Universidade de Aveiro Departamento de Ambiente e Ordenamento
2019

CARLA MANUELA RODRIGUES TEOTÓNIO

ÁGUA, ENERGIA E ECONOMIA:

UMA AVALIAÇÃO INTEGRADA DOS IMPACTOS ECONÓMICOS DAS ALTERAÇÕES CLIMÁTICAS NUM PAÍS MEDITERRÂNICO

WATER, ENERGY AND THE ECONOMY:

AN INTEGRATED ASSESSMENT OF THE ECONOMIC IMPACTS OF CLIMATE CHANGE IN A MEDITERRANEAN COUNTRY

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Tese apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Doutor em Ciências e Engenharia do Ambiente, realizada sob a orientação científica do Doutor Peter Cornelis Roebeling, Investigador Auxiliar do Departamento de Ambiente e Ordenamento da Universidade de Aveiro, do Doutor Miguel Rodríguez Mendez, Professor Titular do Departamento de Economia Aplicada da Universidade de Vigo, e da Doutora Patrícia Fortes, Investigadora do Centro de Investigação em Ambiente e Sustentabilidade da Universidade Nova de Lisboa

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Dedico este trabalho aos meus pais, ao meu marido, e à nossa filha.

o júri

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palavras-chave

cenários de alterações climáticas; impactos das alterações climáticas; recursos hídricos; nexus ‘água-energia’; hidroeletricidade; modelação energia-economia-ambiente; modelos híbridos top-down/bottom-up; equilíbrio geral computável.

resumo

As alterações climáticas são consideradas uma das mais sérias ameaças ao mundo natural e à economia global. Por essa razão, a avaliação dos impactos das alterações climáticas e a definição de políticas de mitigação têm merecido a atenção das comunidades científica e política em todo o mundo. Uma das principais causas das alterações climáticas são as variações da concentração de gases com efeito de estufa (GEE) na atmosfera, que são maioritariamente emitidos pelo setor energético. Por outro lado, o impacto físico mais evidente das alterações climáticas é o aquecimento global, que interfere com o ciclo da água, em particular através de alterações da precipitação, e afeta a disponibilidade e a variabilidade da oferta e da procura de recursos hídricos. A água é, por sua vez, essencial na cadeia de produção do setor energético, e um input crucial para o setor elétrico – em particular, para a produção hidroelétrica. Assim, o setor energético não só contribui para as alterações climáticas, como é, também, vulnerável aos seus impactos. Ao mesmo tempo, o setor energético tem um significativo potencial de mitigação das alterações climáticas, nomeadamente através de aumentos de eficiência e da produção a partir de fontes renováveis, como a hidroelétrica. O objetivo global desta tese é analisar os impactos e feedbacks entre recursos hídricos, o setor energético e a economia, considerando os objetivos de energia e clima e as alterações climáticas. Para o caso de Portugal, país Mediterrânico, a análise foca-se i) nos impactos económicos das metas fixadas pelas políticas de energia/clima em vigor e ii) nos impactos económicos da redução da disponibilidade e da competição pela água, decorrentes das alterações climáticas. Os resultados mostram que: i) a forma mais custo-eficaz de alcançar objetivos de poupança de energia é através da redução do consumo de energia primária de origem fóssil, e que a forma mais custo-eficaz de alcançar objetivos de poupança de energia final é através da redução do consumo de todos os produtos (fósseis e renováveis); ii) impactos mais severos das alterações climáticas e a redução da disponibilidade de água que lhes está associada implicam um papel crescente dos combustíveis fósseis no mix elétrico, o que provoca um aumento das emissões de GEE e pode pôr em causa o cumprimento de objetivos climáticos; iii) os impactos macroeconómicos e setoriais das alterações climáticas são mais fortes se a concorrência pela água entre a produção hidroelétrica e os restantes setores económicos não for considerada, e se a concorrência transfronteiriça for tida em conta; e iv) os impactos das alterações climáticas na disponibilidade de água levam a uma redução do produto interno bruto entre -0.1% e -3.2%. Para além da quantificação dos impactos económicos das políticas de energia/clima e dos efeitos das alterações climáticas na disponibilidade de recursos hídricos, a análise fornece elementos relevantes para a definição de políticas de energia e clima.

keywords

climate change scenarios; climate change impacts; water resources; ‘water-energy’ nexus; hydropower; energy-economy-environment modelling; hybrid top-down/bottom-up models; computable general equilibrium.

abstract

Climate change is considered one of the most severe threats to the natural world and global economy. For that reason, the assessment of climate change impacts and mitigation policies have deserved the attention of the scientific and political communities worldwide. One of the main drivers of climate change are the variations in atmospheric concentrations of greenhouse gases (GHG), which are primarily released by the energy sector. On the other hand, the most evident physical impact of climate change is global warming, which interferes with the water cycle, in particular through changes in precipitation, thereby affecting the availability and variability of supply of and demand for water resources. Water, in turn, is essential in the energy production chain and a key input for the power sector – in particular for hydropower generation. Hence, the energy sector, not only, contributes to climate change but is, also, vulnerable to climate change impacts. Simultaneously, the energy supply sector has significant potential for climate change mitigation, notably through increased efficiency and the deployment of renewable-sourced technologies, such as hydropower. The overall objective of this thesis is to analyse the impacts and feedbacks between water resources, the energy sector and the economy in the face of energy and climate goals as well as climate change. For the case of the Mediterranean country of Portugal, the analysis focusses on i) the economic impacts of current energy/climate policies and targets, and ii) the economic impacts of future climate-driven changes in water resources availability and competition. Results show that: i) attaining energy saving targets is most cost-effectively achieved through a reduction in primary energy consumption of fossil fuels and that achieving a reduction in final energy consumption is most cost-effectively achieved through the taxation of all energy products; ii) stronger climate change impacts and associated reductions in water resources availability imply an increasing role of fossil fuels in the power mix, thus increasing GHG emissions and undermining the compliance with climate goals; iii) macroeconomic and sectoral impacts of climate change are stronger if competition for water between hydropower and the other economic sectors is not considered and if transboundary competition for water is taken into account; and iv) the impacts of climate change related reductions in water resources availability result in decreases in gross domestic product (GDP) of between -0.1% and -3.2%. Hence, beyond the quantification of the economic impacts of climate/energy policies and climate-driven changes in water resources availability and competition by 2050, the analyses provide relevant insights that are of utmost importance for energy and climate policy-making.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AEEI	Autonomous Energy Efficiency Index
AIM	Asia-Pacific Integrated Model
BaU	Business-as-usual
CES	Constant elasticity of substitution
CGE	Computable General Equilibrium
CO_2	Carbon dioxide
COP	Conference of the Parties
E3	Energy - Economy - Environment
ETS	Emissions Trading System
EU	European Union
EU-28	European Union - 28 countries
GAMS	General Algebraic Modelling System
GCAM	Global Change Assessment Model
GDP	Gross Domestic Product
GHG	Greenhouse gas
GVA	Gross Value Added
GW	Gigawatt
GWh	Gigawatt hour
HadCM3	Hadley Centre Coupled Model Version 3
HadRM2	Hadley Centre Regional Model Version 2
HCF	Hydropower Capacity Factor
IAM	Integrated Assessment Models
IMAGE	Integrated Model to Assess the Global Environment
I-O	Input-Output
IPCC	Intergovernmental Panel on Climate Change
kgoe	Kilograms of oil equivalent
ktoe	Thousand tonnes of oil equivalent
MBTU	Million British Thermal Unit
MCP	Mixed Complementarity Problem
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impact
MIBEL	Iberian Electricity Market
MPSGE	Mathematical Programming System for General Equilibrium
Mtoe	Million tonnes of oil equivalent
MW	Megawatt
MWh	Megawatt hour
NDC	Nationally Determined Contributions
NEEAP	National Energy Efficiency Action Plan
NUTS 2	Nomenclature of Territorial Units for Statistics level 2
OECD	Organization for Economic Cooperation and Development
PESETA	Projection of Economic impacts of climate change in Sectors of the European Union based on bottom-up Analysis
PNPCC	Portuguese National Program on Climate Change
PRIMES	Price-Induced Market Equilibrium System
PRUDENCE	Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects
RCP	Representative Concentration Pathways
RES	Renewable Energy Sources
SAM	Social Accounting Matrix
SIAM	Scenarios, Impacts and Adaptation Measures
PV	Photovoltaic
SRES	Special Report on Emissions Scenarios
SSP	Shared Socioeconomic Pathways
SWAT	Soil & Water Assessment Tool
tCO_2	Tonne of carbon dioxide
TIMES	The Integrated MARKAL-EFOM System
UNFCCC	United Nations Framework Convention on Climate Change
USD	United States dollar
VIC	Variable Infiltration Capacity
W/m^2	Watts per square meter

CHAPTER 1

INTRODUCTION

1.1. Motivation

Climate change is recognized as one of the most important threats to the natural world and global economy, as it interferes with several domains of Earth and Life – namely with ecosystems, coastal areas, water, health, human settlements, food production, industry and the energy sector. According to the Intergovernmental Panel on Climate Change (IPCC, 2013a: p.1450), climate change can be defined as "a change in the state of the climate that can be identified (e.g., by 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".

The most evident effect of climate change is on air temperature. Historical data shows that each of the last three decades has been successively warmer than any preceding decade since 1850 (IPCC, 2013b). Global warming has, as a consequence, led to changes in the natural and human environment, including changes in the global water cycle, alterations in weather patterns, reductions in crop productivity, the decline in energy technologies efficiency and energy resources' availability, among others.

The main drivers of climate change are the variations in atmospheric concentrations of greenhouse gases (GHG) and aerosols, changes in land cover and variations in solar radiation that alter the energy balance of the climate system (IPCC, 2007a). The resulting positive or negative changes in energy balance due to these factors are termed "radiative forcing". Anthropogenic action has been recognized as the main cause of global warming as it results in the emission of six long-lived GHGs: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6), where the latter three are also known as F-gases. CO_2 emissions are, primarily, due to fossil fuel combustion and, to some extent, land-use change. CH_4 emissions are due to the production and transport of fossil fuels, livestock, and rice cultivation, and the decay of organic waste in solid waste landfills. N_2O emissions result from agricultural and industrial activities as well as combustion and human waste disposal. F-gases emissions result from industrial processes (IPCC, 2014b).

Global atmospheric concentrations of CO_2, CH_4 and N_2O have increased sharply since the industrial revolution, thereby noting that half of the cumulative anthropogenic CO_2 emissions from 1750 to 2010 has been released between 1970 and 2010. From 1970 to 2010, total GHG emissions increased from 27 to 49 gigatonnes of CO_2 equivalent (GtCO2eq) per year (around +80%), while the world population grew by 87%, global gross domestic product (GDP) per capita doubled (+1.8% per year), total energy use increased by 130% and primary energy use per capita increased by 31% (IPCC, 2014b). Per capita production and consumption growth are, therefore, amongst the main drivers of GHG emissions. At the sectoral level, in 2010 (IPCC, 2014d), the largest source of GHG emissions is energy supply (35%), followed by agriculture, forestry and land use (24%), industry (21%), transport (14%) and buildings (6%). Despite the global economic crisis of 2007/2008, the decade 2000-2010 recorded the highest total antrophogenic GHG emissions – growing by 2.2% per year between 2000 and 2010 as compared to 1.3% per year between 1970 and 2000 (IPCC, 2014d). During these four decades, CO_2 emissions increased by 90%, CH_4 emissions increased by 47% and N_2O emissions by 43%, with CO_2 representing 76% of total anthropogenic GHG emissions in 2010 (IPCC, 2014b). In particular, the share of CO_2 emissions resulting from fossil fuel combustion for energy purposes increased steadily since 1970, reaching 69% of global GHG emissions in 2010.

The energy supply sector is, thus, one of the main drivers of climate change. In an increasingly developed world, however, energy is critical for economic growth as almost no human need can be satisfied without energy services. Thus, the challenge faced by modern societies is to provide energy services with low environmental impacts and GHG emissions. In this respect, the energy sector's potential to adapt to and to mitigate climate change impacts is essential, which may be achieved through improvements in energy efficiency and the promotion of renewable energy (notably increasing the share of endonegenous renewable energy sources, which may also contribute to the increase in energy security). Despite all economic sectors are expected to contribute to reduce GHG emissions, the power sector is considered to have the greatest potential. Electricity can, not only, replace fossil fuels for transports, buildings and heating/cooling needs, but also, it can be produced from renewable sources.

The energy sector is, however, also vulnerable to climate change. Changes in the average surface temperature and weather patterns impact energy demand mainly concerning heating and cooling needs, while impacts on energy supply are related to the availability of energy resources, the technical efficiency of fuel-to-electricity conversion (particularly in thermal power systems) and the increased competition for scarce resources (notably water resources). Hydropower merits special attention. On the one hand, hydropower is a mature and cost-effective renewable energy power generation technology that fits in the framework of a clean energy mix and is, therefore, envisaged as one of the most auspicious technologies to increase renewable electricity generation. On the other hand, hydropower is likely to be one of the technologies most vulnerable to climate-driven changes in water resources availability, which can interfere with its potential and, consequently, its role in the energy mix. Furthermore, in a climate change context, hydropower is likely to be affected by the increasing competition for scarce water resources – both between economic sectors as well as between countries sharing river basins. Hydropower is, thus, one of the most direct links in the so-called 'water-energy' nexus, which synthethizes the relationship between water resources, the energy sector and resulting externalities.

The 'water-energy' nexus is usually addressed using a technological perspective. However, being water and energy two of the most critical resources in the world economy, the 'water-energy-economy' nexus emerges as a key perspective for the comprehensive understanding of the climate change impacts on the economy. This through the quantification of the interdependency between water resources and the energy sector, that, ultimately, condition economic performance.

1.2. Climate and energy policies in Portugal

Climate change is a global problem and, for that reason, has to be tackled at an international scale. Portuguese climate change policy is shaped by international treaties to fight climate change, by the European Union (EU) climate legislation and targets, and further complemented by national policy instruments that assure that the Portuguese commitments agreed within the international community and the EU are put into practice. All these climate policies, including both adaptation and mitigation policies, are underpinned by projections of climate change impacts and, broadly speaking, aim that the most pessimistic projections are not realised.

The main international treaty designed to combat climate change is the United Nations Framework Convention on Climate Change (UNFCCC), adopted in 1992 at the "Rio Earth Summit". Since then, the main international negotiations about climate change occur in the annual Conference of the Parties to the UNFCCC (COP), which is its maximum decision-body. Here the international community agreed to keep global warming below 2°C compared to pre-industrial levels, as a means of preventing anthropogenic dangerous interference with the climate system. Under the Paris Agreement reached in 2015 during the COP21, 195 countries (EU as a whole and Member States included) adopted the first universal and legally binding global climate deal. The main goal of the Paris Agreement is to keep a global temperature increase in the 21st century below 2°C above pre-industrial levels, and to pursue efforts to limit the temperature increase even further to 1.5°C. Also in the scope of the Paris Agreement, Parties are required to submit "nationally determined contributions" (NDCs) to attain this goal. Until 2020, however, the world's only legally binding instrument for cutting GHG emissions is the Kyoto Protocol, signed in 1997, and presently in its second commitment period (since 2013).

Mitigating climate change is a priority for the EU. Beyond the internal and external policies that reflect this commitment, the EU has its own climate strategy which relies on targets that will enable EU's transformation towards a low-carbon economy, by 2050. In particular, within the 2020 Energy and Climate Package, currently in force, the EU has set the so-called '20-20-20' targets, namely: 20% of renewable energy sources (RES) in final energy consumption; 20% improvement in energy efficiency (substantiated in a 20% saving in primary energy consumption as compared to the 2007 baseline projection for 2020); and 20% reduction in GHG emissions as compared to 1990 levels (which corresponds with the EU target set in the framework of the Kyoto Protocol second commitment period). Between 2020 and 2030, the EU climate strategy will be established in the 2030 Climate and Energy Framework, which encompasses the following targets: at least 27% share for renewable energy; at least 27% improvement in energy efficiency; at least 40% reduction in GHG emissions as compared to 1990 levels (which corresponds with the EU NDC in the scope of the Paris Agreement). The fulfilment of these targets is the necessary pathway towards EU's long-term goal of an 80% cut in GHG emissions as compared to 1990 levels.

In Portugal, the EU targets for 2020 were transposed to national legislation through the National Renewable Energy Action Plan and the National Energy Efficiency Action Plan. These set the Portuguese targets of a 31% share of renewable sources in final energy consumption, a 10% share of renewable sources in energy consumption in transport, and a 25% saving in primary energy consumption as compared to the use of energy projected by the EU for Portugal in 2020. Regarding GHG emissions, the +1% cap set for 2020 by the EU Effort Sharing Decision for emissions not included in the EU Emissions Trading Scheme (European Union, 2009) was further extended with the goal of an 18% to 23% reduction in GHG emissions by 2020 (as compared to 2005) under the Portuguese Green Growth Commitment (MAOTE, 2015). For the 2030 horizon, Portuguese climate policy is set in the Strategic Framework for Climate Policy (RCM 56/2015), which gathers the main climate policy instruments – notably the second phase of the National Strategy for Climate

Change Adaptation 2020 and the National Program for Climate Change 2020/2030. The latter establishes the following targets for 2030: a share of 40% renewable sources in final energy consumption; a reduction of 30% in final energy consumption as compared to baseline projections; and a 30% to 40% reduction in GHG emissions as compared to 2005 (RCM 56/2015). For the 2050 horizon, during the COP22 (Marrakesh, 2016), Portugal committed to the carbon neutrality of GHG emissions.

1.3. Objectives

The foregoing constitutes the background and the motivation for this thesis: to advance the understanding of the economic impacts of climate change, with emphasis on the 'water-energy-economy' nexus.

With the **overall objective** of analysing the impacts and feedbacks between water resources, the energy sector and the economy in the face of energy and climate goals as well as climate change, the analysis adopts a double perspective: first, focusing on the policy side of climate change (specifically, on mitigation policies in force); and, second, focusing on the physical side of climate change (specifically, on the impacts on natural resources availability and competition). A case study is provided for the Mediterranean country of Portugal. This is accomplished through the following three **specific objectives**:

1. To assess the economy-wide effects of the near-term energy and climate policies and goals designed to mitigate climate change;

2. To assess the long-term sectoral effects of climate change on hydropower generation and the power sector; and

3. To assess the economy-wide effects of long-term climate change-driven impacts on water resources availability, under sectoral (between hydropower generation and the remaining production sectors) and transboundary (between Portugal and Spain) competition for water.

1.4. Methodology

The objectives of this thesis are addressed with the adaptation and further specification of a commonly used methodology to assess the economic impacts of energy, environmental or climate policies – the so-called ‘E3 models’. These are a particular category of Integrated Assessment Models that gather the Energy-Environment-Economy relationships into a single basis. E3 models usually follow a top-down or a bottom-up approach, which differ, above all, on the assumptions regarding market behaviour and technological detail. To overcome their limitations, hybrid models, combining “the technological explicitness of bottom-up models with the economic comprehensiveness of top-down models” (Böhringer & Rutherford, 2008), are increasingly used.

Although top-down general equilibrium models have been widely used to assess the economy-wide impacts of economic instruments, such as taxes, these lack the detailed technological representation of the energy sector that an accurate assessment of energy and climate policies require. Specific objective 1 is addressed with a hybrid top-down/bottom-up general equilibrium model for the Portuguese economy to assess the economic and environmental impacts of complying with the energy efficiency targets, thereby specifically including the technological representation of the “Electricity” production sector that allows for the comprehensive analysis of the impacts of reductions in energy consumption such as those imposed by climate policies.

Although bottom-up technological models of the energy sector have been used to assess the sectoral economic impacts of climate change, inputs on projected water availability are usually not considered – a gap that is even more critical as the impacts of climate change on natural resources strongly depend on the climate region. Specific objective 2 is addressed with a bottom-up partial equilibrium model of the Portuguese energy sector to quantify the impacts of climate change on energy supply, with specific focus on the power sector and hydropower potential, as well as considering the reduction in water resources availability for hydropower generation resulting from climate change, in a Mediterranean context.

