarios, it becomes obvious that these are significantly influenced by the assumed degree of impact of CC: the greater is the impact of CC the higher is the cost. For CC scenarios, due to the reduction of hydro or wind power output, the system needs to increase the installed capacity of RES power, natural gas or coal power with higher investment and fossil fuel costs.

5.4. Concluding remarks

This chapter aimed to demonstrate how CC can impact the structure of electricity production in the future, recognizing however that the design of electricity scenarios is also largely constrained by the CO_2 limits imposed by the international commitments. This way, several scenarios were considered representing different policies for the sector. Scenario B_1 analysis mainly assumed cost minimization objectives constrained by the CO_2 emissions. As for scenario B_2, although the same CO_2 limits were imposed it was also constrained by minimum amounts of wind and solar power. Finally, scenario B_3 analysis assumed a more constrained CO_2 perspective, reducing its maximum level by 75% comparatively to scenario B_1.

This section summarizes the obtained results in order to make easier potential comparisons between the scenarios. This summary is presented in Tables 5.8 to 5.10, describing the share of electricity generation from each power source under the reference scenarios and considering CC impacts.

Table 5. 8 - Electricity generation share: Reference scenario B_1 against CC scenarios

	Scenario without CC	**Scenarios with CC impact**		
	Scenario B_1 2023	Scenario L_1 2023	Scenario M_1 2023	Scenario E_1 2023
Coal power	-	-	-	-
CCGT power	30,6%	33,2%	34,5%	36,6%
Wind power	17,6%	16,8%	15,9%	15%
Hydro power	46,5%	45,1%	44,6%	43,5%
Solar power	0,5%	0,51%	0,51%	0,51%
Small hydro power	4,7%	4,6%	4,4%	4,4%

Table 5. 9 - Electricity generation share: Reference scenario B_2 against CC scenarios

	Scenario without CC	**Scenarios with CC impact**		
	Scenario B_2 2023	Scenario L_2 2023	Scenario M_2 2023	Scenario E_2 2023
Coal power	6,8%	8,4%	12%	13,9%
CCGT power	4%	4,9%	3,8%	4%
Wind power	34,1%	32,3%	30,7%	29,1%
Hydro power	47,7%	45,9%	46,3%	45,8%
Solar power	5%	5,01%	5,03%	5,06%
Small hydro power	2,4%	2,3%	2,3%	2,2%

Table 5. 10 - Electricity generation share: Reference scenario B_3 against CC scenarios

	Scenario without CC	**Scenarios with CC impact**		
	Scenario B_3 2023	Scenario L_3 2023	Scenario M_3 2023	Scenario E_3 2023
Coal power	-	-	-	-
CCGT power	9,9%	12,3%	10,5%	13,8%
Wind power	37,3%	36,9%	34,9%	33,5%
Hydro power	47,8%	45,8%	45,2%	43,4%
Solar power	0,5%	0,51%	5%	5,1%
Small hydro	4,6%	4,4%	4,4%	4,3%

The results clearly show that although CC will have a negative impact on the electricity generation from hydro and wind, the imposition of CO_2 restrictions or of minimum RES share will result in an increase of the share of these sources. For example comparing the results obtained for the extreme CC scenario it is evident that for both scenarios B_2 and B_3 it would be possible to achieve a higher RES production than under the same conditions for scenario B_1.

Climate change is a key aspect to be taken into account during energy planning as under extreme CC scenarios, the share of wind power can be reduced between 2,6% and 5%, the share of hydro power can be reduced between 1,9% and 4,4% but the share of solar power can increase by 4,6% comparatively to the base case scenarios. Even for low CC scenarios the reduction of hydro and wind power is already evident, supporting the need to include these aspects on business evaluation and energy policy decision making.

6. Conclusions

RES have an increasingly important role in mitigating the production of GHGs and reduce dependence on external energy. Therefore the assessment of the impacts of CC on renewable energy production must be properly considered and included in the electricity planning process. Recognizing this, the main objective of this dissertation was to assess the impact of CC scenarios on the use of RES in Portugal and on the Portuguese electricity system for 10 years (2014-2023).