Finally, although E3 hybrid top-down/bottom-up models have been used to support energy and climate mitigation policy-making, they usually represent the interaction and feedbacks between the energy sector, the environment and the economy though disregard the inherent effects of natural resources availability (notably resulting from climate change). This thesis advances in the modelling of an E3 top-down/bottom-up hybrid general equilibrium model with the inclusion of raw water as a factor of production. The inclusion of natural resources is acknowledged as one of the necessary improvements for research on sustainability. As to water resources in particular, these play a crucial role within the economic analyses of climate change impacts – not only, because these are vital to life in all its dimensions, but also, because their availability is projected to be significantly affected by climate change. Accounting for the availability of water resources under climate change scenarios is a key element to address Specific objective 3 and to advance the understanding of the impacts of climate change on the real economy – the research question that motivated this thesis.

1.5. Thesis outline

The thesis is structured in two parts. The first part (Chapters 2 to 5) reviews the literature on the relevant topics for this thesis and presents the Portuguese case study. The second part (Chapters 6 to 8) addresses the three specific objectives of the thesis. Chapter 9, finally, provides the conclusions and discussion.

Chapter 2 provides a general framework of climate change impacts on water resources and the associated effects on hydropower generation. These impacts, alongside with the role of hydropower in the energy mix of a low carbon economy, are further discussed in the light of the 'water-energy' nexus. **Chapter 3** reviews existing projections of climate change impacts on hydrological variables and hydropower generation potential for Southern Europe, in general, and Portugal, in particular. **Chapter 4** provides an overview of the Portuguese energy sector, based on statistical information over the period 1990 to 2015. **Chapter 5** broadly describes the methodological approach adopted in the thesis. Different approaches of E3 models (top-down, bottom-up and hybrid) are briefly presented. The enrichment of the conventional E3 models with the inclusion of natural resources (in particular water) is also addressed.

Chapter 6 assesses the economic and environmental impacts of climate policies, specifically those of achieving the energy efficiency targets set in Portugal. To this end, a static hybrid Computable General Equilibrium (CGE) model for a small open economy, comprising 31 production sectors and a technological disaggregation of the electricity production sector, is used. Alternative scenarios simulate the economic, technological (power mix) and environmental (CO_2 emissions) impacts of different energy policies designed to attain the Portuguese energy efficiency targets by 2020.

Chapter 7 assesses the effects that a reduction in water endowments (resulting from climate change) will have on hydropower generation and, further, on the Portuguese electrical system, by 2050. A bottom-up model of the energy system (TIMES_PT) is used to simulate the impacts of alternative scenarios for changes in water availability, derived from the IPCC projections for the region by 2050.

Chapter 8 assesses the economic impacts from the simultaneous effects of climate-driven changes in the availability of and competition for scarcer water resources in Portugal by 2050, departing from the 'water-energy' nexus. To this end, the CGE model (from Chapter 6) is extended with the inclusion of raw water as a production factor and an integrated modelling approach through a soft link between the CGE and the TIMES_PT bottom-up model (presented in Chapter 7). Departing from a quantification of the 'water-energy' nexus via hydropower, different scenarios are developed to assess, using the hybrid CGE model, the economic impacts of reduced water availability arising from climate change, considering water competition between sectors and countries.

Finally, **Chapter 9** concludes with an overview of the research main results and their policy implications, an exposition of the research main limitations, and suggestions for future research.

CHAPTER 2

CLIMATE CHANGE IMPACTS ON WATER RESOURCES AND HYDROPOWER GENERATION

AND THE 'WATER-ENERGY' NEXUS

Climate change is currently recognized as one of the main threats to the natural world and global economy. The most evident effect of climate change is on air temperature. Available data have shown a warming of 0.85ºC between 1880 and 2012 as well as that each of the last three decades has been successively warmer than any preceding decade since 1850 (IPCC, 2013b). Global warming has been triggering changes in the natural and human environment, such as on the water cycle, weather patterns, acidification of oceans, crop productivity, energy technology efficiency and natural resources availability.

It is extremely likely (i.e. more than 95% certain) that the dominant cause of global warming since the mid-20th century is the accumulation of greenhouse gases (GHG) produced by human activities (IPCC, 2013). The energy sector is currently responsible for the major part of global greenhouse gas (GHG) emissions (IPCC, 2014d) and may, itself, have an important role in climate change mitigation, notably through improved efficiency and the widespread diffusion of renewable-sourced technologies. Furthermore, energy use is vital to human society, and a critical factor for economic development. For these reasons, the energy sector has received significant attention in climate change analyses.

Following the context and motivation of this thesis, this chapter focus on a particular dimension of climate change impacts – namely water resources – and on a specific component of the energy sector which is simultaneously recognised by its potential to mitigate climate change and its vulnerability to climate change impacts – namely hydropower generation. Section 2.1 broadly describes the climate change impacts on key hydrological variables. Section 2.2 presents the climate change impacts on hydropower generation. Section 2.3 describes the 'water-energy' nexus that frames the relationship between water resources and the energy sector, with particular emphasis on the role of hydropower.

2.1. Climate change impacts: hydrological variables

Climate change directly affects several hydrological variables, which interfere with the availability, timing and variability of demand and supply of water resources and, therefore, with numerous domains of life and economic activity. Climate change is expected to deepen water stress and this constitutes a growing challenge for policymaking concerning land use, energy planning and, more broadly, economic development. For these reasons, water resources are often considered in climate change impact assessment studies (e.g. (Ciscar et al., 2014; OECD, 2015)).

The most evident effect of climate change is on temperature, which will interfere with the hydrological cycle through changes in hydrological variables such as potential precipitation and evapotranspiration. The former is determinant for soil moisture, groundwater, and the amount and temporal distribution of runoff that is further influenced by factors such as streamflow diversion/regulation, seasonal changes in riverflows, and interactions between surface and groundwater. Other relevant impacts of climate change are the melting of glaciers and polar ice, sea level rise resulting from the thermal expansion of ocean waters, and the higher incidence of extreme weather events, such as droughts, heat waves and extreme rainfall leading to floods, as the hydrological cycle accelerates (Berga, 2016; Cunha, Oliveira, Nascimento, & Ribeiro, 2007; Falloon & Betts, 2010; Schneider, Laizé, Acreman, & Flörke, 2013).

Given its effects on hydrological variables, climate change is expected to impact, in particular, river flow regimes (García-Ruiz, López-Moreno, Vicente-Serrano, Lasanta–Martínez, & Beguería, 2011; Schneider et al., 2013). Altered precipitation regimes influence the water quantity reaching the soil and, hence, runoff generation and the magnitude of river discharge[1]. The relationship between changes in precipitation and runoff is not one-to-one – (Arnell, 2004) shows that the reduction in runoff can be 2 to 4 times larger than the reduction in precipitation and (Turral, Svendsen, & Faures, 2010) estimate that a 20% reduction in precipitation may lead to a 50% reduction in runoff. Finally, river discharge is influenced by snowmelt and snow accumulation – particularly important in mountain basins. On the one hand, snowmelt occurs earlier and more rapidly in the year. On the other hand, with increased temperatures, less snow is accumulated in the headwaters and less rain falls as snow in winter. Such impacts significantly alter river regimes and streamflow characteristics through greater and more irregular runoff in winter, higher runoff in earlier spring, lower summer flows, and anticipated exhaustion of headwater reservoirs (Erol & Randhir, 2012; López-Moreno, Beniston, & García-Ruiz, 2008; Schneider et al., 2013).

Besides the hydrological effects, climate change also interferes with biophysical parameters that, ultimately, affect water resources. Increased temperatures reduce the moisture content of soils and intensify transpiration processes in plants, and evaporation

[1] “River discharge is a function of meteorological runoff (precipitation minus evaporation) and drainage basin area” (Milliman, 2001: p.754).

from soil and water bodies. Such changes in evapotranspiration resulting from changes in temperature also influence runoff – (Nash & Gleick, 1993) show that an increase of 2°C to 4°C in average temperature could result in a decrease of 4% to 21% in streamflow, even if precipitation remains stable. Hence, these changes cause river regime disturbances, concerning not only the quantity and quality of water resources, but also, their temporal distribution.

The effects of climate change on water resources are, undoubtedly, multiple, complex and interlinked. Therefore, their accurate evaluation requires going beyond temperature and precipitation by assessing, in particular, associated changes in runoff as this is the most representative component of the hydrological cycle to describe freshwater availability (Cunha et al., 2007; Papadimitriou, Koutroulis, Grillakis, & Tsanis, 2016).

2.2. Climate change impacts: hydropower generation

The energy sector may have an important role in mitigating climate change impacts, as it can actively contribute to reduce GHG emissions through improved efficiency and renewable energy technologies. Hydropower plays a key role, due to two main reasons: first, hydropower produces around 100 times less GHG emissions than thermal power plants (Berga, 2016); second, it is the most widely exploited form of renewable energy generation, accounting, in 2016, for 17% of worldwide electricity and for 71% of renewable generation (IEA, 2017; WEC, 2016). However, considering that hydropower generation is highly dependent on river discharge and seasonal distribution patterns (Rübbelke & Vögele, 2012) that are determined by the amount and regularity of rainfall (Costa, Santos, & Pinto, 2012; Schaefli, 2015), hydropower will probably be one of the renewable energy sources to be most affected by climate change given the expected increased variability in precipitation and associated changes in water availability.

Climate change impacts on hydropower generation can be grouped into two categories: i) direct climate-induced impacts that influence hydro-meteorological variables and, hence, directly affect the availability of water for hydropower generation, and ii) indirect impacts, such as increased competition for water resources, which are a result of the amplified scarcity of the natural resource and lead to changes in social and economic activities that, in turn, may increase water stress (APA, 2013; Mukheibir, 2013).

Direct impacts of climate change on hydropower generation

The main mechanisms through which climate change can directly affect hydropower generation are: changes in precipitation, changes in river flows, changes in evaporation, melting of freshwater glaciers and dam safety (Chandramowli & Felder, 2014; Mideksa & Kallbekken, 2010). The first two, if positive, could strengthen the potential for hydropower generation. In addition, climate change impacts on hydropower generation will vary according to the infrastructure type: i) hydropower plants with storage capacity are less vulnerable to short-term variations than run-of-river power plants (Lehner, Czisch, & Vassolo, 2005); ii) deep dams with smaller surface areas will likely be less affected by climate change impacts (namely higher temperatures and resulting increased evaporation) than those with large surface areas (Mukheibir, 2013); and iii) reservoirs allow for a better management of flashflow events and river flow variability (Gaudard & Romerio, 2014). Therefore, climate change impacts (namely reduced precipitation and runoff; average or seasonal) will be distinct for storage and run-of-river hydropower plants. Whereas in the former it may be possible to manage storage and maintain the normal generation of electricity during the dry period (thus allowing for the matching between power supply and demand), in the latter it may not because these depend on the designed river flow to maintain their electricity output and because they are sensitive to short-term changes in runoff (Mukheibir, 2013; Schaefli, 2015).

Hydropower plant locations and sectoral policies have always been designed under the assumption that hydrology and climate would remain relatively stable over time (Ebinger & Vergara, 2011; García-Ruiz et al., 2011). Nonetheless, climate variability is already interfering with the planning and operation of hydropower systems. Hence, climate change will not only affect the operation of existing hydropower plants, but also, compromise the viability of new investments (Ebinger & Vergara, 2011). Climate change may, thus, accentuate the existing uncertainty in the operation of hydropower systems (Schaeffer et al., 2012).

Indirect impacts of climate change on hydropower generation

Regarding the indirect impacts of climate change, two different types of competition for water resources should be considered. On the one hand, competition among economic sectors; on the other hand, competition between countries sharing common river basins that deepen the conflicts over the alternative uses of water (APA, 2013; WWAP, 2014).

Competition for water resources between economic sectors is expected to increase with climate change, as reduced runoff and increased sectoral water use (namely irrigation/agriculture, industry and domestic consumption) will reduce water availability for hydropower generation. Therefore, increased sectoral competition for water resources in a situation of water stress will likely become more frequent and intense. As shown by (Pereira-Cardenal et al., 2014; Valverde et al., 2015), lower inflows and higher irrigation demands will lead to an increase in water values – thus increasing the price and reducing hydropower generation. Water allocation among sectors is, thus, an important issue in the context of climate change.

Competition for water resources between countries is expected to increase with climate change, and will exacerbate the existing complexity of transboundary water management. Any change in water availability or use in the upstream country affects the availability and quality of water resources in the downstream country. Thus, in a climate change scenario, if the upstream country increases its water withdrawals, the downstream country will face reduced water availability that will negatively affect water dependent-economic sectors such as hydropower generation and agriculture (Flörke, Wimmer, et al., 2011). Climate change is, thus, expected to pose additional challenges in the relations between countries regarding the fulfilment of the transnational treaties regulating the water use and exploitation of transboundary river basins (Zeitoun, Goulden, & Tickner, 2013).

2.3. The ‘water-energy’ nexus and the role of hydropower generation

Climate change impacts on water resources availability are, thus, expected to exacerbate the existing competition among countries (sharing common river basins) and sectors (economic activities and households; (IEA, 2016; WWAP, 2014)). In particular the bi-directional link between water resources and the energy sector is of major importance. On the one hand, water resources are essential in all phases of energy production processes, notably in the extraction and mining of fossil fuels, irrigation of biofuel crops, cooling of thermal plants and, finally, hydropower generation. On the other hand, energy is indispensable to water provisioning services, from extraction and pumping to distribution and treatment (Brouwer et al., 2017; IEA, 2016; Khan, Linares, & García-González, 2017). Water resources and the energy sector are thus closely interlinked and any management or political decision concerning the allocation of water will have broader, economy-wide, impacts. Such interlinkages and resulting externalities are the cornerstone of the so-called ‘water-energy’ nexus (WWAP, 2014).

The interdependency between water resources and the energy sector is particularly acute for hydropower generation, which is the largest water-using technology within the power generation sector (WWAP, 2014). This may be explained by two main reasons. First, the uncertainties associated with the impacts of climate change on the hydrological cycle, water availability and energy production have already evidenced the conflicts between distinct and concurrent uses for scarce water resources (Khan et al., 2017; WWAP, 2014). Second, following trends in favour of a low carbon economy, energy mixes are rapidly shifting from fossil to renewable energies that need to be backed-up – with hydropower considered the most feasible and cost-effective option for the management of intermittent renewable energy sources in the grid (IRENA, 2012; REN21, 2011; Schaefli, 2015; WWAP, 2014).

The critical role of hydropower in the ‘water-energy’ nexus is further strenghtened by the stage of hydropower development. Hydropower has developed significantly over the last decade (+38% between 2004 and 2013; (REN21, 2014)) and is expected to maintain a vital role in many countries’ energy mix (IEA, 2015). It is, therefore, envisaged as one of the most auspicious technologies to increase renewable electricity generation (Berga, 2016). Morevoer, according to (IPCC, 2007b) 85% of unexploited hydroelectric potential from OECD countries can reduce CO_2 emissions at a negative marginal abatement cost.

The stage of hydropower development is very much owed to its comparative advantages relative to alternative power generation technologies (IRENA, 2012). Hydropower is considered the cheapest, most mature, reliable and cost-effective renewable power generation technology currently available (Berga, 2016; IEA, 2011). It is capital-intensive but operating costs are low and the lifespan is long (Berga, 2016; REN21, 2011). Hydropower plants can start-up rapidly and operate in an efficient way almost immediately – in contrast with thermal plants where start-up periods are longer. Hence, it is considered the most flexible source of power generation as it can satisfy demand fluctuations in minutes (IRENA, 2012). Finally, hydropower is one of the most efficient technologies at producing and storing electricity, performing clearly better than alternative technologies in energy storage to meet system peaks, for periods that range from days to years, depending on the size of the reservoir (Gaudard & Romerio, 2014; IEA, 2011; IPCC, 2011).

From an environmental perspective, GHG emissions from hydropower generation come mainly from construction and silting of reservoirs. Overall, as compared to other power generation technologies, hydropower performs quite well environmentally (Berga, 2016; Gaudard & Romerio, 2014). The most important environmental impacts associated with hydropower generation relate to modifications in river flows, water quality deterioration, changes in biodiversity and population displacement (IRENA, 2012; Santos & Miranda, 2006; Schaefli, 2015; Scherer & Pfister, 2016). Hydropower advantages, in terms of costs, storage capacity, energy security and environmental impacts, thus cover different and important issues that need to be considered in the design of any energy system as well as in the scope of climate and energy policies pursuing sustainability. Hydropower appears, therefore, to become increasingly important in the future (Gaudard & Romerio, 2014; Lehner et al., 2005; Zarfl, Lumsdon, Berlekamp, Tydecks, & Tockner, 2014).

Nevertheless, different factors may affect the comparative advantage of hydropower relative to alternative energy technologies (Gaudard & Romerio, 2014). On the one hand, the role of hydropower may be strengthened due to the increasing share of intermittent energy sources, such as wind or solar energy (Berga, 2016; Schaefli, 2015; Scherer & Pfister, 2016). Given its flexibility and storage capacity, hydropower provides the necessary backup to balance demand and supply – thus optimising the use of variable renewable energy sources in the electrical system, assuring security of supply and establishing itself as a solution for the challenges of a power system in transition (Eurelectric, 2015). On the other hand, its role may be impaired due to the development of new storage technologies as well by climate change impacts on water resources availability.

Concerning water resources consumption, hydropower generation is one of the greatest water users while final water consumption is relatively low (mainly through evaporation). The water used to drive turbines is returned to the river system, either near the dam or further downstream. Moreover, hydropower systems provide other services than energy generation, namely: i) water storage for irrigation, industry and domestic consumption; ii) improved conditions for navigation, fishing, tourism and leisure activities; and iii) minimization of the effects from natural variability of precipitation and floods through river flow control (IPCC, 2011; IRENA, 2012; Santos & Miranda, 2006; Tapiador et al., 2011).

Finally, it must be noted that the 'water-energy' nexus is mostly approached from a technological perspective (Hamiche, Stambouli, & Flazi, 2016), and the majority of studies only highlight the linkages, problems, risks and opportunities in water and energy resources management (Dai et al., 2018). Nonetheless, the likely climate change impacts on water resources availability, as well as their implications for the energy sector and the wider economy, evidences the relevance of approaching the ‘water-energy’ nexus from an economic perspective and, thus, extending the analysis to the ‘water-energy-economy’ nexus.

CHAPTER 3

PROJECTED CLIMATE CHANGE IMPACTS IN SOUTHERN EUROPE AND PORTUGAL: WATER RESOURCES AND HYDROPOWER GENERATION

Portugal, the case study of this thesis, belongs to a climate region that embraces the whole Southern European region (Köppen-Geiger classification; (Kottek, Grieser, Beck, Rudolf, & Rubel, 2006)). Following a brief overview of the climate change scenarios from which climate change projections are derived (Section 3.1), this chapter reviews available projections of climate change impacts on water resources (Section 3.2) and hydropower generation (Section 3.3) for Southern Europe, in general, and Portugal, in particular.

3.1. Climate change scenarios: equating plausible futures

Climate change scenarios are obtained from global and regional circulation models and emissions scenarios. At present, the climate change scenarios most commonly used in literature are those from the Intergovernmental Panel on Climate Change (IPCC) – namely those developed for the Special Report on Emissions Scenarios (SRES; (IPCC, 2000)) and that update the IS92 scenario series (Leggett et al., 1992; Pepper et al., 1992). More recently, the Representative Concentration Pathways (RCP; (van Vuuren, Edmonds, et al., 2011)) were developed for the IPCC 5th assessment report (IPCC, 2014c). This section summarizes the SRES and RCP scenarios.

3.1.1. Special Report on Emissions Scenarios (SRES)

The SRES encompasses four alternative families of scenarios (A1, A2, B1 and B2), which led to the formulation of 40 different scenarios (IPCC, 2000). These four storylines describe possible future developments concerning economic growth, demography, technological change, environmental protection, governance and behavioural patterns (excluding any climate policy). While the A1 and B1 storylines put emphasis on economic global convergence and social and cultural interactions, the A2 and B2 storylines are regionally-oriented and describe diverse development pathways (see Table 3.1).

Table 3.1. SRES storylines overview and main characteristics

Family	A1*				A2	B1	B2
Scenario Group / Variable	A1C	A1G	A1B	A1T	A2	B1	B2
Population growth	Low	Low	Low	Low	High	Low	Medium
GDP growth	Very high	Very high	Very high	Very high	Medium	High	Medium
Energy use	Very high	Very high	Very high	High	High	Low	Medium
Land-use changes	Low/medium	Low/medium	Low	Low	Medium/high	High	Medium
Resource availability of oil and gas	High	High	Medium	Medium	Low	Low	Medium
Pace and direction of technological progress	Rapid	Rapid	Rapid	Rapid	Slow	Medium	Medium
Change favouring	Coal	Oil & gas	Balanced	Non-fossils	Regional	Efficiency & dematerialization	"Dynamics as usual"

Source: (IPCC, 2000)
Note: * This scenario family develops into four groups describing alternative directions of technological change in the energy system: coal, oil and gas, balanced and non-fossils

The A1 storyline and scenario family describe a future world with a low population growth rate and very rapid economic growth, where regional average income per capita converge. Economic convergence derives, in particular, from technological progress and international cooperation. Energy and mineral resources are abundant, technical progress increases their productivity and final energy intensity decreases. Four alternative directions reflect the uncertainty in the development of energy sources and conversion technologies: i) evolution along a carbon-intensive (coal-based) energy path; ii) evolution with increasing dependence on oil and gas; iii) evolution towards a balanced technological and supply sources mix; and iv) transition to renewable energy sources and nuclear energy (IPCC, 2000).

The A2 storyline and scenario family describe a very heterogeneous world in which different economic regions coexist. Population growth is high, global economic growth is uneven, the income gap between industrialized and developing regions remains and, thus, average per capita income is low. International cooperation is weak and technological change is differentiated between regions. Energy intensity declines but global environmental concerns are relatively poor (IPCC, 2000).

The B1 storyline and scenario family describe a fast-changing and convergent world where population growth is low, mainly due to social and environmental concerns. Economic development is balanced worldwide and gains are invested in resource efficiency improvement ("dematerialization"). Technological change and diffusion play an important role. The transition from conventional to alternative energy sources is smooth and accommodates the introduction of clean and resource-efficient technologies. Thus, environmental quality is high (IPCC, 2000).

Finally, the B2 storyline and scenario family describe a world in which emphasis is put on local and regional solutions to economic, social and environmental development. Population growth is moderate. Income per capita also grows moderately and both local and global inequities decrease. Energy systems differ among regions due to natural resources endowments, which leads to heterogeneous technological change – growing regions poor in natural resources invest more in technology and innovation than regions rich in natural resources. At the global scale, energy intensity declines (IPCC, 2000).

3.1.2. Representative Concentration Pathways (RCP)

The RCP are internally consistent sets of projections of the components of radiative forcing[2] (emissions, concentrations, land use and land cover) compared to pre-industrial levels. The RCP are derived from Integrated Assessment Models and represent the emissions scenarios available in literature – covering the whole range of associated forcing levels. Accordingly, four RCP were produced, leading to radiative forcing levels of 8.5, 6, 4.5 and 2.6 Watts per square meter (W/m^2) by 2100 (see Table 3.2). Note that the various RCP do not constitute a set with its own internal logic – i.e. there is no consistency between RCP relative to each other, as each RCP relies on its own set of emissions scenarios and corresponding socio-economic, biophysical and technological assumptions. Therefore, differences among them must not be read as a result of a specific climate policy or socio-economic pathway (van Vuuren, Edmonds, et al., 2011).

[2] Radiative forcing “is the net change in the energy balance of the Earth system due to some imposed perturbation. It is usually expressed in watts per square meter averaged over a particular period of time and quantifies the energy imbalance that occurs when the imposed change takes place” (Myhre et al., 2013: p.664). This concept is used to evaluate and compare the strength of the various mechanisms – natural and anthropogenic – affecting the Earth’s radiation balance and, thus, leading to climate change. Radiative forcing is dominated by the long-lived GHGs and is used to compare warming or cooling influences on global climate. The IPCC considers only those whose emissions are covered by the UNFCCC: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6).

Table 3.2. RCP scenario overview and main characteristics

RCP	Description	Scenario component			Integrated Assessment Model
		GHG emissions	Agricultural area	Air pollution	
RCP8.5	Rising radiative forcing pathway leading to 8.5 W/m^2 in 2100.	High baseline	Medium for cropland and pasture	Medium-high	MESSAGE
RCP6	Stabilization without overshoot pathway to 6 W/m^2 at stabilization after 2100	Medium baseline; high mitigation	Medium for cropland but very low for pasture (total low)	Medium	AIM
RCP4.5	Stabilization without overshoot pathway to 4.5 W/m^2 at stabilization after 2100	Medium-low mitigation	Very low for cropland and pasture	Medium	GCAM
RCP2.6	Peak in radiative forcing at ~ 3 W/m^2 before 2100 and decline	Very low	Medium for cropland and pasture	Medium-low	IMAGE

Source: (van Vuuren, Edmonds, et al., 2011)

In the RCP8.5, greenhouse gas (GHG) emissions increase over time. It is a baseline scenario that does not consider any specific climate mitigation target. The RCP8.5 is based on the SRES A2r scenario, which describes a heterogeneous world where population is continuously increasing, while per capita income growth and the rate of technological change are low. The combination of high population growth, inherent high energy demand and a fossil-fuel based energy system, generate high and increasing levels of GHG emissions and concentrations over time – leading to the highest radiative forcing among the RCP by 2100 (Riahi, Grübler, & Nakicenovic, 2007; Riahi et al., 2011).

The RCP6, RCP4.5 and RCP2.6 are climate policy scenarios, meaning that if climate policies to reduce GHG emissions were not considered, then radiative forcing would exceed the target by 2100. Both the RCP6 and RCP4.5 are stabilization scenarios in which total radiative forcing is stabilized shortly after 2100, without overshooting the target level. In the RCP6, the socio-economic reference scenario is an updated version of the SRES B2 scenario with respect to demographic and economic parameters (Masui et al., 2011). Stabilization is achieved through the implementation of technologies and strategies to reduce GHG emissions (Hijioka, Kainuma, Masui, Matsuoka, & Nishimoto, 2008). The RCP4.5 is derived from its no-climate-policy scenario, which encompasses population growth until the mid-century and a decline by 2100, a growth in gross domestic product (GDP), increased primary energy consumption, and the predominance of fossil-fuels despite the proliferation of renewable and nuclear energy. In the RCP4.5 stabilization results from a climate policy based on global GHG prices (Thomson et al., 2011). The RCP2.6 corresponds to the aim of limiting global mean temperature increase to 2°C. It is a 'peak-and-decline' scenario, as radiative forcing level reaches around 3.1 W/m^2 by mid-century and returns to 2.6W/m^2 by 2100. It is based on the SRES B2 scenario, which represents a medium development scenario for population, income, energy use and land use. The radiative forcing target is achieved through a significant reduction in GHG emissions over time, which is due to improved energy efficiency, increased use of renewables and nuclear power, expansion of bioenergy, and carbon capture and storage (van Vuuren, Stehfest, et al., 2011).

3.2. Projected climate change impacts

Based on the SRES and RCP scenarios, projections from the IPCC show that climate change is increasing the existing vulnerability associated with the present use of water resources and augmenting the uncertainties concerning water quantity and quality over the coming decades (IPCC, 2013b). Expected changes in precipitation and temperature will lead to changes in runoff and water availability. Regions prone to droughts are anticipated to become larger. In regions where precipitation is expected to decrease, extreme rainfall events may increase and flooding risks intensify.

These large-scale climate change projections do not reduce, however, the usefulness of regional and local analyses of climate change impacts, as change signals and magnitudes may differ considerably from the large-scale means (Christensen, Carter, Rummukainen, & Amanatidis, 2007; Jacobeit, Hertig, Seubert, & Lutz, 2014). Given this likely discrepancy, several studies concerning specific regions – ranging from world regions to local watersheds – have been carried out. This section reviews the literature analysing the likely climate change impacts in Southern Europe and Portugal. The climate projections presented are, almost all, based on the IPCC SRES scenarios, while limiting the analysis to ranges of variation to come-up with clear tendencies.

Southern European countries will be among the most affected by climate change, and most vulnerable to water scarcity – even in a low water demand scenario it is expected that more than 60% of the area in Southern Europe will suffer severe water stress in summer by 2050 (Flörke, Wimmer, et al., 2011). Whereas forecasts for Northern and Central Europe comprise an increased risk of inland flash floods, coastal flooding and reduced snow cover in mountain areas, projections for Southern Europe point towards a significant warming in summer and a decrease in rainfall already by 2030 (IPCC, 2007b).

Hence, resulting droughts and inherent water shortages are considered the major threats of climate change in Southern Europe (Ciscar et al., 2014).

In Portugal, climate conditions are influenced by those that generally describe Southern Europe and the Mediterranean basin, i.e. by Mediterranean climate conditions, according to the Köppen-Geiger classification (see (Kottek et al., 2006)). Thus, Portugal is considered a hot-spot region where temperature is expected to increase, precipitation is expected to decrease, and, hence, runoff is projected to decrease (Cunha et al., 2007; Giorgi, 2006; Pulquério, Garrett, Santos, & Cruz, 2014). These effects are anticipated to increase from the Northern region, with Atlantic influence, towards the South, with Mediterranean characteristics (APA, 2013).

Temperature

Temperature projections for Southern Europe consensually forecast warmer conditions. (Schneider et al., 2013) simulations point towards a 2.3°C increase by 2050, and (Jacob et al., 2014) report a 1°C to 4.5°C increase for a moderate and a 2.5°C to 5.5°C for a severe climate scenario by 2100. The latter is in accordance with the comprehensive analysis drawn up in the PESETA project (Ciscar et al., 2014)[3], which points towards an increase of 2.3°C to 3.7°C in Southern Europe for the period 2071-2100 – coherent with the average projected for Europe (+2.4°C to +3.9°C). These annual average values comprise a degree of seasonal heterogeneity, as projections for winter suggest an increase of between 1.7°C and 3.3°C while projections for summer encompass an increase of between 2.6°C and 4.2°C. Compared to the European average, temperature increases in Southern Europe will be smaller in winter but larger in summer (for Europe, projections range between +2.7°C and +4.0°C in winter and between +2.2°C and + 4.2°C in summer). For a global warming of +2°C relative to pre-industrial climate, (Vautard et al., 2014) also projected stronger increases in summer temperatures for Southern Europe than for Europe (+2°C to +3°C against +1.7°C, respectively), with the Iberian Peninsula recording one of the largest increases. These projections are in line with broader analyses for the Mediterranean basin (Southern Europe included), notably those from (IPCC, 2013b) that forecast increases in temperatures ranging between 1°C and 4°C in winter up to 6°C in summer by 2100, and from (Erol & Randhir, 2012) that project temperature increase of 3.5°C to 4.3°C by 2100. All these projections thus substantiate

[3] The PESETA project used climate simulations forced by two IPCC scenarios (A1B and RCP 8.5) and one ENSEMBLES scenario (E1) (see https://ec.europa.eu/jrc/en/peseta-ii).

(Giannakopoulos et al., 2009), that argue the Mediterranean basin will face 2°C warming over the period 2031-2060.

Temperature projections for Portugal are based on the HadCM3 and HadRM2 climate models[4] (Cunha et al., 2007), and indicate an increase in annual mean temperatures of between 2.0°C and 3.0°C by 2050, and of between 3.5°C and 5.0°C by 2100 – particularly in summer (between +3.0°C and +5.0°C by 2050, and between +5.0°C and +7.0°C by 2100 (Santos, Forbes, & Moita, 2002)). Spatial asymmetries are expected, translated in larger increases in the Central and Southern regions than in the Northern region. Likewise, estimates produced in the context of the PRUDENCE project[5] foresee an annual increase of 1.3°C in surface air temperature per degree of global warming. Seasonal differences are also identified: +1.2°C in spring, +1.7°C in summer, +1.3°C in autumn and +1.0°C in winter by 2100 (Christensen, 2005).

Precipitation

Precipitation projections for Southern Europe foresee reductions in annual precipitation by the mid-end 21th century, though ranges of decrease vary. Some projections point towards a reduction of between 4% and 8% (Erol & Randhir, 2012), while others foresee a stronger decrease of 10% to 20% (Ciscar et al., 2014; García-Ruiz et al., 2011; Giannakopoulos et al., 2009). (Schneider et al., 2013; Vautard et al., 2014) seasonal projections are coherent with these results: a 10% to 25% reduction in summer precipitation and a 15% decrease in winter precipitation. By contrast, (Ciscar et al., 2014) projections point towards divergent seasonal patterns for Southern Europe: whereas summer precipitation is also projected to decrease (by 18.7% to 34.9%, against an average decrease of 6.3% to 12.8% in Europe for three out of four scenarios), winter precipitation is expected to increase (by 1% to 4.2%, against an average increase of 1.6% and 14.1% in Europe for three out of four scenarios). The increase in winter precipitation in Southern Europe is also projected by other authors, such as (Jacobeit et al., 2014) and (Erol & Randhir, 2012), who project a 1% to 4% increase in winter season annual precipitation per decade. Differently, some projections only point towards wetter winters in the northwest of the Iberian Peninsula (García-Ruiz et al., 2011). Precipitation changes in the intermediate seasons seem to be less pronounced than in winter and summer

[4] HadCM3 - Hadley Centre Coupled Model and HadRM2 - Hadley Centre Regional Model are produced by the Hadley Centre for Climate Prediction and Research. The former is a Global Circulation Model and the latter a Regional Circulation Model.

[5] PRUDENCE - Prediction of regional scenarios and uncertainties for defining European climate change risks and effects (http://prudence.dmi.dk/)

(García-Ruiz et al., 2011). Extreme precipitation events are also expected to increase in Southern Europe, both in magnitude and frequency, especially in winter and summer (Ban, Schmidli, & Schär, 2015; IPCC, 2013b; López-Moreno et al., 2013; Paxian et al., 2015; Santos, Corte-Real, Ulbrich, & Palutikof, 2007; Scoccimarro, Gualdi, Bellucci, Zampieri, & Navarra, 2016).

Precipitation projections for the Iberian Peninsula point to among the most negative impacts in Europe (Koutroulis et al., 2018), with precipitation decreasing for any temperature increase scenario. This is line with (Jacob et al., 2014) projections of a 25% reduction in summer precipitation in the Iberian territory under a severe climate scenario, by 2100.

Precipitation projections for Portugal foresee an overall decrease by 2050 and 2100, and reinforce the aforementioned spatial and seasonal variability. At the regional level, simulations foresee wide ranges of changes[6]. In particular for 2050, projections point towards a 10% increase in winter precipitation in the North, along with an up to 30% reduction in summer precipitation in the North and the South. As for 2100, winter precipitation is projected to increase by 30% to 45%, whereas summer precipitation may decrease by 50% to 75% (Santos et al., 2002). The projected seasonal variability is in accordance with different authors that highlight a decreasing trend in precipitation in the Iberian Peninsula (de Melo-Gonçalves, Rocha, & Santos, 2016; López-Moreno, Vicente-Serrano, Angulo-Martínez, Beguería, & Kenawy, 2010; Rasilla, Garmendia, & García-Codron, 2013; Rodrigo & Trigo, 2007) – with largest decreases occurring in summer and spring. Likewise, the PRUDENCE project (Christensen, 2005) foresees an annual decrease of -6.1% in precipitation per degree of global warming – resulting from a generalized declining trend in all seasons except winter (+1.5% in winter against -11.6% in spring, -19% in summer and -9.2% in autumn by 2100). At the regional level, (Guerreiro, Kilsby, & Fowler, 2016) projections for changes in annual precipitation by 2100 encompass: -33% to +7% for the Douro river basin (North), -34% to +10% for the Tagus river basin (Centre) and -41% to +10% for the Guadiana river basin (South).

[6] The main source of projections for precipitation and runoff in Portugal is SIAM project results' (Santos et al., 2002; Santos & Miranda, 2006).

Droughts

Due to the intensification of the existing intra- and inter-annual variability of precipitation and temperature in Southern Europe (Fayad et al., 2017; Ozturk, Ceber, Türkeş, & Kurnaz, 2015), an increase in the length of the dry season is foreseen (Dubrovský et al., 2014; Hertig & Tramblay, 2017; Michaelides et al., 2017). As a consequence, heat waves may become more frequent, additional dry days are expected and consecutive drought years are likely to increase (EEA, 2017a; Lehner, Döll, Alcamo, Henrichs, & Kaspar, 2006; Lehner et al., 2017; Orlowsky & Seneviratne, 2012; Pascale, Lucarini, Feng, Porporato, & ul Hasson, 2016; Prudhomme et al., 2014; Santos et al., 2002). Southern Europe's drought risk has increased considerably over the 20th century due to the higher temperatures (Ciscar et al., 2014; Gudmundsson & Seneviratne, 2016) – in particular, (Flörke, Wimmer, et al., 2011) simulations point out that by 2050 the region will face a 50-year drought of today's magnitude more than once per decade. This is in accordance with (Roudier et al., 2016), who assessed the effects of +2ºC global warming on hydrological extremes (floods and droughts) to conclude that Southern European countries will experience an increase in the intensity and duration of droughts.

For the Iberian Peninsula, (Koutroulis et al., 2018) project a 5% to 25% increase in drought periods and duration. Besides these trends, increases in the severity and frequency of both moderate and severe droughts are also projected (Stagge, Rizzi, Tallaksen, & Stahl, 2015).

Runoff and river discharge

As most studies forecast lower precipitation, higher temperatures and higher evapotranspiration rates for Southern Europe, runoff rates and riverflows are expected to decrease by the end of the 21st century. Hydrological changes triggered by climate change encompass a considerable decrease in average annual runoff (Arnell & Gosling, 2013; IPCC, 2013b; Koutroulis et al., 2018), ranging between 0% and 23% by 2020 (Falloon & Betts, 2010), between 10% and 30%-50% by 2050 (Arnell, 1999; Gosling & Arnell, 2016; Milly, Dunne, & Vecchia, 2005), and between 20% and 50% by 2100 (Hagemann et al., 2013). River flows will be remarkably modified and increasingly intermittent by 2050, with Southern Europe being the most affected region in Europe. River discharge will be lower during the whole year (this trend is already observed in many rivers since the 1980s), and both the maximum and the minimum flow magnitude will be considerably affected; summer flows will be increasingly lower, and winter discharges will be more irregular (García-Ruiz et al., 2011; Schneider et al., 2013). Minimum flows may reduce by 10% to 20% by 2020 and by up to 40% by 2080, notably in the Iberian Peninsula (Forzieri et al., 2014), and streamflow droughts may become more severe and persistent (Ciscar et al., 2014; Papadimitriou et al., 2016).

In Portugal, the runoff regime is strongly influenced by seasonal and spatial variability of precipitation. Although the increased potential evapotranspiration and reduced precipitation are expected to decrease annual water availability, the main constraint to water management are their seasonal changes (Santos et al, 2002). Projected impacts show an increasing seasonal asymmetry and a generalized decrease in runoff (Cunha et al., 2007; Santos et al., 2002; Santos & Miranda, 2006)). At the territorial level, runoff is highly variable across regions as the wet northern coastal river basins contrast with the dry inland southern basins (Santos et al., 2002). Annual runoff, by 2050, is projected to decrease in all seasons, and by up to 10% in the North and 50% in the South (see Section 7.2.1.; Table 7.1). By 2100, expected reductions (also projected by (Almeida et al., 2015)) intensify in the North and in the South while noting that the projections' signs are contradictory between models (Santos et al., 2002). Also, (Almeida et al., 2015) project a 23% reduction in runoff by 2100, under an extreme climate scenario.

These results are coherent with other studies focusing on specific Portuguese river basins. Considering severe climate change scenarios by 2100 (Papadimitriou et al., 2016) project a 35% reduction in average runoff for the Guadiana river basin, while (Mourato, Moreira, & Corte-Real, 2014) projections for the Cobres basin (South) point towards annual variations ranging between -35% and -80%, with autumn and spring recording the strongest reductions (between -61% and -96%, and between -40% and -99%, respectively). (Nunes, Seixas, & Pacheco, 2008) compared the Ribatejo (Centre/South) and Alentejo (South) basins to conclude that surface runoff will decrease by, respectively, 76% and 62% under a 40% reduction in precipitation.

As to river discharges, (Guerreiro, Birkinshaw, Kilsby, Fowler, & Lewis, 2017) project an overall decrease for the international basins of the Douro, Tagus and Guadiana rivers by 2045-2070, despite significant regional and seasonal variability. At the regional level, projections encompass a -52% to +25% change in mean annual discharge in the Douro river, a -60% to +32% change for the Tagus and a -82% to +68% change for the Guadiana. At the seasonal level, the largest changes are projected for autumn (exceeding -60% for the Douro, -70% for the Tagus, and -90% for the Guadiana), closely followed by spring. Also focusing on the Tagus river basin, (Lobanova, Koch, Liersch, Hattermann, &

Krysanova, 2016) project a 30% to 60% reduction in river discharge by 2100, under a moderate and severe emission scenario, respectively.