For this, in an initial phase, international case studies and especially in southern Europe were analyzed in order to be able to collect data that revealed to be useful for the particular case of Portugal.

During the research conducted it was verified that the impacts of CC vary by geographic region. The analyzed studies showed that the production of hydroelectricity power technology is potentially the most affected by CC, in the case of southern Europe and particularly in Portugal. The reduction of water availability can lead to decreasing production of hydroelectricity power. As in Portugal an increase in temperature and a decrease in precipitation is foreseen, then a negative change in hydroelectricity production can be expected. Several studies point to this precipitation decrease to the south of Europe, and consequently for Portugal.

The analyzed case studies for the wind resource showed that changes in wind speed may have positive or negative impacts, taking into account possible increase or decrease in the wind speed. The number of studies assessing the impact of CC on wind technology on southern Europe are scarce. However, some projections already assume that there will be a decrease in wind speed over Mediterranean Europe, including Spain.

In the case of solar resource, the increase of radiation and decrease of cloudiness due to temperature increase can lead to an increase in the number of days of clear skies. These are the main factors driving the expected increase on the availability of the solar resource throughout the 21st century for southern Europe and in particular for Portugal.

As such, in the Mediterranean region an increase of the available solar resource is expected to increase, thereby increasing the ability to produce electricity from the sun.

Given the variety of results obtained from the case studies analyzed, the impact of CC scenarios on the electricity production potential for hydro, wind and solar was assessed for the case of the Portuguese electricity system simulating different projections.

Three reference scenarios (B_1, B_2 and B_3) were assumed, with different emissions limits for CO_2 and with different installed power. For each reference scenario different projections (low, medium and extreme) of CC impacts designed for Portugal in the years 2014-2023 were applied. For all simulations electricity demand was assumed to increase about 2,3% per year. The analysis of the reference scenarios allowed us to understand the evolution and behavior of the electricity system by 2023 and to make a comparison between them and their respective CC scenarios in order to identify the impacts on the national electricity system.

Using the modeling tool SEPP, twelve scenarios of evolution of the electricity system were analyzed, in order to assess the impact of CC on electricity production and on the RES output. The study showed that the electricity sector is vulnerable to CC, but there are differences between the impacts on renewable technologies, according to the imposed limits on CO_2.

Without the effect of CC, by 2023, it was found that RES share can reach 90% of electricity production under the assumed B_3 scenario conditions (CO_2 constrained scenario). For scenario B_2 this share is also very close to 90%. As for scenario B_1 the production of electricity from RES almost reached 70%. These differences occur because the scenario B_3 is limited by the allowed CO_2 emissions to a much lower value than in scenario B_1. Thus, for scenario B_3, electricity from RES is required to meet the imposed limit of CO_2. Scenario B_2 departs from a limit on the emissions of CO_2 equal to scenario B_1, but imposes minimum values for the installed wind power and for solar power. This means that there is also a large production of electricity from RES power. Also for this reason, is the reference scenario with higher cost (24.9 €/MWh) mainly due to the high investment costs of solar power.

The modeling of the installed capacity in CC scenarios have revealed that the total installed power will not be significantly affected, changes are mainly on the energy source used under CC scenarios with medium and extreme projections. The modeling of the electricity produced in the CC scenarios allowed to establish that RES power production, such as hydro, small hydro and wind will be reduced. The solar power output will increase with only a marginal impact on the overall electricity system.

The CO_2 emissions remain constant comparatively to the reference scenarios (B_1, B_2 and B_3), as maximum amount was established as a model constraint.