It can be concluded that the scale of climate change impacts on runoff/river discharge increase from North to South and that the magnitude of projected decreases are larger than projected increases (Santos & Miranda, 2006). In addition, considering that the larger Portuguese river basins are transboundary, climate conditions in Spain are also determinant for the Portuguese hydrological regime. Expected climate changes are similar to those for Portugal and, hence, reduced runoff from the Spanish sub-basins implies that the reductions in water availability in the Portuguese sub-basins may be amplified. In addition to decreased runoff, the likely retention of water in the Spanish part of the river basins will deepen the negative change in water availability across the Portuguese sub-basins (APA, 2013; Cunha et al., 2007).

3.3. Projected climate change impacts on hydropower generation

Numerous authors have shown that small changes in water inputs can induce major alterations in reservoir functioning. According to (CCSP, 2007), the sensitivity of hydropower generation to changes in precipitation and river discharge is greater than unity. (Nash & Gleick, 1993) states that a 20% reduction in runoff may induce a 60%-70% decrease in annual water storage and a 60% reduction in power generation. (Kao et al., 2015) show that there is a strong linear relationship between annual hydropower generation and annual runoff, such that runoff explains 66% to 98% of the variation in annual hydropower generation for 16 out of 18 study areas in the United States of America. Finally, (Simões & Barros, 2007) concluded that the reduction in hydropower reservoir water levels in Brazil, which led to the energy crisis in the beginning of the 21st century, was caused by seasonal changes in precipitation and higher temperatures over the previous two decades, rather than by changes in the frequency and intensity of precipitation and extreme events.

The most commonly used methodology to assess climate change impacts on hydropower resource endowments consists in translating long-term climate variables into runoff (Ebinger & Vergara, 2011; Schaeffer et al., 2012). The likely impacts of climate change on runoff are evaluated by hydrological models that use precipitation and temperature projections from General Circulation Models or hypothetical scenarios. In turn, the impacts of climate change on hydropower generation are assessed by introducing simulated river flows in electric power models (Schaeffer et al., 2012). Climate change effects determine seasonal and regional conditions for hydropower generation, given that some regions will be negatively affected in summer and positively in winter production (Flörke, Wimmer, et al., 2011). Technological aspects also condition the potential for hydropower generation. In this regard, (Flörke, Wimmer, et al., 2011) estimate a loss in hydropower potential for run-of-river power plants in Western and Southern Europe as well as storage plants in Southern Europe, due to the likely reduced water availability resulting from decreased precipitation.

One of the reference studies on the climate change impacts on European hydropower sector is the (Lehner et al., 2005) assessment for the 2070 horizon. The expected decrease in hydropower gross potential[7] ranges between 3.3% and 5.6%, while strong regional asymmetries are foreseen – from a reduction of 20% to 50% in Mediterranean countries to an increase of more than 30% in Northern Europe. These results are coherent with (van Vliet, Vögele, & Rübbelke, 2013), who estimate that the reduction in hydropower gross potential in Southern Europe (France, Spain and Portugal) will surpass 15% in the period 2031-2060, against a 4% to 5% decrease for Europe. As for the mid-end 21st century, projections point towards a reduction of 20% to 50% in Southern European hydropower gross potential (IPCC, 2007b; Jochem & Schade, 2009; van Vliet, van Beek, et al., 2016).

Nonetheless, a more realistic interpretation of changes in future hydropower generation considering existing hydropower plants is provided by developed hydropower potential[8]. Concerning the latter, (Lehner et al., 2005) projects a reduction of between 6.7% and 12.4% for Europe by 2070 – with impacts varying between -8.9% for run-of-river and -15.1% for reservoir plants. (Dowling, 2013) project that hydropower generation in Europe will reduce from 10% of total power generation in 2013 to less than 6% by 2050, thereby noting that hydropower generation may increase in Northern Europe and decrease in Southern Europe (especially in summer). These estimates are in line with other studies, such as the (Golombek, Kittelsen, & Haddeland, 2012) projections of a 15% net decrease in hydropower generation for Western Europe by 2085, and (Turner, Ng, & Galelli, 2017) projections of a 20% to 40% reduction in hydropower generation for Southern Europe by

[7] 'Gross hydropower potential' is defined as "the annual energy potentially available if all natural runoff at all locations were to be harnessed down to the sea level without any energy losses" (Lehner et al., 2005: p. 842). Hydropower potential is, by convention, forecast based on the 90% dependable river flow (Jain & Singh, 2003).

[8] 'Developed hydropower potential' corresponds to "a country's supplied electricity by hydropower", i.e., to the part of gross potential which is being or will be used in the future (Lehner et al., 2005: p. 842).

the end of the 21st century. For the Iberian Peninsula, (Pereira-Cardenal et al., 2014) project a 15% to 32% reduction in hydropower generation by the mid-21st century.

For Portugal, (Lehner et al., 2005) point to a reduction in hydropower generation between -44.4% and -22.1% by 2070. Given that both high and low flows are expected to become more extreme, the impact on run-of-river plants may be stronger than on reservoir plants (-24.9% and -15.1%, respectively). These results are coherent with (Turner et al., 2017) projections of a 21% reduction in hydropower generation in Portugal by 2050, and both considerably more unfavourable than the -2.5% and -5% reduction in hydropower generation in Portugal projected by (Hamududu & Killingtveit, 2012) in the scope of a global analysis. (Cleto, 2008) project that hydropower generation will be 7% lower under a severe climate change scenario than under a moderate one, whereas (Alves, 2013) conclude that hydropower generation in Portugal will decrease by 7% by 2050 (as compared to 2010). Particularly for the Tagus river basin, (Lobanova et al., 2016) conclude that hydropower generation by 2100 will decrease by between 10% and 50% under a moderate climate change scenario, and between 40% and 60% under a climate change extreme scenario. However, some studies indicate that climate change will not negatively affect projections for runoff and hydropower generation (APA, 2013) or will even improve the potential for hydropower generation (EC, 2009) in Portugal. As a result, (Bonjean Stanton, Dessai, & Paavola, 2016) conclude that existing projections for climate change impacts on hydropower generation in Portugal by 2050 are not consistent; still, projections for 2100 consistently point towards a decrease in annual hydropower generation in Portugal.

Considering that the main Portuguese river basins are transboundary, competition is likely to intensify in a context of increased water scarcity induced by climate change. Moreover, competitive energy companies pursue their own interests and profits and, thus, their management strategies do not encompass global optimization criteria for the sector (e.g. benefiting from cascade effects (APA, 2013)). Portugal is likely to be negatively affected by increased international competition, especially in hydropower systems located in the Douro and Tagus rivers (downstream of relevant Spanish hydropower plants). In the Guadiana river this issue may not be so problematic due to the existing large storage capacity in the Alqueva dam (APA, 2013). It is, therefore, plausible that competition for water in hydropower generation between Portugal and Spain will intensify due to climate change and, thus, constitute an increasing challenge for policymakers. Hence, projected changes in runoff conditions in Southern Europe may put the reliability of hydropower generation in jeopardy (IPCC, 2014a; Lobanova et al., 2016) – also in Portugal.

Despite it is widely recognized that climate change impacts on hydropower will be of importance, country-specific research on their quantification is relatively scant – even considering the relevance of spatial analysis for policymaking (Chandramowli & Felder, 2014). Furthermore, the abovementioned projections are the outputs of research focusing on the climate change biophysical impacts on hydropower generation. Naturally, when the preponderant role of water resources in all dimensions of life (namely human and animal consumption, ecosystem maintenance, economic activity or even land use competition) is brought to the analysis, complexity of energy modelling increases. It is essential to consider and understand these sectoral impacts and the existing interrelations, and even take into consideration that potential developments in water demand by upstream users may aggravate the potential climate impacts (Kundzewicz et al., 2008; Schaefli, 2015). Indeed, as argued by (Pollitt et al., 2010), including biophysical data as well as resource use and availability are among the modelling improvements needed to analyse sustainability in the scope of macroeconomic development.

CHAPTER 4

KEY FIGURES OF THE PORTUGUESE ENERGY SECTOR

Given the overall goal of analysing the impacts and feedbacks between water resources, the energy sector and the economy in Portugal, this chapter contextualizes the research by summarizing some key figures of the Portuguese energy sector over the period 1990-2015, with particular emphasis on the power generation and hydropower sectors. Data presented cover several dimensions of the energy sector, such as production (Section 4.1), consumption (Section 4.2), prices (Section 4.3), economic indicators (energy intensity and dependency; Section 4.4) and greenhouse gas (GHG) emissions (Section 4.5). Presented data are derived from (Eurostat, 2018a).

4.1. Energy production

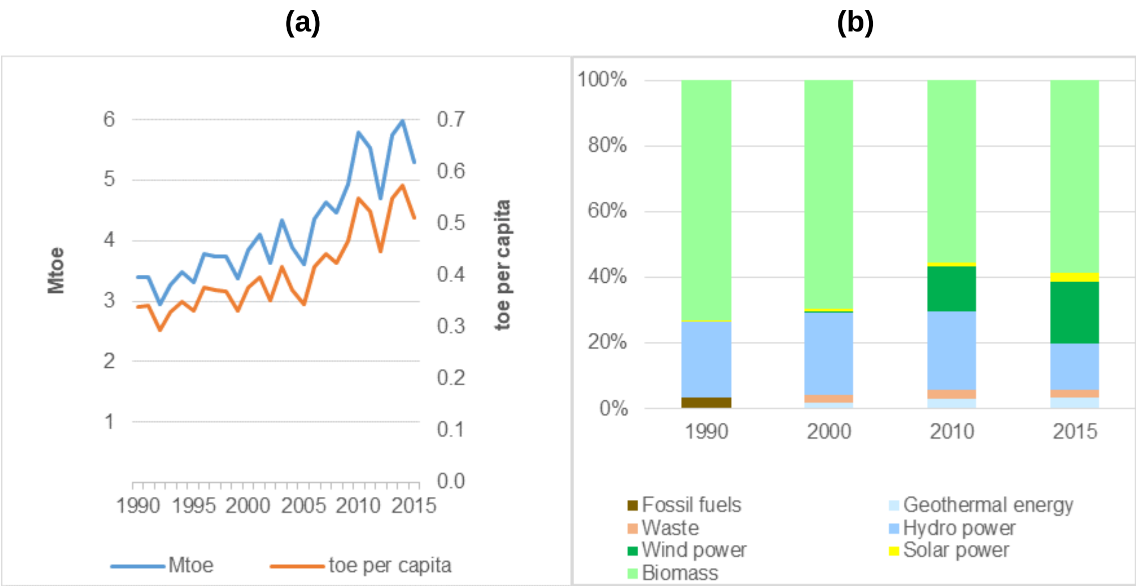
Energy production in Portugal over the period 1990 to 2015 is differentiated by primary production of energy, electricity generation and hydropower generation. Primary production of energy refers to the extraction of energy products in a useable form from natural sources (Eurostat, 2018b); electricity generation refers to the electricity produced by transforming other forms of energy (Eurostat, 2018b); and hydropower generation refers to the electricity generated from the potential and kinetic energy of water in hydroelectric plants (Eurostat, 2018b).

Primary production of energy

Despite the inter-annual variations, primary production of energy in Portugal increased by 56% between 1990 and 2015 (from 3.4 to 5.3 million tonnes of oil equivalent (Mtoe)), corresponding to an average annual growth rate of 1.8% (see Figure 4.1a). Thus, primary energy production per capita shows a positive growth in Portugal (+51%), whereas in the EU-28 a negative growth was recorded over the same period (-24%). Nevertheless, primary energy production per capita is systematically lower in Portugal than in the EU-28 (0.5 toe per capita against 1.5 toe per capita, respectively, in 2015).

Portuguese primary energy production relies almost entirely on renewable sources (Figure 4.1b). Biomass has been the main source of primary energy production, though its share in total primary energy production decreased from 73% in 1990 to 59% in 2015. Hydropower is the second source of primary energy production in the country, fluctuating between 10% (2012) and 33% (1996) due to hydrological variability. Wind power is becoming an important source of primary energy production in Portugal, as its share has been continuously increasing since it started to gain importance in the production structure since 2000 (from 1% in 2001 to 19% in 2015). Solar power and geothermal energy still have an incipient role, respectively accounting for approximately 3% and 4% of total primary energy production in 2015. Non-renewable wastes (both industrial and municipal) represent a small portion of total (2% in 2015), and fossil fuels (coal) were used only until the mid-90s (around 3% of total).

Figure 4.1. Primary energy production in Portugal over the period 1990-2015 – total and per capita (a) and by source (b)



Source: Based on (Eurostat, 2018a)

Note: 'Fossil fuels' refers to coal, natural gas and petroleum products; 'Waste' refers to industrial and non-renewable municipal waste; 'Solar power' refers to solar thermal and solar photovoltaic; 'Biomass' refers to wood, renewable waste, black liquors and biofuels.

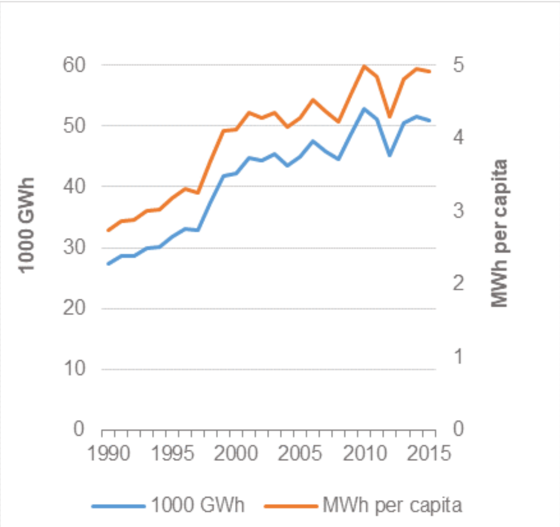
Power Generation

The gross production of electricity in Portugal has increased by almost 86% over the period 1990 to 2015 (from 27,449 Gigawatt hour (GWh) to 50,938 GWh), corresponding to an annual average growth rate of 2.5% (Figure 4.2a). Hence, power generation per capita in Portugal increased by almost 80% (i.e. +2.4% per year; see Figure 4.2a), in contrast with the 18% increase recorded in the EU-28 (+0.7% per year). Notwithstanding the greater growth rates recorded in Portugal, Portuguese electricity production per capita was below the EU average in 2015 (approximately 80% – although the gap has narrowed from 2.4 MWh Megawatt hour (MWh) per capita in 1990 to 1.1 MWh per capita in 2015).

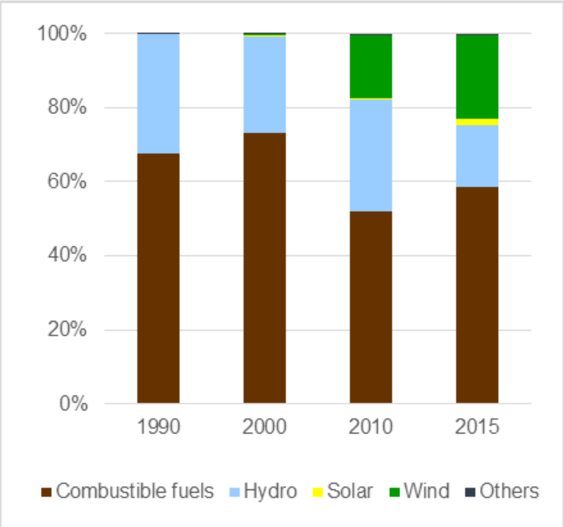
Thermal power has always been the most important source of electrical energy production in Portugal, although its share fluctuates due to the variable performance of renewable energies (Figure 4.2b). Accordingly, while in 1990 electrical energy in Portugal was provided by only two sources (thermal power, 68%; hydropower, 32%), in 2015 the production mix is more diversified (thermal power, 59%; wind power, 23%; hydropower, 17%; solar, 2%). The evolution of the electricity production mix reveals a clear choice for renewable and endogenous sources of energy as to promote sustainable development and to reduce energy dependency (in accordance with political guidelines as stated in (RCM 20/2013)). Accordingly, the share of renewable energy sources in the power mix increased from 32% in 1990 to 41% in 2015 (surpassing 50% in 2013 and 2014, wet hydrological years).

Figure 4.2. Gross production of electricity in Portugal over the period 1990-2015 – total and per capita (a) and by source (b)

(a)



(b)

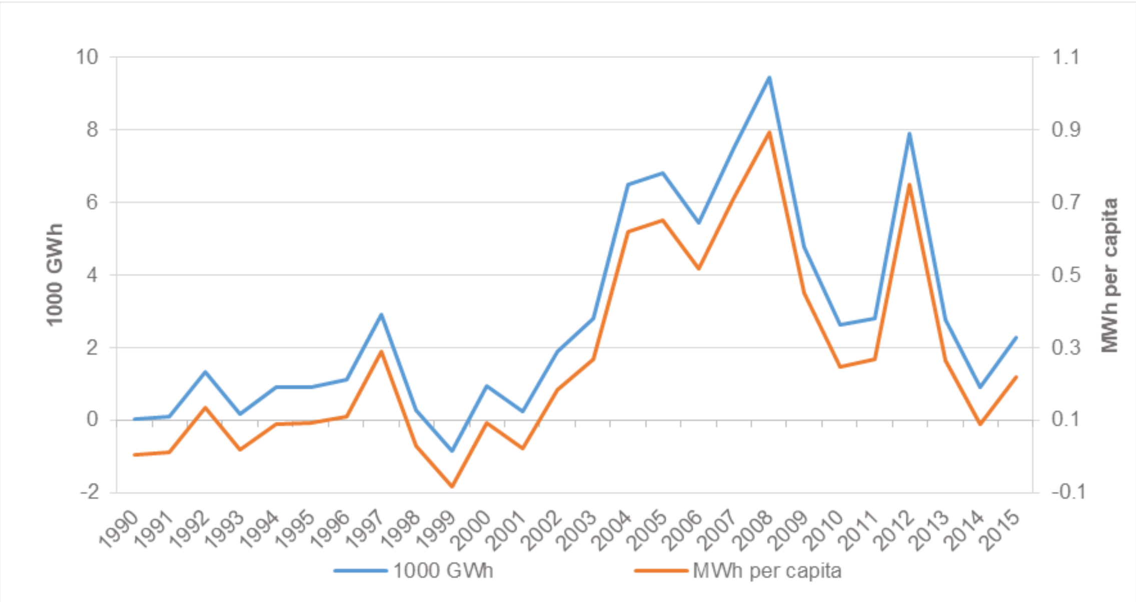


Source: Based on (Eurostat, 2018a)

Note: 'Combustible fuels' includes coal, crude oil, natural gas, biomass, waste; 'Others' correspond to geothermal energy, tide, wave and ocean, heat from chemical sources and other sources.

Portugal has been a net importer of electricity. Net imports increased from nearly zero GWh in 1990 to 2,266 GWh in 2015, corresponding to an annual growth rate of 17.9%. Net electrical imports in Portugal were negligible between 1990 and 2001; since then these were consistently higher, due to the operational start-up of the Iberian Electricity Market (reaching their maximum in 2008; 9,431 GWh or 21% of total net generation in the country; Figure 4.3). There is also a straight relation between net electricity imports and hydrological conditions, as dry years result in general in higher values of imports with negative impacts on the energy bill. Net imports per capita in Portugal are somewhat above those for the EU-28 until 2002 (on average about +0.04 MWh per capita) and well above those for the EU-28 after 2002 (on average about +0.4 MWh per capita). In 2015 net imports per capita were of 0.22 MWh in Portugal and 0.03 MWh in the EU-28.

Figure 4.3. Net imports of electricity in Portugal over the period 1990-2015 – total and per capita

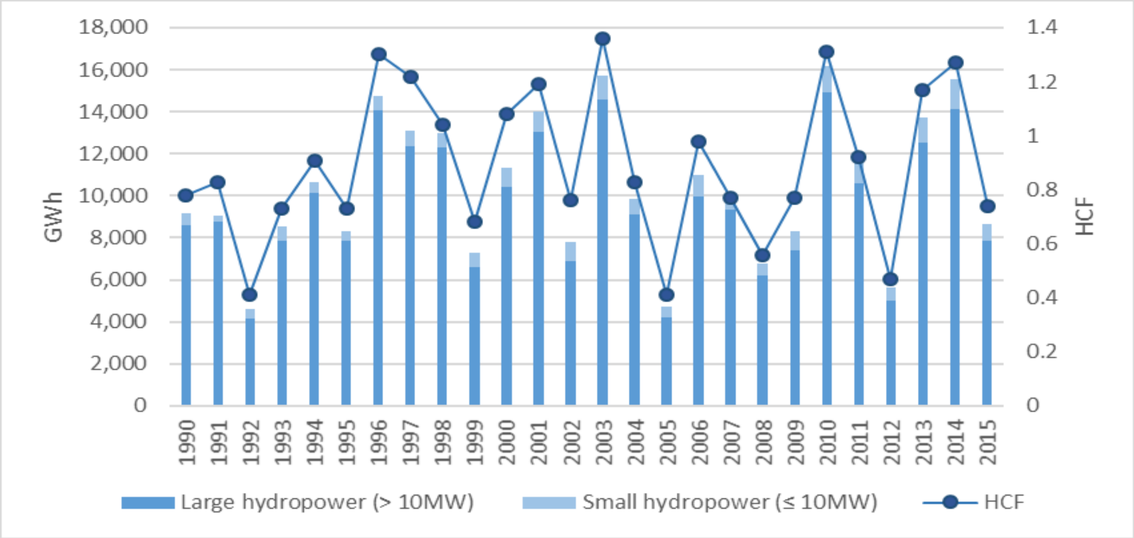


Source: Based on (Eurostat, 2018a)

Hydropower generation

Hydropower has always played an important role in the Portuguese energy system (see Figure 4.1b). The power mix took advantage of the relative abundance of endogenous water resources in the country, which contribute to offset the lack of fossil fuels. Nonetheless, electricity generation from hydropower is quite variable due to hydrological cycles – as reflected in the Hydropower Capacity Factor (HCF) that, over the period 1990-2014, ranged between 1.37 (in 2003) and 0.41 (in 1992 and 2005; see Figure 4.4).

Figure 4.4. Hydropower Capacity Factor and Electricity generation from hydropower in Portugal over the period 1990-2015

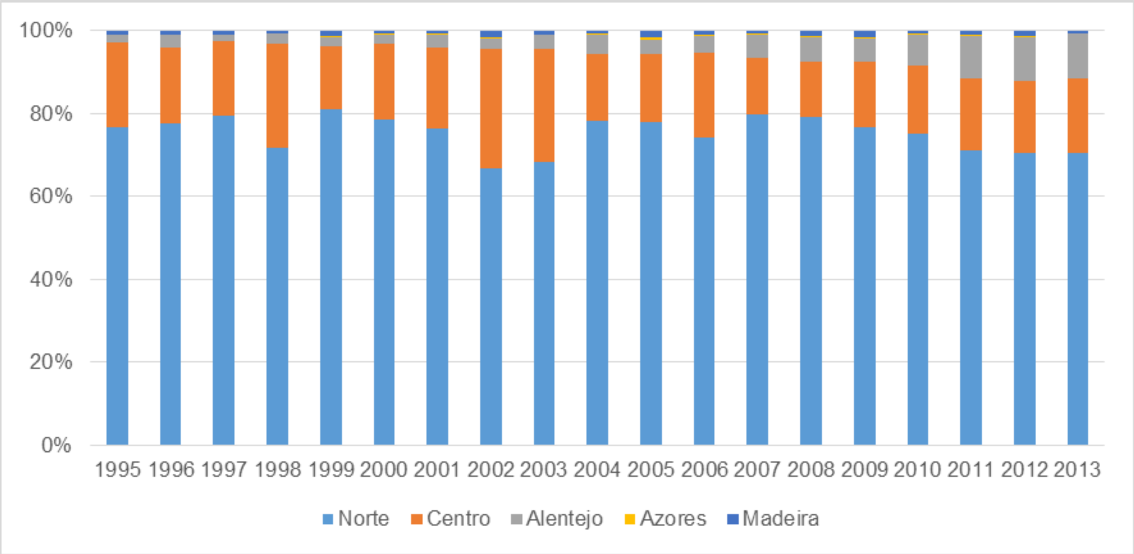


Source: Based on (Eurostat, 2018a) and (REN, 2015)

The irregular HCF is fully reflected in hydropower generation (see Figure 4.4). Thus, over the period 1990-2015, maximum hydropower generation outputs were recorded in 2010, 2003 and 2014 (16,148 GWh, 15,723 GWh and 15,570 GWh, respectively) and minimum outputs in 1992 and 2005 (4,608 GWh and 4,731 GWh, respectively). On average, large hydropower plants (over 10 Megawatts (MW)) provide around 92% of total output in Portugal – small-scale hydropower plants (less than 10MW) providing the remaining 8%.

At the regional level (NUTS 2), the Norte region is the main provider of electricity from hydropower, contributing yearly with more than 70% to total national production (see Figure 4.5). The Centro region accounts for around 20% and the Alentejo region accounts for the remaining 10% of hydropower generation in Portugal. Note that the Algarve and Lisboa regions do not enter in the hydropower generation mix.

Figure 4.5. Electricity generation from hydropower in Portugal, by region (NUTS 2), over the period 1990-2015



Source: Based on (INE, 2014)

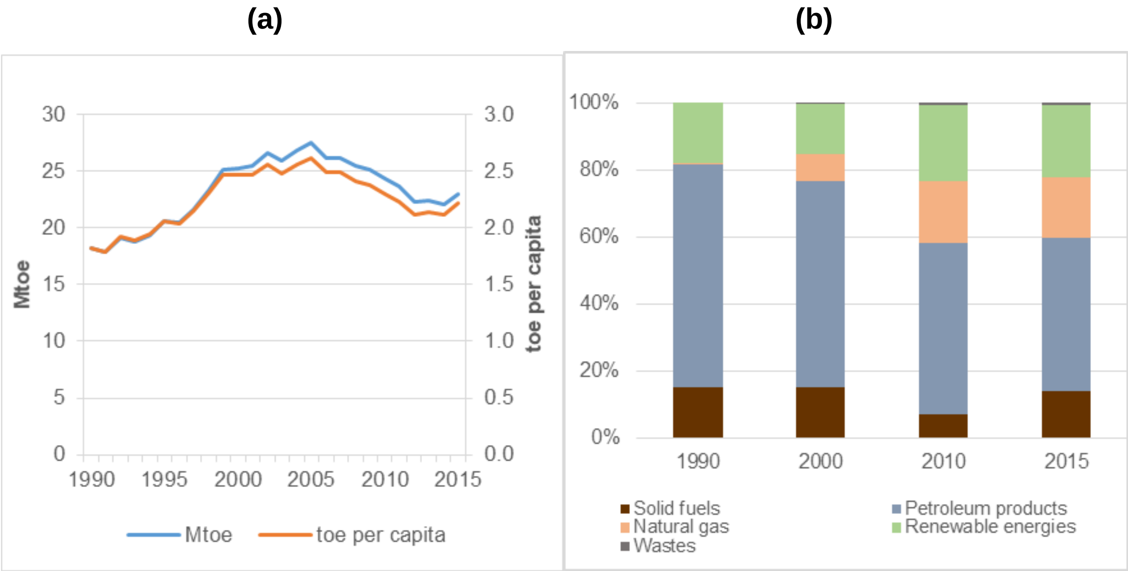
4.2. Energy consumption

Energy consumption in Portugal over the period 1990 to 2015 is differentiated by gross inland and final energy consumption. Gross inland energy consumption refers to the total energy demand of a country (Eurostat, 2018b); final energy consumption refers to the total energy consumed by end users, excluding that which is used by the energy sector itself (Eurostat, 2018b).

Gross inland energy consumption

Gross inland energy consumption in Portugal has kept an almost continuously increasing trend between 1990 and 2005, while showing a declining trend between 2006 and 2012 (see Figure 4.6a). It has increased by 26% between 1990 and 2015 (from 18.2 to 23.0 Mtoe), corresponding to an average annual growth rate of 0.9%. The corresponding gross inland energy consumption per capita increased by 22% over the same period (from 1.8 to 2.2 toe per capita), whereas in the EU-28 it decreased by 9% (from 3.5 to 3.2 toe per capita). Note, however, that gross inland energy consumption in Portugal has always been considerably below the European average. Fossil fuels (solid fuels, petroleum products and natural gas) represent the major share in gross inland energy consumption by fuel (more than 75%), although their consumption has been declining since 1990 (from 82% in 1990 to 78% in 2015) and renewables play an important and increasing role (from 18% in 1990 to 22% in 2015; Figure 4.6b).

Figure 4.6. Gross inland energy consumption in Portugal, total and per capita (a) and by fuel (b) over the period 1990-2015



Source: Based on (Eurostat, 2018a)

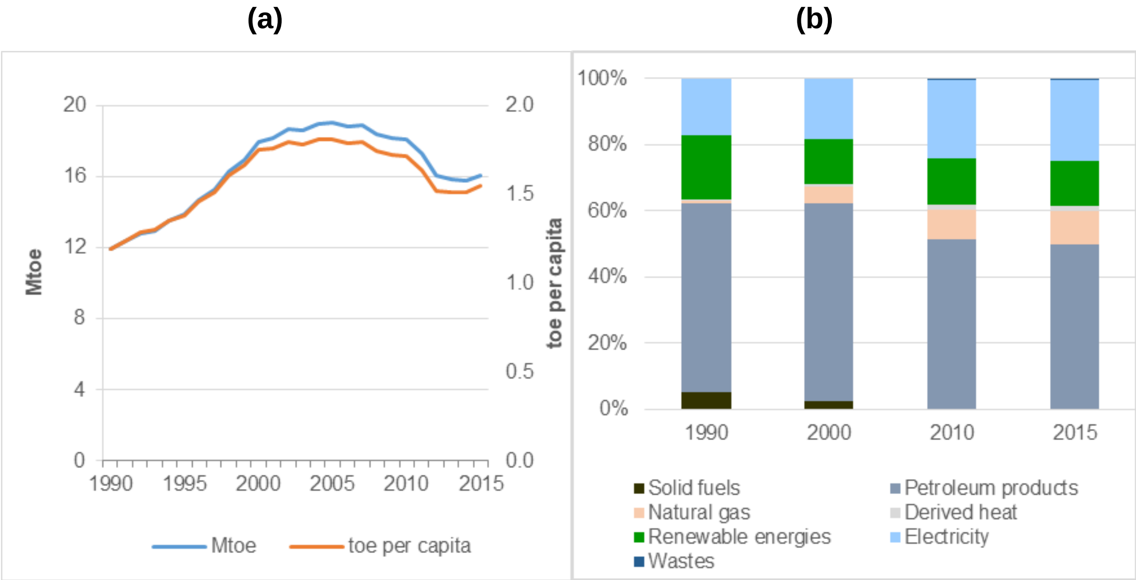
Final energy consumption

Final energy consumption in Portugal increased continuously until 2005, though started to decline as of 2008 due to the financial crisis (Figure 4.7a). Even so, it increased from 11.9 Mtoe in 1990 to 16.0 Mtoe in 2015 – corresponding to a 35% increase and an average annual growth rate of 1.2%. Per capita final energy consumption in Portugal increased by 30% (1.1% per year; see Figure 4.7a), while in the EU-28 it decreased by 6.6% (-0.3% per year). Despite these different trends, per capita energy consumption in Portugal is lower than in the EU-28, although the gap has been shrinking over time (from 48% lower in 1990 to 27% in 2015).

Final energy consumption in Portugal relies mainly on fossil fuels (solid fuels, petroleum products and natural gas; see Figure 4.7b). Although their share has been decreasing over time, they still represent almost 60% of Portuguese final energy consumption in

2015. Concerning the other energy products, electrical energy and renewables also play an important role in Portugal – accounting for 25% and 14% of final energy consumption in 2015, respectively.

Figure 4.7. Final energy consumption in Portugal, total and per capita (a) and by product (b), over the period 1990-2015

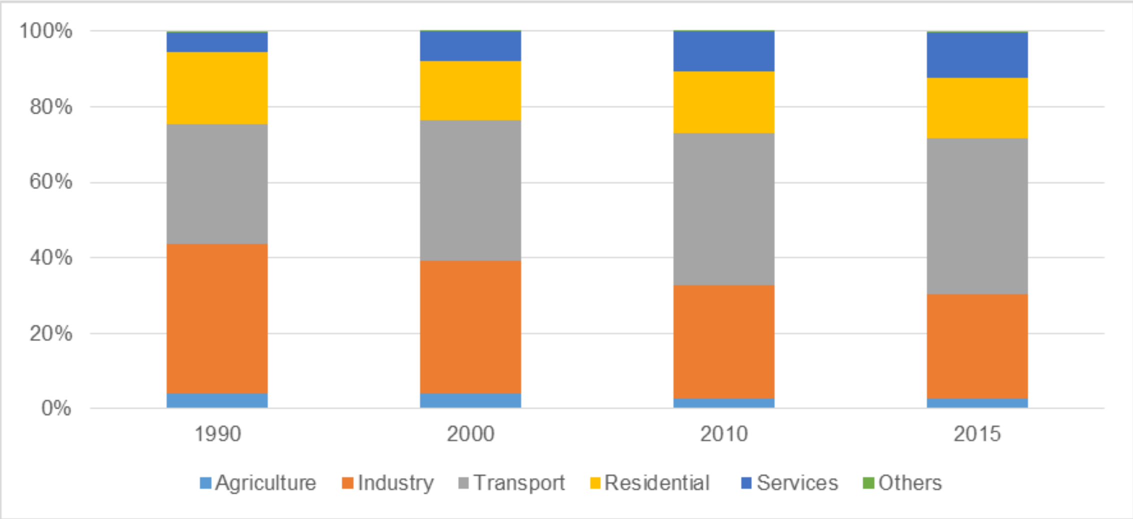


Source: Based on (Eurostat, 2018a)

The transport sector is the main consumer of final energy (41% of total), followed by industry (28%), households (16%), services (12%) and agriculture (3%) – resulting in a sectoral breakdown that differs from the past (Figure 4.8). On the one hand, final energy consumption by the industry sector decreased (from 40% in 1990) while, on the other hand, consumption by the transport sector increased (from 32% in 1990). Finally, consumption by the services sector has also increased due to the tertiarisation of the economy, increasing its share from 5% in 1990 to 12% in 2015.

Concerning the share of renewable energy in gross final energy consumption, the 2020 target is set at 31% for Portugal and at 20% for the EU-28 ((RCM 20/2013); Figure 4.9). Whereas in the EU-28 the share has been continuously increasing since 2009 (when the 2020 target was enacted in legislation), in Portugal the share increased until 2009, remained almost constant between 2009 and 2012 (during the financial crisis) and increased between 2012 and 2015. Note that Portugal's performance is better than the average EU-28 and, accordingly, the Portuguese target is more ambitious than that for the EU-28 as a whole.

Figure 4.8. Final energy consumption by sector in Portugal (%) over the period 1990-2015

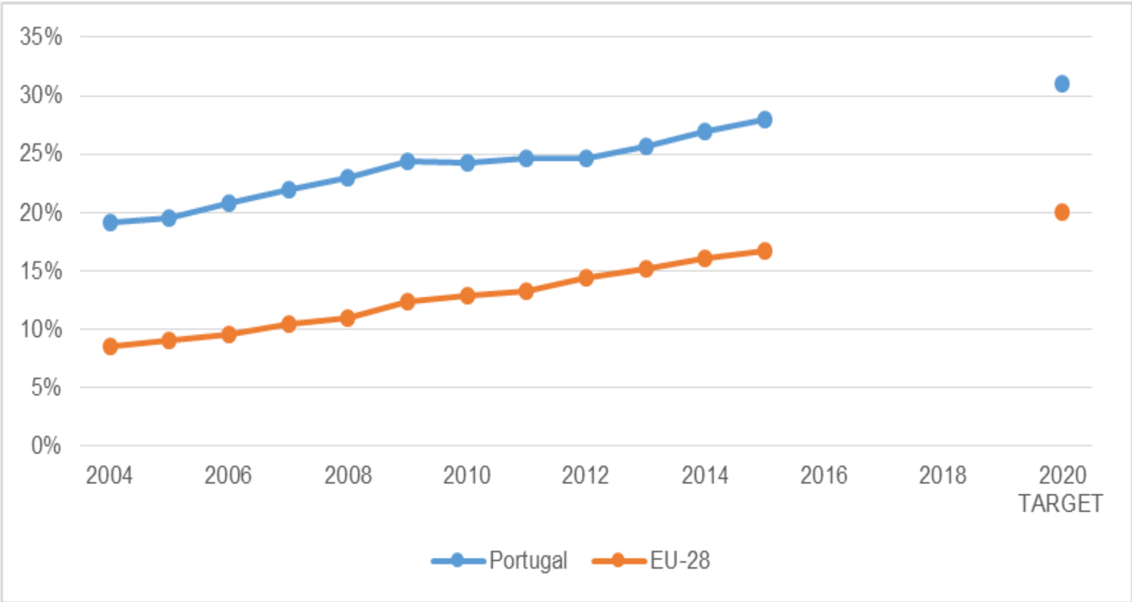


Source: Based on (Eurostat, 2018a)

As to electricity consumption in particular, in Portugal it increased by 95% between 1990 and 2015 (from 23,5 to 45,8 GWh), corresponding to an average annual growth rate of 2.7% (Figure 4.10a). Accordingly, between 1990 and 2015 electricity consumption per capita increased by 87% in Portugal (from 2.4 to 4.4 MWh per capita), as compared to 19% in the EU-28 (from 4.6 to 5.4 MWh per capita). Nevertheless, and although the gap is tightening, Portuguese electricity consumption remains lower than the European (-18% in 2015).

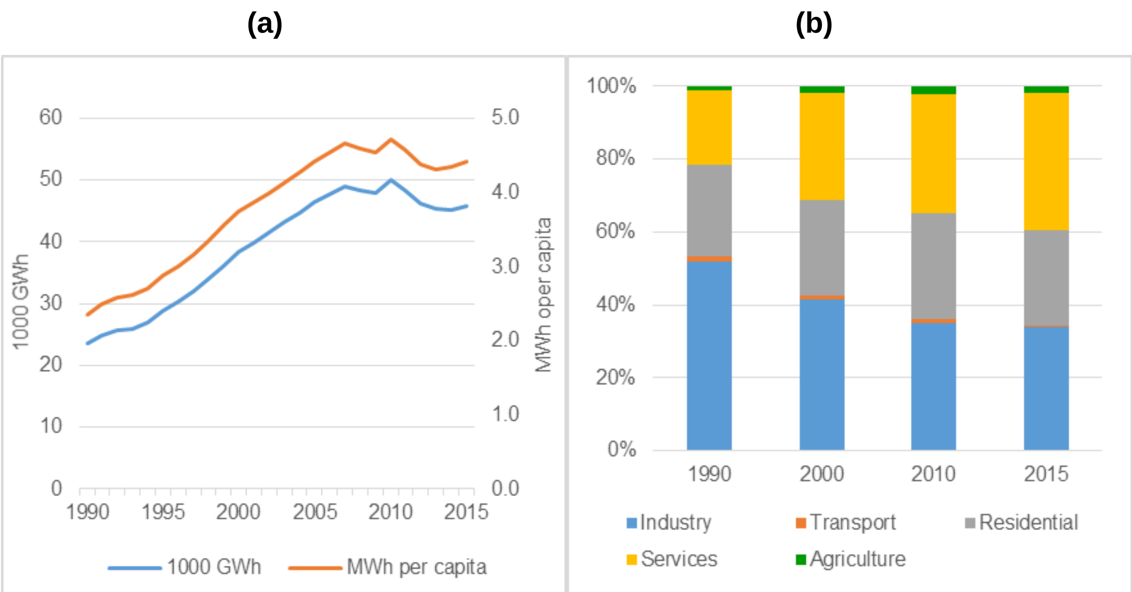
In 2015, the main consumers of electricity in Portugal are the services (38%), industry (34%) and residential (26%) sectors (Figure 4.10b). The situation in 2015 is considerably different from the one in 1990, when industry and services accounted for 52% and 21% of electricity consumption, respectively. This results, also, from the growing tertiarisation of the economy. Residential consumption shares barely changed between 1990 and 2015 (+1 percentage point). Electrical consumption in the transport sector is still incipient at present (<1%).