Taking into account the reference scenario B_1 (CO_2 emissions < $6{,}11x10^7$ ton), for 2023 under CC conditions:

- The installed capacity does not undergo significant changes. The installed capacity of natural gas grows slightly in scenarios M_1 and E_1, in order to offset the decline in production from hydro and wind power plants.
- A reduction of electricity production of 1,4% for hydro power and of 0,1% for small hydro power is expected in scenario L_1, due to the assumed decrease of precipitation. A higher reduction of the amount of precipitation (scenario M_1) leads to a 2% reduction in hydro power production and a 0,3% reduction in small hydro power production. For scenario E_1, the extreme reduction of precipitation results in a reduction of hydro power production of about 3% and a reduction of about 0,3% in small hydro power.
- A reduction of production of 0,8% for wind power is seen in scenario L_1, due to the assumed potential decrease of the wind speed. A more significant reduction of the wind speed (scenario M_1) leads to a 1,7% decrease in production of wind energy. For the extreme scenario E_1, a decrease of about 2,6% in wind electricity production is obtained due to the foreseen wind speed reduction.
- For all scenarios with CC, solar power presents a very slight increase of its output, due to the expected increase on the solar radiance
- The cost of CC scenarios exceeds the cost of the reference scenario (without CC impact). The larger is the assumed CC impact the higher is the system cost. The reference scenario (B_1) presents a cost of 15.7 €/MWh, and the scenario E_1 (extreme projections) presents a cost of 18.5 €/MWh. The higher costs are obtained when the electricity system requires more expensive investments and increase fossil fuel consumption to compensate for the reduced availability of hydro and wind power.

Taking into account the reference scenario B_2 (CO_2 emissions < $6,11x10^7$ ton and minimum installed capacity equal to 4000 MW for wind power and 1400 MW for solar power), for 2023:

- The installed capacity does not indicate significant changes. The installed capacity of coal slightly increases in both scenarios M_2 and E_2, compared to scenario B_2. This increase allows to offset the loss of production from hydro and wind power, due to CC.
- A reduction of electricity production of 0,5% for hydro power and a reduction of 0,1% for small hydro power under scenario L_2 is obtained. For the medium and extreme CC scenarios, the reduction of precipitation is even more accentuated leading to the increasing trend of large and small hydro power output reduction.
- A reduction of production of 1,8% for wind power in scenario L_2 is evident. A reduction about 10% in production potential wind (scenario M_2) leads to a 3,4% decrease in production of wind power plants. As for scenario E_2, the 15% reduction in wind speed leads to a potential decrease about 5% in wind power ouput.
- The solar power output has a very slight increase of 0,01% in scenario L_2 due to the increased solar radiation. For more restricted CC scenarios (M_2 and E_2) solar power output tends to increase, but its share in the overall electricity production remains low.
- The obtained cost for CC scenarios exceeds the cost of the reference scenario B_2 (without CC impact). Also in this case the higher costs obtained for the CC scenarios is justified because of the required new investments and the increase on fossil fuel costs.

As for the reference scenario B_3 (CO_2 emissions < $1,5x10^7$ ton), for 2023 the following results should be underlined:

- The obtained total installed capacity presents some changes in 2023. There is an increase in installed capacity of natural gas power plants for scenarios L_3 and E_3. Also the installed capacity of wind power and hydro power increases in all scenarios with CC. The same goes for the installed capacity of solar power in scenarios M_3 and E_3. These changes are mainly due to the need to compensate for production losses of RES due to CC impacts.

- Both the hydro and small hydro power output is reduced comparatively to the base case scenario. This trend increases for more restricted CC scenarios due to the assumed increasing reduction of precipitation. The reduction of hydro production is 2% for large hydro power plants and 0,2% for small hydro power plants in scenario L_3. For the extreme scenario (E_3) there is a reduction of production in hydro power production of about 4,4% and a reduction of about 0,3% in small hydro power output.

- Also for the wind power, the output also declines under more extreme CC scenarios. The results indicate a reduction of electricity production of 0,4% from wind power in scenario L_3 and this reduction achieves about 3,8% under scenario E_3.

- The solar power output slightly increases for all CC scenarios. Under scenario L_3, an increase of its output of 0,01% is to be expected. This increase reaches 4,6% for scenario E_3 (+1% solar radiation).