Figure 4.9. Share of renewable energy in gross final energy consumption in Portugal and the EU-28, over the period 1990-2015



Source: (Eurostat, 2018a)

Figure 4.10. Final electrical energy consumption in Portugal, total and per capita (a) and by sector (b), over the period 1990-2015

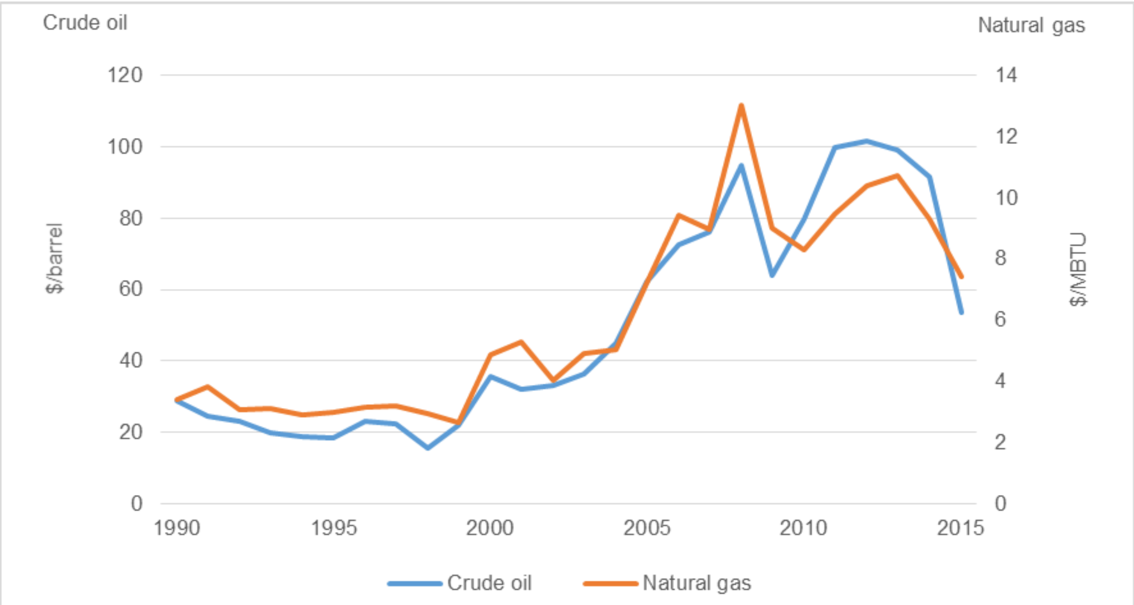


Source: Based on (Eurostat, 2018a)

4.3. Energy prices

Energy prices in Portugal are largely determined by the international market, given the country's dependence on the import of fossil fuels (see Section 4.4 below). Crude oil import prices increased continuously between 2001 and 2008 (Figure 4.11), from 32 to 95 USD/barrel (+197%, corresponding to an average annual growth rate of around 17%). Despite a sudden drop in 2009, due to the global financial crisis that led to a reduction in oil demand, import prices increased again between 2009 and 2012 – reaching a historical maximum in 2012 (102 USD/barrel). Similarly, natural gas import prices increased consecutively between 2002 and 2006 (+134%; +24%/year), and reached their maximum in 2008 (13 USD/MBTU; Figure 4.12).

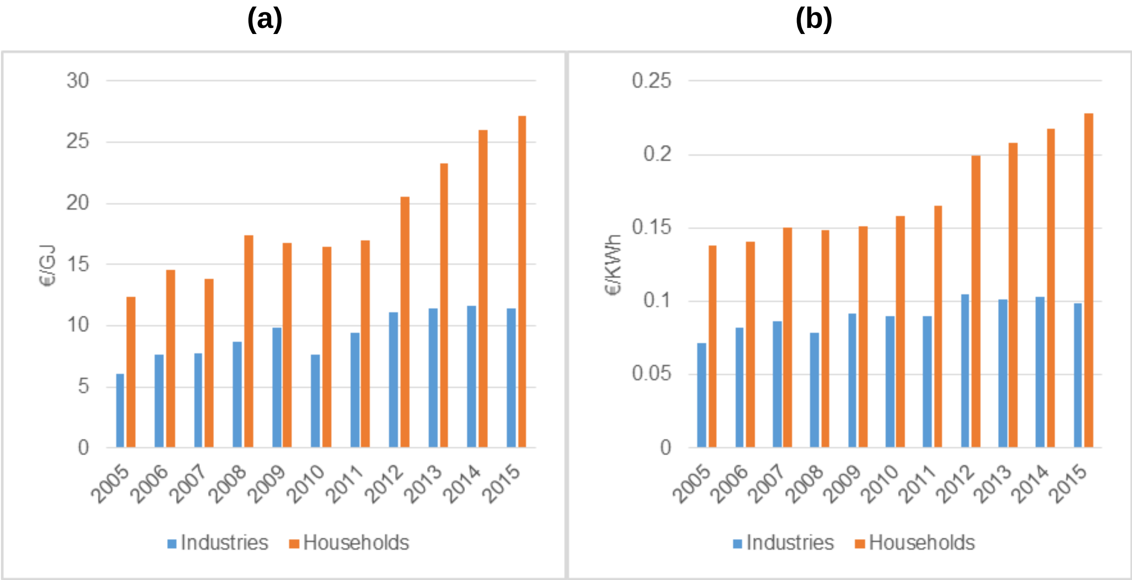
Figure 4.11. Crude oil and natural gas import prices in Portugal (real 2010 USD) over the period 1990-2015



Source: (World Bank, 2018)

Regarding the energy prices charged to end-users (Figure 4.12), gas prices in the industrial sector increased by 53% between 2005 and 2016 (+4.0% per year, against 2.2% in the EU-28), whereas electricity prices increased by 32% over the same period (+2.6% per year, against 1.6% in the EU-28). Regarding energy prices charged to households, gas prices increased by 106% (+6.8% per year) and electricity prices increased by 70% (+5.0% per year) over the period 2005-2016, whereas in the EU-28 they both increased by 4% per year over the same period.

Figure 4.12. Energy prices charged to end-users in Portugal, gas (a) and electricity (b), over the period 2005-2016



Source: Based on (Eurostat, 2018a)

4.4. Energy indicators

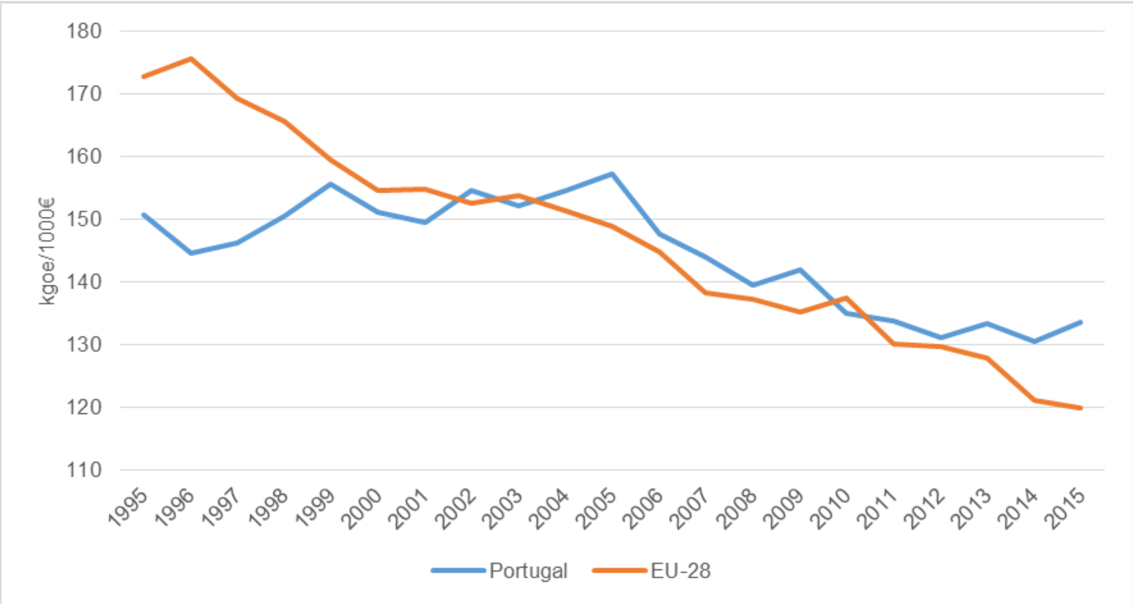
Energy indicators in Portugal over the period 1990 to 2015 comprise energy intensity and energy dependency. Energy intensity is the ratio between the gross inland consumption of energy and the gross domestic product (Eurostat, 2018b), and energy dependency refers to the ratio between net energy imports and the sum of gross inland energy consumption plus international maritime bunkers (Eurostat, 2018b).

Energy intensity

The energy intensity indicator is usually considered a proxy of the economies' energy efficiency. The Portuguese energy intensity (Figure 4.13) decreased from 150.8 kilograms of oil equivalent (kgoe) per 1000€ in 1995 to 133.6 kgoe/1000€ in 2015 (-11%). In 2015, the amount of energy required to produce a unit of economic output in Portugal was 11%

higher than the EU-28 average (120.0 kgoe/1000€). Nonetheless, Portuguese energy intensity has been decreasing almost continuously since 2005, following the EU-28 trend.

Figure 4.13. Energy intensity in Portugal and the EU-28 over the period 1990-2015



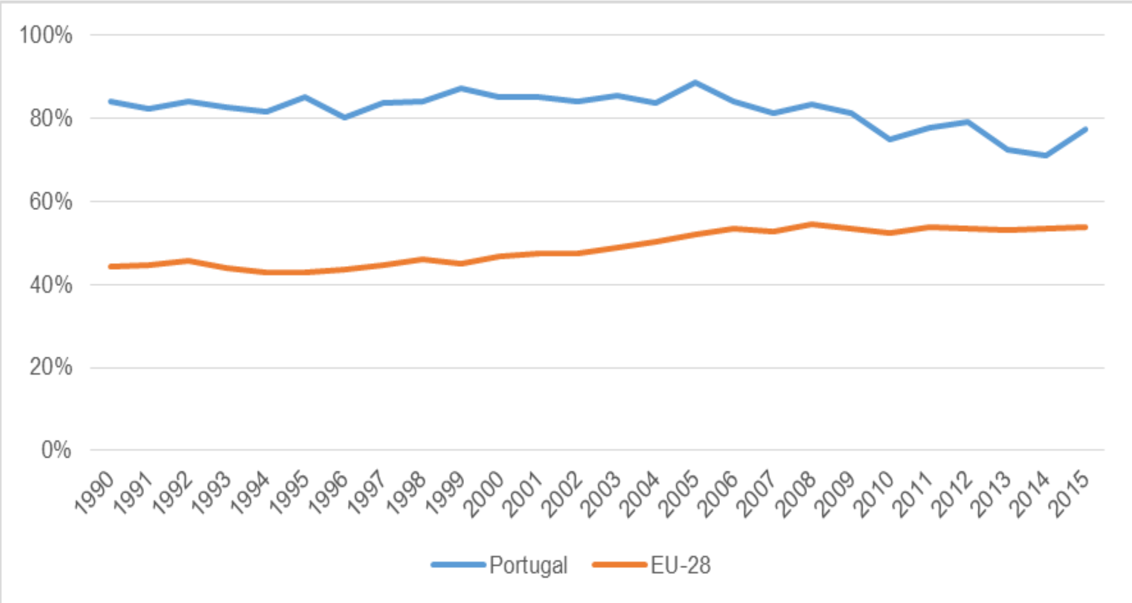
Source: (Eurostat, 2018a)

In the same vein, the inverse of energy intensity is usually considered as a proxy for the level of energy productivity, thus reflecting the degree of decoupling of energy use from growth in GDP. In coherence with energy intensity indicator, energy productivity is lower in Portugal (7.5€/kgoe) than in the EU-28 (8.3€/kgoe) in 2015. However, between 1995 and 2001, Portugal achieved a higher level of energy productivity than the European Union.

Energy dependency

Portugal is a net energy importer, with a national rate of energy dependency that is not only high (exceeding 80% between 1990 and 2009) but also consistently higher than the EU-28 average (54% in 2015; see Figure 4.14). The minimum rate reached in Portugal was 71.2% in 2014. The decreasing trend in energy dependency since 2005 is due to the promotion of endogenous renewable resources – mainly wind energy. Historically, the oscillations in Portuguese annual dependency rates are associated with hydrological conditions (see Figure 4.4). At the European level, energy dependency has been increasing and the dependency rate in 2015 (54%) was 10 percentage points higher than in 1990 (44%).

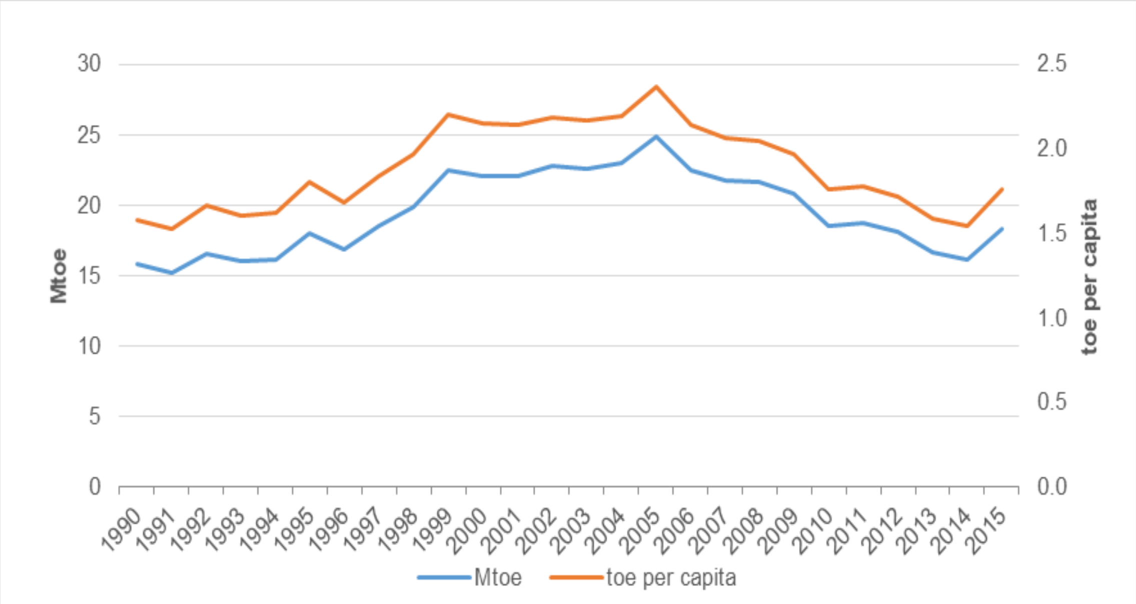
Figure 4.14. Energy dependency in Portugal and the EU-28 over the period 1990-2015



Source: (Eurostat, 2018a)

Over the period 1990 to 2015, Portuguese net imports of energy products recorded a total growth of 16% and an annual growth of 0.6% (see Figure 4.15). Net imports increased over the period 1990 to 2005 and decreased afterwards – mainly due to the combined effects of import reductions and export accruals. Concerning net imports per capita (Figure 4.15), Portugal and the EU-28 recorded identical growth over the period 1990-2015 (+11%; 0.4%/year). Between 1997 and 2005, Portuguese net imports of energy products per capita were considerably higher than those in the EU-28, due to the increase in gross inland energy consumption (see Figure 4.6a) that outpaced the increase in national energy production (see Figure 4.1a). Conversely, in recent years the gap reduced and European net imports became larger than the Portuguese, although in 2015 Portuguese and EU-28 net imports per capita were identical (1.8 toe per capita).

Figure 4.15. Net imports of energy products in Portugal, total and per capita, over the period 1990-2015



Source: Based on (Eurostat, 2018a)

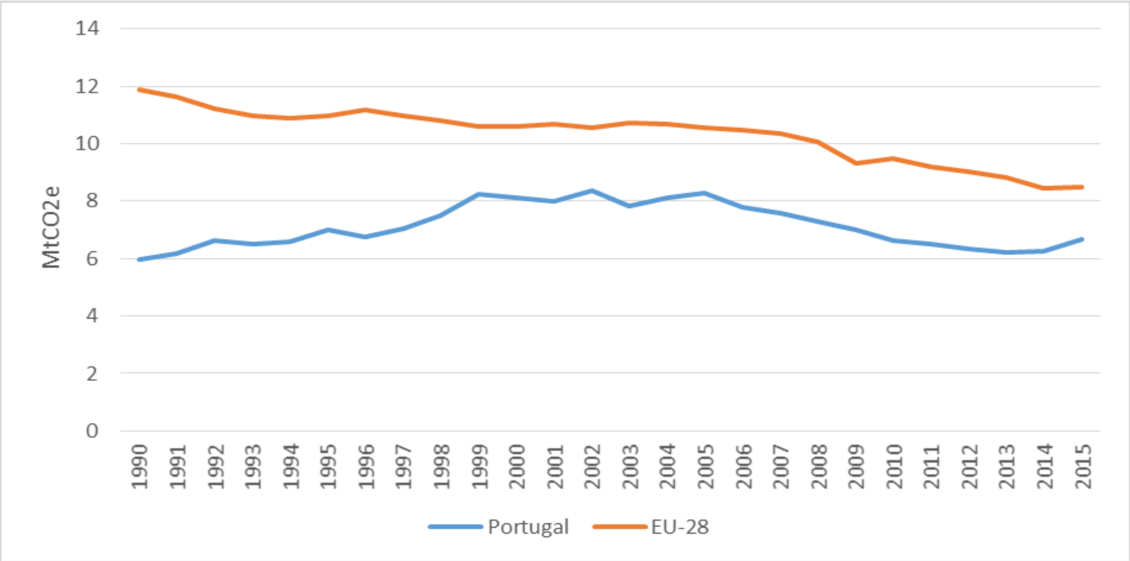
4.5. GHG emissions

GHG emissions in Portugal, excluding emissions and sinks related to land use, land-use change and forestry, increased by 16% between 1990 and 2015 (from 59.8 to 69.4 Mtoe), corresponding to an average annual growth rate of 0.6% (see Figure 4.16). Therefore, GHG emissions per capita shows a positive growth in Portugal (+12%), whereas in the EU-28 a negative growth (-29%) was recorded over the same period. Nevertheless, GHG emissions per capita are systematically lower in Portugal than in the EU-28 (6.7 tonnes of CO_2 equivalent (tCO_2e) per capita against 8.5 tCO_2e per capita, respectively, in 2015).

The sectoral share of GHG emissions in Portugal has not changed significantly over the period 1990-2015. The energy sector is responsible for the largest share of GHG emissions (around 70% over the period 1990-2015; see Figure 4.17a), followed by industry and agriculture (11% and 10% in 2015, respectively). Within the energy sector, fuel combustion in energy industries represents the major part of GHG emissions, although this varies with the share of renewable energy sources in the power mix. The share of GHG emissions from energy industries increased from 30% in 2010 to 39% in 2015 and, accordingly, the share of renewable energy sources decreased from 48% to

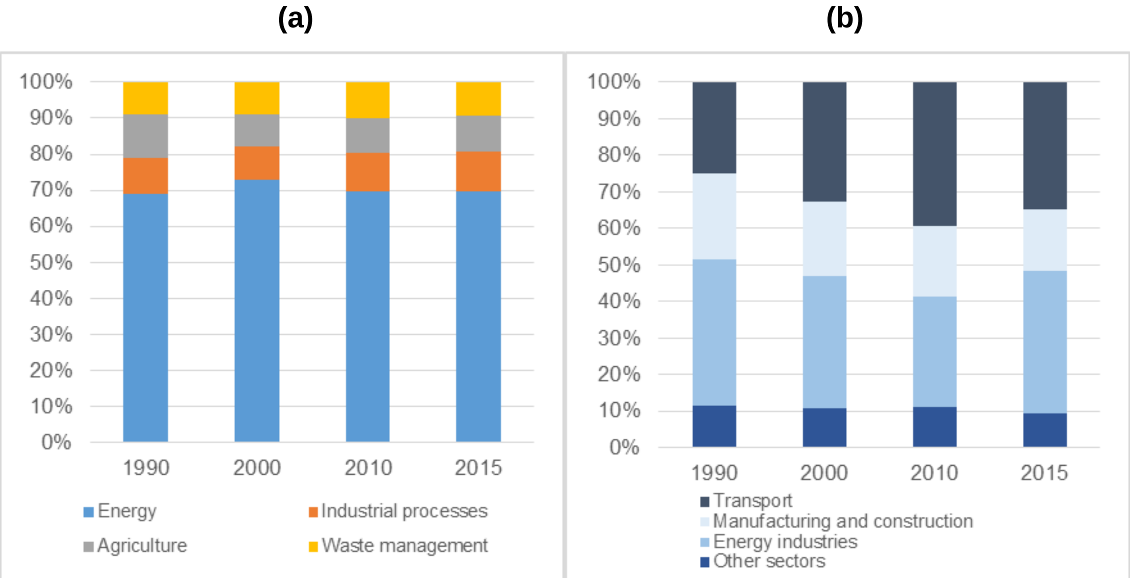
41% over the same period (see Figure 4.2b). Fuel combustion from transport is the second major emitter, representing 35% of energy-related GHG emissions in 2015. The manufacturing and construction sectors represent less than 20% of fuel combustion related GHG emissions.

Figure 4.16. GHG emissions per capita in Portugal and the EU-28 over the period 1990-2015



Source: Based on (Eurostat, 2018a)

Figure 4.17. GHG emissions in Portugal, total (a) and in the energy sector (b) over the period 1990-2015



Source: Based on (Eurostat, 2018a)

CHAPTER 5

ECONOMIC MODELS FOR CLIMATE CHANGE ANALYSES

Due to the magnitude of the issue, climate change and impacts have been widely studied by several disciplines. As climate change may ultimately affect economic growth and compromise sustainable development, the economic side of climate change has been attracting increased attention from researchers and policymakers. In particular, special attention has been devoted to the main driver of anthropogenic climate change – i.e. the energy sector.

The growing interest in the relationship between the energy sector and climate change dates back to the 1980s, when the Bruntland Report (Brundtland, 1987) identified the energy sector as a key factor for sustainable development. This, on the one hand, because of its essential character in modern societies and, on the other hand, because it is responsible for the major part of greenhouse gas (GHG) emissions and, thus, climate change (Nakata, Silva, & Rodionov, 2011). Accordingly, energy system analyses widened their scope[9] to highlight the energy-economy and environment connection and later, in the 1990s, to the broader relationship between energy-economy-environment and climate change (Bhattacharyya & Timilsina, 2010).

Such a holistic analysis of the energy-economy-environment components of any energy or climate mitigation policy requires an integrated assessment framework that simultaneously considers the feedbacks and the interactions between these three spheres. This can be achieved using Integrated Assessment Models (IAM), which "combine knowledge from a wide range of disciplines to provide insights that would not be observed through traditional disciplinary research. They are used to explore possible states of human and natural systems, analyse key questions related to policy formulation, and help set research priorities" (IPCC, 1996: p.14).

In addition, informed policy-making requires a full understanding of the costs and benefits of energy/climate policies regarding employment, competitiveness, and economic structure. Economic impacts derive from the responses of economic agents (consumers; firms) to policy signals that, ultimately, are intended to shift the economic course to an environmentally desirable pathway of the energy system (Bataille, Jaccard, Nyboer, & Rivers, 2006; Hourcade, Jaccard, Bataille, & Ghersi, 2006). In this context, E3 models (a particular type of IAM), which gather the energy-environment-

[9] Energy system analysis dates back to the 1950s, based on the energy accounting approach (Hoffman & Wood, 1976), which relies on energy balances to comprehensively account for how energy is consumed, converted and produced in a region or economy. However, the first oil crisis in the mid-1970s raised new concerns about energy security and vulnerability to oil prices, and energy-economic models thrived to produce more reliable and comprehensive information (Nakata et al., 2011).

economy relationships into a single basis, have been extensively used (e.g. (APA, 2012; EC, 2011b; OECD, 2015)).

Within E3 models, two distinct approaches are commonly used: top-down and bottom-up. Building on their strengths, hybrid models merging top-down and bottom-up features are prospering in literature. This chapter reviews the conventional top-down and bottom-up approaches (Section 5.1), describes the usual methodologies to construct hybrid models to address energy-environment-economic policy issues (Section 5.2), and presents an advancement in the integrated assessment modelling of climate change issues by enriching the E3 hybrid models with the inclusion of biophysical parameters (in particular water resources availability; Section 5.3).

5.1. E3 modelling approaches: top-down and bottom-up

The quantitative assessment of energy/climate policy impacts is conducted with either top-down or bottom-up models. Top-down models are mainly used by economists, while bottom-up models are preferably used by engineers. Accordingly, these two approaches differ, above all, by the assumptions on market behaviour and specification of technological detail (Böhringer & Rutherford, 2008; van Beeck, 1999). The next subsections briefly describe (Subsections 5.1.1. and 5.1.2) and compare (Subsection 5.1.3) the main features of each modelling approach.

5.1.1. Conventional top-down

Usual top-down approaches rely on economic theory (micro- and macroeconomic foundations). They adopt an economy-wide perspective to examine a broad equilibrium framework through the representation of goods and factors markets as well as their interactions. Top-down models are, thus, able to capture the market interactions and inefficiencies arising from market distortions or market failures (Böhringer & Rutherford, 2008).

Top-down models may follow a partial equilibrium approach if they represent the interactions of a limited number of markets (e.g. electricity generation and consumption), or a general equilibrium framework if they comprise a full representation of all markets and agents. Since the 1980s, Computable General Equilibrium (CGE) models are the most common expression of the top-down approach (Hourcade et al., 2006). They include aggregate economic variables to evaluate the overall macroeconomic performance of the economy (Böhringer & Rutherford, 2008; Nakata, 2004; Nakata et al., 2011).

Consistent with their economic nature, top-down models are not technology explicit. Production of each good or service is represented by an aggregate production function, which is usually characterized by the shares of inputs (e.g. capital, labour, energy and materials) and the elasticities of substitution between them (Nakata, 2004). The energy sector is represented, following the same approach, by aggregate production functions that capture substitution (transformation) possibilities through constant elasticities of substitution (transformation) (Böhringer & Rutherford, 2008). Top-down models thus use a weak representation of the energy system (notably of energy sources, conversion technologies and end-use demand). Technological change is, usually, represented by an "Autonomous Energy Efficiency Index"[10] (AEEI; (van Beeck, 1999)), thereby reflecting technology efficiency improvements and capital stock turnover independent from technology prices or other policy or economic variables (Bataille et al., 2006). Elasticities of substitution/transformation and energy efficiency parameters are exogenous and, usually, estimated from historical data, which may compromise their intertemporal validity – especially in the context of technological breakthroughs and new energy/climate policies (Grubb, Köhler, & Anderson, 2002; Hourcade et al., 2006).

5.1.2. Conventional bottom-up

Bottom-up approaches are dominated by partial equilibrium models of the energy sector (Böhringer & Rutherford, 2008). These have an engineering character and focus exclusively on the energy sector, containing a detailed representation of the energy system (Böhringer & Rutherford, 2008; Nakata et al., 2011; Pandey, 2002). Energy, partial equilibrium models use highly disaggregated data to describe technological options and technical constraints, costs, primary energy sources, and emissions factors

[10] The AEEI is a heuristic representation of non-price driven changes in energy use over time, notably of improvements in energy intensity that are explained by technological change and changes in the economic structure, rather than by changes in fuel prices (Paltsev et al., 2005).

(Nakata, 2004). They consider current and future energy technologies, both on the supply and the demand side.

Bottom-up models usually disregard market behaviour and agent preferences, assuming that consumer and firm decisions are based on cost-effectiveness criteria to attain equilibrium in quantities and prices (Hourcade et al., 2006; Jaccard, Nyboer, Bataille, & Sadownik, 2003; Nakata et al., 2011; van Beeck, 1999). Due to their sectoral scope (partial equilibrium approach), conventional bottom-up models do not consider the interactions between the energy sector and the rest of the economy and, thus, the macroeconomic impacts and feedbacks of energy/climate policies and agent behaviour (Böhringer & Rutherford, 2008). Some consider simpler price response through exogenous energy service-price elasticities, which may reflect part of the feedback effects from the economy to the energy system. However, good estimates of these elasticities are rare and, moreover, the full macroeconomic interaction between the energy sector and the broad economy, notably the impacts on gross domestic product (GDP), employment and economic structure, remains out of reach (Fortes, Pereira, Pereira, & Seixas, 2014).

5.1.3. Comparative overview

Due to the different purposes, structures and assumptions, top-down and bottom-up models usually produce divergent results (Nakata, 2004). Broadly speaking, top-down and bottom-up models can be distinguished by the comprehensiveness of policy impacts captured as well as by their maximum/minimum degree of endogenization of market/agent behaviour and aggregation/disaggregation of technologies, respectively (Böhringer & Rutherford, 2008; Nakata, 2004; van Beeck, 1999).

Bottom-up models allow for a comprehensive analysis of technology-specific policy impacts on the energy sector, but fail in representing the macroeconomic feedbacks of such policies – assuming that the anticipated estimation of financial costs, using the social discount rate, corresponds to the full cost of switching technologies (Jaccard et al., 2003). As a consequence, bottom-up models tend to underestimate the efforts to achieving a low-carbon society (Hourcade et al., 2006; van Vuuren et al., 2009).

Conversely, top-down models allow to assess economy-wide price policy instruments (e.g. taxes), but they lack the detail on present and future technological options and, thus, treat technology as a ‘black box’ from an engineering point of view (van Beeck, 1999). Thus, top-down models usually point towards higher costs of compliance with climate policies than bottom-up models because they disregard the technological development that would reduce costs and enhance substitution possibilities between inputs (Hourcade et al., 2006; Jaccard et al., 2003).

This may explain why the top-down approach is generally associated with the “pessimistic” economic paradigm, and the bottom-up approach with the “optimistic” engineering paradigm (Grubb, Edmonds, ten Brink, & Morrison, 1993). The described features of top-down and bottom-up approaches show they are rather complementary than competitors. Such complementarity is highlighted within hybrid models, whose integrated framework includes “feedbacks between energy supply and demand, and between the energy system and the structure and output of the economy” (Jaccard et al., 2003: p.56).

5.2. Combined top-down and bottom-up: hybrid modelling approaches

E3 models have proven to be valuable tools for policy-making. To be genuinely useful, an E3 model may perform well in three different dimensions: technological explicitness, behavioural realism and macroeconomic completeness (Hourcade et al., 2006; Jaccard et al., 2003). As mentioned before, bottom-up conventional approaches provide the necessary technological explicitness, but lack the economic dimensions; by contrast, top-down approaches possess the necessary micro- and macroeconomic features, but disregard the technological component. Hence, in isolation, top-down and bottom-up approaches seem insufficient to fully answer energy-economy-environment policy issues.

A comprehensive framework of analysis for energy-economy-environment policies can thus be achieved through hybrid approaches, which combine “the technological explicitness of bottom-up models with the economic comprehensiveness of top-down models” (Böhringer & Rutherford, 2008: p.575). For that reason, hybrid models are widespread in literature as a means to, simultaneously, overcome limitations of both top-down and bottom-up approaches as well as maximize their potentials. Different methodologies are used in the construction of hybrid models and, following (Böhringer

& Rutherford, 2008), these can be broadly grouped into three categories, as presented below.

Soft-link between two independent models

Within this methodology, independent top-down and bottom-up models “communicate” through iterative data exchange until convergence is achieved. The main advantages of this approach are transparency and detail, as structural changes of the original models are minimal (Labriet et al., 2010; Martinsen, 2011). However, due to the distinct characteristics of top-down and bottom-up models, namely on behavioural assumptions and accounting concepts, difficulties are often encountered to achieve overall consistency and convergence (Böhringer & Rutherford, 2008). Examples of this approach include (Fortes et al., 2014; Krook-Riekkola, Berg, Ahlgren, & Söderholm, 2017; Labandeira, Linares, & Rodríguez, 2009; Labriet et al., 2010; Messner & Schrattenholzer, 2000).

Linking one model type to a reduced form of the other

This methodology consists in focusing on one modelling approach (top-down or bottom-up) and using a simplified form of the other (Böhringer & Rutherford, 2008) in such a way that a reduced version of one of the models is incorporated into the other. The most usual practice is to link a bottom-up model to a highly aggregate one-sector macroeconomic model producing a non-energy good within a single optimization framework (Böhringer & Rutherford, 2008). However, as explained in (Labandeira, Linares, et al., 2009: p.5), this approach “involves a significant reduction in the level of detail provided by the model […] which in turn means lower heterogeneity of industries and therefore reduced substitution opportunities and higher costs from any simulated policy“, thus hampering the analysis of sector-specific impacts of simulated policies. Examples of this practice include, for instance, (Messner & Schrattenholzer, 2000; Rivers & Jaccard, 2005; Strachan & Kannan, 2008). Conversely, (Bosetti, Carraro, Galeotti, Massetti, & Tavoni, 2006) include a reduced form of a bottom-up model into a top-down model.

Integration of models in a single framework

This methodology relies on the integration of the two modelling approaches (top-down and bottom-up) into a single framework (see Böhringer, 1998). The most common practice is to include the technological detail of bottom-up models (usually, including the power generation sector through a set of discrete technologies, rather than covering the whole energy system; see e.g. (Böhringer & Rutherford, 2008; Wing, 2008)) into a top-down general equilibrium framework. There have been several attempts to accomplish this approach and to overcome the major technical challenges involved (Labandeira, Linares, et al., 2009), but the most usual approach is to develop an integrated hybrid model as a Mixed Complementarity Problem (MCP). Examples from the empirical literature include (Bohringer & Loschel, 2006; Eskeland, Rive, & Mideksa, 2012; Frei, Haldi, & Sarlos, 2003). The mixed complementarity format does not solve, however, the consistency problems between engineering and macroeconomic data from bottom-up and top-down models, respectively, nor the dimensionality and complexity inherent to the complete integration of heterogeneous models (Labandeira, Linares, et al., 2009; Wing, 2008). Taking these limitations into account, (Wing, 2008) defined a methodology to overcome data inconsistencies (further applied by, e.g., (Dai, Masui, Matsuoka, & Fujimori, 2011; Proença, 2013)) and (Böhringer & Rutherford, 2009) established a method to decompose and solve iteratively a MCP model to surpass dimensionality problems (also applied by (Lanz & Rausch, 2011; Tuladhar, Yuan, Bernstein, Montgomery, & Smith, 2009)).

5.3. Advancing hybrid E3 modelling: the inclusion of water resources

Hybrid E3 models, thus, provide a comprehensive framework of analysis for energy-environment-economy policies. Even though the interactions and feedbacks between the energy sector (supply and demand), the environment (usually greenhouse gas (GHG) emissions) and the economy (production sectors and economic agents) exist, the inherent effects on/of natural resources availability are not accounted for (typically, these are not included in the model). Moreover, economic outputs of production processes that enter the environment (e.g. GHG emissions) and their implications (such as pollution or climate change) are usually treated as externalities, which are given a price in the model (Pollitt et al., 2010). However, a full assessment of impacts requires that these pressures are measured in physical units and, hence, including resource use and availability is envisaged as one of the main improvements for research on sustainability (Pollitt et al., 2010), which, *a fortiori*, also apply to the assessment of economic impacts of climate change. In particular, the inclusion of water resources plays a crucial role in economic analyses of climate change impacts, both because water resources are vital to life in all its dimensions and because water resources availability is projected to be significantly affected by climate change – particularly in some regions of the World, such as the Mediterrean region (see Chapters 2 and 3).

In this respect, the increased use of top-down water-oriented CGE models constitutes a remarkable advancement in the understanding of the economic consequences of transdisciplinary problems such as climate change. According to (Calzadilla, Rehdanz, Roson, Sartori, & Tol, 2016), water-oriented CGE analyses can be grouped into two broad categories. One refers to the economic impacts (e.g. on consumption, costs, water demand or the whole economic system) driven by economic instruments and policies, such as water pricing systems, water-related taxes and subsidies, water use efficiency improvements, and the introduction of water markets. The other, which is relevant for this thesis, refers to the economic impacts of changes in water endowments triggered by climate change. Concerning the latter, the economy-wide effects of climate change (i.e. changes in precipitation, temperature and river flows) on water endowments have been studied for different geographic areas, from single countries to the world (see e.g. (Faust, Gonseth, & Vielle, 2015; Jason Koopman, Kuik, Tol, & Brouwer, 2017; Roson, 2017)). Within this strand of literature, much attention is devoted to the agricultural sector (e.g. (Berrittella, Rehdanz, Roson, & Tol, 2008; Calzadilla et al., 2013; Calzadilla, Zhu, Rehdanz, Tol, & Ringler, 2014)), as this is one of the largest water consumers in the economy and plays an essential role in food security in a water-scarce world. Hence, research has mostly focused on the ‘water-food’ nexus and, less so, on the ‘water-energy’ nexus.

Although the majority of these water-oriented CGE analyses seek to address the impacts of restricted water supply, changes in water availability are frequently modelled via exogenous shocks in productivity rather than through an explicit change in water endowments (Ponce, Bosello, & Giupponi, 2012). Furthermore, in these cases the interaction between the economy and natural resources availability exists through the interaction between demand and supply, while the implications for the energy sector and the corresponding environmental and economic consequences are out of scope.

This means that, due to their characteristics, both the commonly used hybrid E3 and water-oriented CGE models disregard the ‘water-energy’ nexus. Hence, these two approaches can be combined in order to fill this gap – i.e. closing the ‘water resources – energy – environment – economy’ loop and thus providing insight in the ‘water-energy-economy’ nexus.

CHAPTER 6

ASSESSING SECTORAL, ECONOMIC AND ENVIRONMENTAL IMPACTS OF ENERGY EFFICIENCY TARGETS, USING A HYBRID COMPUTABLE GENERAL EQUILIBRIUM APPROACH *

* This chapter has been submitted at "*Renewable & Sustainable Energy Reviews*" (November 2018).

A preliminary version of this paper was presented at the 1st AIEE Energy Symposium - Current and Future Challenges to Energy Security, 30 November-2 December 2016, Milan, Italy.

Abstract

Energy efficiency is an increasingly critical issue in public policies, because it is the key to decoupling economic growth and environmental pressures. The European Union has already defined its strategy for 2030 and outlined general goals for 2050, but many Member States are still working to accomplish the 20-20-20 targets. This paper fills a gap in literature by analysing the sectoral, economic and environmental impacts of attaining energy efficiency targets through an energy fiscal policy, simulated by a hybrid computable general equilibrium model with technological detail. Six scenarios are defined for energy savings in primary or final energy consumption of fossil-fuelled or all energy products. For the case study of Portugal, results show reductions in GDP of 0.5% to 6.2% along with a reduction in energy dependency (up to -18.5p.p.), energy intensity (up to -21%) and CO_2 emissions (up to -55%). Important policy relevant results include that: (i) primary energy saving targets lead to lower economic costs than final energy saving targets and that (ii) larger and more distorting impacts on electricity generation arise from a relatively low taxation of all energy products (fossils and renewables) than from higher taxes on fossil fuels only. This paper highlights the trade-off between economic performance and environmental concerns. It shows that the size of these trade-offs depends on where (primary or final energy consumption) and what (fossil or all energy products) energy savings are targeted, yielding relevant insights for policy makers.

6.1. Introduction

The energy sector represents around two-thirds of total anthropogenic greenhouse gas (GHG) emissions (OECD/IEA, 2015a), which are recognized as the main factor causing climate change (IPCC, 2013b). Given the crucial role of energy in modern societies and the multiple associated impacts of fossil energy consumption (such as resource depletion, pollution, climate change, and energy and economic security), energy efficiency emerges as the key to prevent the increase in energy consumption without sacrificing the use of energy services and economic progress (i.e. to decouple economic growth and energy use). Even though a rebound effect[11] is likely to occur, increased efficiency may reduce energy consumption – thus catalysing a series of beneficial effects on the environment, economy and society (e.g. decreasing GHG emissions, reducing production costs, improving human health) (EC, 2014b).

In the European Union (EU), energy efficiency is a priority political action towards a low-carbon economy as well as a critical factor in the short, medium and long-term strategies for energy and climate action. For the short-term, it is one of the three pillars (along with GHG emissions and Renewable Energy Sources (RES)) of the 2020 Energy and Climate Package. For the medium-term, it is embodied in the 2030 Climate & Energy Framework (EC, 2014a) and substantiated in the binding target for 2030 that was proposed in the update to the Energy Efficiency Directive (EC, 2016). For the long term, the EU political guidelines for energy and climate (EC, 2011a, 2015) emphasize energy efficiency as a priority to face the challenges posed by the growing interdependency of global markets and as a driver of the EU energy system transformation.