- Also in this case, the cost of CC scenarios exceeds the cost of the reference scenario (without CC impact). The reference scenario (B_3) presents a cost of about 20.9 €/MWh, and the scenario E_3 (extreme projections) presents a cost of 30.1 €/MWh. As in the other scenarios, the greater the assumed impact of CC is the highest is the costs to the system. The highest costs are derived by the need to invest in more expensive technologies (such as solar) and by the increasing use of fossil fuel.

As expected, it was possible to observe lower availability of hydro power for electricity production in 2023. This reduction can reach values between 3% and 4,4%, according to the scenarios E_1 and E_3, respectively. Small hydro may also reach a reduction of about 0,3%, according to scenarios M_1, E_1 and E_3. Also for wind power the expected reduction of wind speed can result in a reduction of electricity production in 2023 that can reach 5% according to scenario E_2. It can be concluded that the electricity production of hydro, small hydro and wind power is always lower in all CC scenarios comparatively to scenarios without CC. On the contrary, the production of electricity from solar power is always higher in CC scenarios. This increase can be between 0,01% and 4,6% comparatively to scenarios without CC impacts.

CC does not reduce the total electricity production in 2023, but will change the type of energy source used. This happens because the model did not take into consideration the CC impacts on the total demand and on the electricity consumption pattern through the year. In general, electricity system must compensate the reduction of hydro and wind power production with other RES mainly solar power, but also with the increasing use of fossil fuels.

Regarding costs, it can be stated that the greater the impact of CC on electricity production, the highest the electricity costs will be. This includes both investments, fixed and variable operating costs. Higher costs are obtained when the energy system increases capacity of more expensive technologies, such as solar power, or increases the consumption of fossil fuels, to compensate for the reduction of hydro or wind power.

In general, RES share is always higher than the share of electricity produced from fossil fuels for all the analyzed scenarios. This is due to the imposed constraints on the CO_2 emissions and RES share driven by the high RES potential and optimal conditions in Portugal for RES electricity production.

Finally, although the decrease in the availability and potential for RES electricity production is minimal in percentage terms some cautions should be taken when analyzing the results. In fact, these percentage terms are relatively low as the number of years in the study is also small and relatively close today. CC impacts are expected to be particularly relevant in 50 or 100 years planning period and long term planning models must be developed under these assumptions.

The main contribution of this study is to demonstrate the impact that CC can have on the RES output and consequently on the economic and environmental characteristics of the electricity system. This research topic can provide fundamental results to investors and policy makers.

It must be however underlined that this study also presents important limitations that should be assessed in future research. Namely the lack of existence of studies on specific climate projections for Portugal, especially for solar and wind resource. This increases the uncertainty of the projections and of course can affect the quality of results. As highlighted before, particularly important is also the fact of using a limited time planning of 10 years, although recognizing that CC impacts will be felt for a much longer period. Recognizing these limitations, a few topics for future research can be proposed.

6.1. Future work

In drawing up this dissertation improvements that may contribute to a better perception of the impact of CC in Portugal were identified, namely:

- To extend the time period of the study (simulations for the entire 21st century or for the beginning of the 22nd century). As the planning process was based on a 10 years period the CC impacts on the electricity system are still minor but, for a planning period of 50 or more years these impacts can be much more relevant.

- To include in this study other RES power technologies, such as wave and tidal, biomass or geothermal. The adoption of the SEPP model required adaptations and limited the possibility of including a large number of technologies but, in the future the importance other RES must be also assessed.

- To conduct studies on the impacts of CC on hydro, wind and solar resources, in Portugal. The information used in this work was based on the literature review but future work should depart from regional climate modeling for the more precise calculation of the potential of each source in Portugal in the future.

- To recognize the CC impacts on the demand side and not only on the supply. This will require the modeling of the total demand and of its seasonal behavior, as this work for sake of simplicity assumed that demand would not be affected by CC. However, demand values and its yearly pattern are fundamental assumptions for the SEPP model and can severely affect the obtained results.

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