Although medium and long term energy and climate targets are already being set, the EU is still working to meet the 20-20-20 targets, namely: 20% reduction in GHG emissions as compared to 1990 levels; 20% of RES in final energy consumption; and 20% saving in primary energy consumption as compared to the 2007 baseline projection for 2020 (EC, 2008) (this latter corresponding to the energy efficiency target). For the EU as a whole, GHG and RES targets are likely to be achieved while the energy efficiency target is expected to fall short of the target by around 2 percentage points (EC, 2014b). Moreover, the EU recognizes that only two-thirds of the progress made towards the 2020 target

[11] The rebound effect occurs because energy efficiency may lead to a reduction in energy prices. Such reduction may have income and substitution effects that stimulate energy demand that, therefore, may reduce the initial potential energy-savings from energy efficiency improvements (Broberg et al., 2015; Yu et al., 2015).

derives from improved efficiency, while the remaining one-third results from the lower economic growth as compared to projections (due to the financial crisis that hit Europe in 2008). This means that the EU energy-saving potential is not fully realised (EC, 2014b).

Following the EU law, the 2020 package was transposed to national legislation and each Member State defined its own targets. Portugal defined: i) a 31% share of RES in final energy consumption and 10% for energy consumption in transport; ii) a 25% saving in primary energy consumption when compared to the use of energy projected by the EU for Portugal in 2020 (EC, 2008), which corresponds to the national energy efficiency target (RCM 20/2013); and iii) an 18% to 23% reduction in GHG emissions by 2020, as compared to 2005 (APA, 2015), which includes the +1% cap set by EU Effort Sharing Decision (European Union, 2009) for the emissions not included in the EU Emissions Trading System. Actual performance points towards a satisfactory positioning by 2020 regarding RES targets as well as primary energy intensity, while final energy intensity was almost 30% above the EU average in 2013 (RCM 20/2013). To overcome this gap, the National Energy Efficiency Action Plan 2016 (NEEAP; (RCM 20/2013)) defined a set of policy instruments to promote energy efficiency through final energy consumption. The goal is to achieve the abovementioned 25% saving in primary energy consumption by 2020.

While energy efficiency is usually measured by energy intensity or its inverse, energy productivity, the energy efficiency targets established by the EU and Portuguese energy and climate policies for 2020 are expressed in terms of energy savings in absolute terms – i.e. a decrease in energy consumption. Thus, it is not measured in relation to any indicator of economic activity, such as Gross Domestic Product (GDP). Although the EU recognizes that alternative measures may be equated (EC, 2014b), the EU energy efficiency target set for 2030 is also expressed in terms of energy savings (EC, 2016).

Energy efficiency is a recurrent subject in literature, notably within climate change and mitigation policies analyses, and computable general equilibrium (CGE) models are increasingly applied (Babatunde, Begum, & Said, 2017). Numerous studies focus on rebound effects (e.g. (Broberg, Berg, & Samakovlis, 2015; Koesler, Swales, & Turner, 2016; Wei & Liu, 2017; Yu, Moreno-Cruz, & Crittenden, 2015)) and on the extent to which they compromise the effectiveness of energy efficiency policies (Bataille & Melton, 2017). Few studies focus on the relationship between energy use and economic growth. Examples of these latter are found in (Bataille & Melton, 2017) and (Cabalu, Koshy, Corong, Rodriguez, & Endriga, 2015), who applied dynamic CGE models to assess the impacts of energy efficiency improvements on economic growth in, respectively, Canada and the Philippines. Both concluded that energy efficiency improvements lead to an increase in GDP and employment, which are the result of an increase in output in almost all sectors except the energy sectors, whose activity levels decrease due to the lower demand for energy products. Previously, (Mahmood & Marpaung, 2014) concluded that while a carbon tax leads to a reduction in GDP in Pakistan, its combination with efficiency measures result in a growth in GDP as well as larger reductions in energy consumption and associated GHG emissions. Nonetheless, the review by (Bataille & Melton, 2017) highlights the limited attention devoted to the relationship between energy efficiency and economic performance in macroeconomic studies on energy efficiency impacts. Furthermore, CGE models are more often used to assess the impacts of economic instruments (notably taxes) to reduce CO_2 emissions (e.g. (Liu & Lu, 2015; Pereira, Pereira, & Rodrigues, 2016; Tian et al., 2017)) than to fulfil energy saving targets.

This paper aims at filling this gap in literature, by assessing the sectoral, economic and environmental impacts of achieving energy efficiency targets (measured as energy saving targets), for the case study of Portugal. To this end, we use a hybrid static CGE model for a small open economy and that comprises 31 production sectors. Results provide some counterintuitive outcomes that are of political and scientific interest at the international scale as they are not specific for the Portuguese case nor for a particular time horizon. In particular: (i) the heterogeneous impact on the efficiency of the energy system depending on whether the energy saving target is directed at primary or final energy consumption; (ii) the heterogeneous and undesirable outcomes with regard to the impact on fossil fuels with lower carbon content; and (iii) the larger and more distorting impacts on electricity generation arising from a relatively low taxation of all energy products (fossils and renewables) than those resulting from higher taxes on fossil fuels only.

The remainder of this paper is organized as follows. Section 6.2 describes the CGE model and data. Section 6.3 describes the assessed scenarios. Section 6.4 presents and discusses the impacts of simulated policies. Finally, Section 6.5 presents the main conclusions.

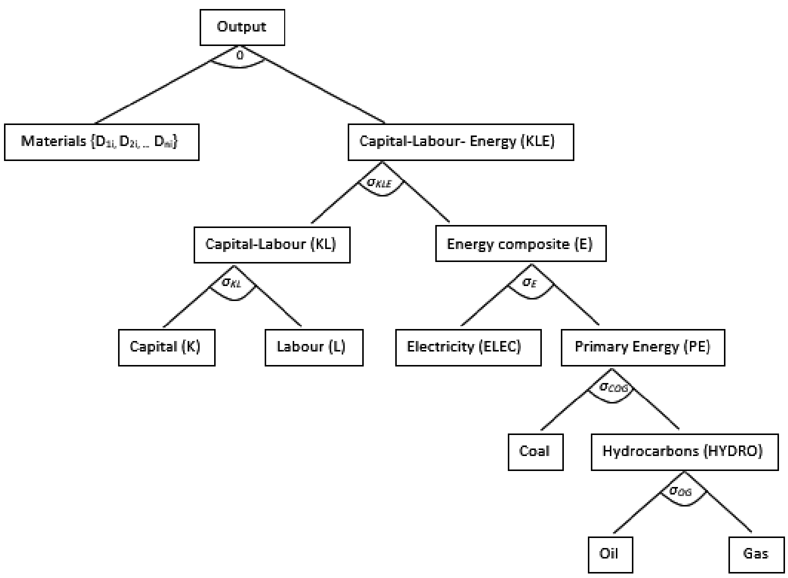
6.2. Model and data

A hybrid static CGE model for a small open economy is used, building on the one developed by (Labandeira, Labeaga, & Rodríguez, 2009). The model is extended with labour market imperfections and the technological disaggregation of the electricity production sector. The model has been programmed within General Algebraic Modelling System (GAMS (Rosenthal, 2012)), using the Mathematical Programming System for General Equilibrium (MPSGE) subsystem (Rutherford, 1999) and solved using the PATH solver (Ferris & Munson, 2008). The model comprises 31 production sectors (4 energy sectors and 27 non-energy sectors) and 3 institutional sectors (private sector, public sector and foreign sector). Primary production factors are capital and labour[12].

6.2.1. Production activities

Producer behaviour is based on the profit maximization principle, such that in each sector a representative firm maximizes profits subject to a constant returns to scale technology – characterized by a succession of nested constant elasticity of substitution (CES) production functions combining intermediate inputs and production factors (Figure 6.1). Produced goods and services are, in turn, split between the domestic and export markets according to a constant elasticity of transformation function (see also Section 6.2.3. Foreign sector).

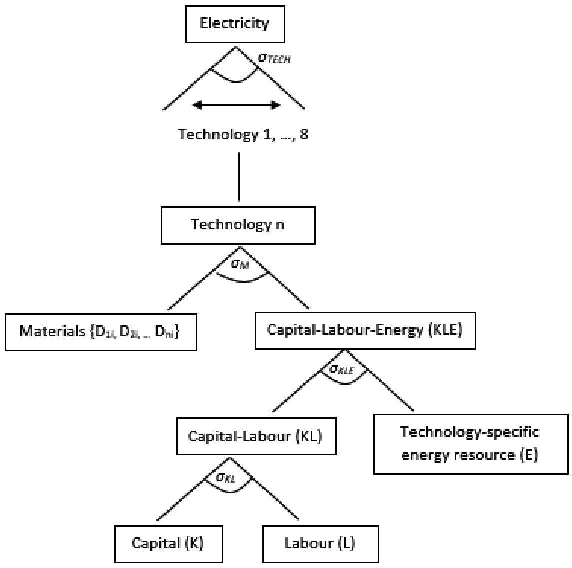
Figure 6.1. Production structure



[12] A full description of the production and consumption functions is provided in Appendix 6.1.

The model includes a bottom-up representation of the Portuguese power sector, which is represented by a set of eight discrete technologies that, together, provide the homogeneous electricity commodity. Each technology is described by a CES function combining different inputs: primary factors (labour and capital), materials and energy resources (Figure 6.2). This approach follows several examples in literature, such as (Proença & St. Aubyn, 2013; Wing, 2008; Cai & Arora, 2015).

Figure 6.2. Electricity sector production structure



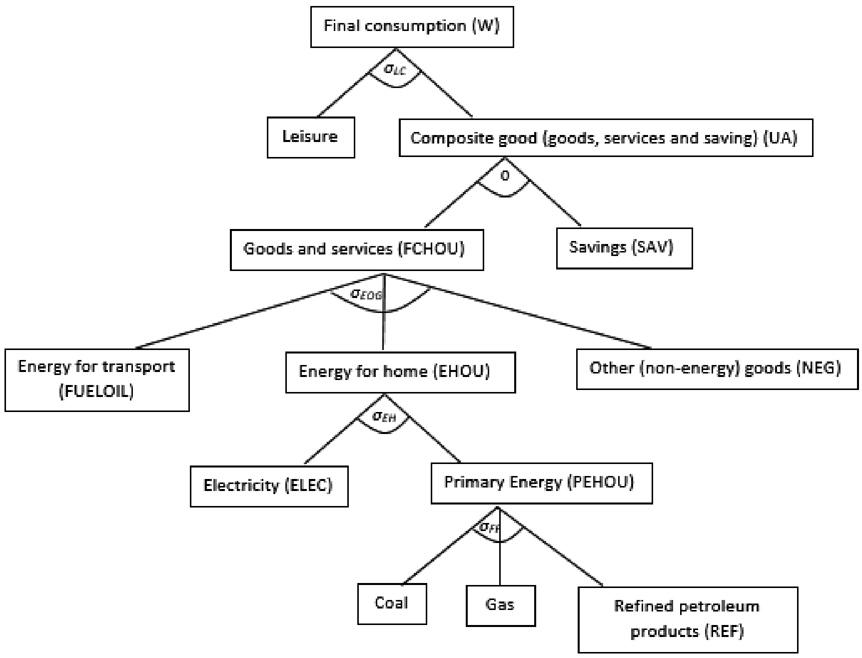
Note: The “technology-specific energy resource" only applies to fossil-fuelled technologies; for renewables, the energy sources are provided by nature at zero cost.

6.2.2. Domestic final consumers

Household behaviour follows the welfare maximization principle, such that a representative consumer maximizes utility (welfare) subject to a budget constraint. Consumption is captured through a succession of nested functions that combine, at the top level, demand for leisure and a composite good (made up of savings, and consumption of goods and services) according to a CES function (Figure 6.3). At the second level, savings trade-off with consumption in fixed proportions, given we assume that marginal propensity to save is constant. At the third nest, CES functions represent consumer decisions between energy and non-energy goods and services.

Government aims to maximize public consumption subject to a budget constraint. Government consumption comprises several goods and services (e.g. social security, healthcare and education). Public expenditure is financed through tax revenues, property and capital rents, and transfers.

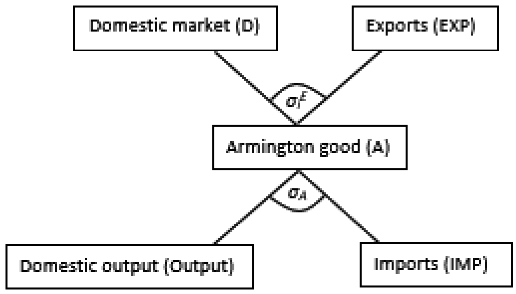
Figure 6.3. Consumption structure



6.2.3. Foreign sector

International trade is modelled under the Armington assumption that domestic and imported goods are imperfect substitutes for domestic consumption (Armington, 1969), meaning that total supply in the national economy (for intermediate and final demand) corresponds to a CES composite good that combines domestically produced and imported goods (the so-called "Armington good"; Figure 6.4). Likewise, domestically produced goods can be supplied to the inner market or exported to satisfy demand from the rest of the world, under a constant elasticity of transformation supply function. Finally, it is assumed that transfers and rents from the exterior, Portuguese consumption abroad, and tourist consumption in Portugal are exogenous.

Figure 6.4. Nesting production structure of Armington good



6.2.4. Factor markets and closure rules

Two primary production factors are considered: capital and labour. These are perfectly mobile between sectors at the national scale, but immobile internationally. Labour is supplied by a representative consumer owning a fixed endowment of time, which is devoted to labour supply and leisure consumption. The labour market is taken to be imperfect, where involuntary unemployment exists. This is introduced by a wage curve, which negatively relates the real wage level and unemployment rate by an elasticity parameter (the elasticity of real wage to unemployment; approximately -0.1) following (Blanchflower & Oswald, 1995). Equilibrium is determined by the intersection of the labour demand curve and the wage curve, setting a real wage that is above the market clearing level. Involuntary unemployment results from the difference between labour supply (given by the wage curve) and labour demand, which becomes endogenous to the model. The demand for labour by each production sector is determined by the solution of the producers' cost minimization problem. Accordingly, the optimal wage becomes endogenous to the model such that it satisfies the market clearance condition.

Capital supply is inelastic and capital demand is determined by the abovementioned cost minimization problem. Capital rents are endogenous to the model, determined by the market clearance condition. Investments correspond to the sum of sectors' gross capital formation, and is formulated as a Leontief function. National savings correspond to the sum of private and public savings and is, therefore, endogenous to the model. The national net lending/borrowing capacity, which corresponds to the difference between national saving and investment, determines the macroeconomic equilibrium.

6.2.5. Energy consumption and CO_2 emissions

The model computes energy consumption in physical units (thousand tonnes of oil equivalent; ktoe). These enter the model based on the sectoral-specific energy consumption per energy carrier (coal, refined petroleum products, natural gas and electricity) in the benchmark. It must be noted that: i) only primary consumption of coal by coal-fired power plants is included in the model because the consumption of coal by other sectors is negligible (DGEG, 2016a); ii) renewables are part of primary energy consumption of the “electricity” production sector (following (DGEG, 2016a)). CO_2 emissions resulting from fossil fuel combustion enter the model in fixed proportions to fossil fuels, according to the specific emission coefficient of each fossil fuel for each sector.

6.2.6. Benchmark data and calibration

The CGE model was calibrated to a base year which reflects the initial/benchmark equilibrium. Base year quantities and prices, together with the exogenous elasticities, determine the free parameters of the model’s functional forms (Böhringer & Rutherford, 2013). The core dataset of the model is a Social Accounting Matrix (SAM) for the year 2008, comprising 31 economic sectors (Appendix 6.2), built on the 2008 symmetric 86-sector Input-Output (I-O) tables for Portugal[13] (DPP, 2011). Unemployment data was taken from official statistics (INE, 2016b), and elasticities of substitution were taken from (Böhringer, Ferris, & Rutherford, 1998; EC, 2013b; Hertel, 1997; Kemfert & Welsch, 2000; Labandeira, Labeaga, et al., 2009; Melo & Tarr, 1992; Wing, 2006) (Appendix 6.3).

While the SAM and the elasticities of substitution provide the macroeconomic comprehensiveness of the model, the technological disaggregation of the electrical generation sector was introduced using a bottom-up approach. To this end, the SAM’s aggregate “Electricity” production sector was split into eight (most representative) technologies in Portugal (DGEG, 2016b) – three fossil-fuelled (coal, oil and natural gas) and five renewable sourced (hydropower, onshore wind power, solar photovoltaic, geothermal and biomass). Hence, the Electricity sector’s total output was broken-down

[13] More recent symmetric Input-Output tables for Portugal (for 2013) were made available in 29.12.2016 (INE, 2016a). The economic structure as of 2013 is broadly similar to that of 2008 – in particular, the weighted average of differences between sectoral shares in 2008 and 2013 is 0.27%.

according to the cost structure and the output shares of each generation technology. In particular, unitary costs of electricity generation per technology were taken from the TIMES_PT database (see (Teotónio, Fortes, Roebeling, Rodriguez, & Robaina-Alves, 2017)). These are disaggregated into capital costs, fuel costs, and operation and maintenance costs (the latter considered a proxy for labour costs, following (Wing, 2008). Although 2008 represents the benchmark year, technological costs for 2015 (from TIMES_PT) were used (Table 6.1). These most recent technological data provide a more accurate portrait of the current Portuguese power sector and are still coherent with the macroeconomic data referring to 2008 (given the stagnation of economic growth since the start of the financial crisis in 2008 and the lower pace at which the national economic structure evolves, as national accounts statistics confirm; see (DPP, 2011; INE, 2016a)). Accordingly, the Portuguese electrical mix considered in the benchmark corresponds to the average of the period 2008-2015. This average provides a better reference point than a single year, which is significantly dependent on the corresponding weather conditions – particularly for hydropower (e.g., hydropower generation in 2015 was 40% lower than in 2014 and 15% lower than the average of the period 2008-2015).

As macroeconomic and technological data derive from different sources, it was necessary to reconcile them so that they could be combined into an integrated framework of analysis. To do so, information on unit generation costs (€/MWh), input cost shares and electricity generated per technology in the period 2008-2015 (Table 6.1) were combined to compute the corresponding capital, labour and fuel costs per technology – thereby converting electrical generation from physical units (GWh) into monetary units that are compatible with the SAM. We thus obtained the necessary technological breakdown of the electricity generation sector in the SAM that is consistent with the TIMES_PT database (see (Teotónio et al., 2017)). These data were introduced in the CGE model to provide the bottom-up representation of the electrical generation sector in the benchmark year. Finally, CO_2 emission coefficients (CO_2 to energy content) were computed from emission data in the benchmark year (UN, 2016), and energy consumption (measured in physical units) was taken from the Energy Balance for Portugal (DGEG, 2016a).

Table 6.1. Electrical generation, unit output costs and cost shares and per technology in the benchmark

	GWh	%	Unit generation cost (€2011/MWh)	Input cost shares		
				Fuel	Capital	Labour
Year	*Average 2008-2015*		*2015*			
Fossil-fuelled technologies	**25 908**	**51.0%**				
Coal	11 576	22.8%	35.43 €	42.2%	23.8%	34.0%
Oil	2 469	4.9%	56.34 €	84.0%	6.3%	9.7%
Natural gas	11 863	23.4%	44.30 €	81.5%	9.1%	9.4%
Renewable technologies	**24 873**	**48.9%**				
Hydropower	11 588	22.8%	14.44 €	0.0%	68.50%	31.5%
Onshore wind power	9 709	19.1%	48.49 €	0.0%	74.6%	25.4%
Biomass	3 010	5.9%	185.19 €	68.4%	16.3%	15.3%
Solar photovoltaic	374	0.7%	137.95 €	0.0%	79.6%	20.4%
Geothermal	192	0.4%	62.29 €	0.0%	57.2%	42.8%
Total electrical generation	**50 780**	**100.00%**				

Source: Electrical generation data were taken from (DGEG, 2016c). Generation and input cost shares were based on the TIMES_PT database (see (Teotónio et al., 2017)).

6.3. Simulated scenarios

We take the economic structure of Portugal in 2008 to simulate the likely impacts of achieving the 25% energy savings set in the Portuguese NEEAP. The national statistics do not show significant structural changes apart from the small change in scale (i.e. the absolute value of GDP; the 2008 and 2013 relative sectoral breakdowns of gross value added (GVA) are broadly similar; (see (INE, 2016a)) and this is what is really relevant for CGE models). Moreover, this is in line with the methodology of the Portuguese Government (APA, 2015), which considers the 2008 sectoral GVA breakdown will persist over the next two decades.

The energy efficiency target is defined as a 25% reduction in primary energy consumption, while the expected impacts of the NEEAP are set both in terms of primary and final energy savings. Accordingly, we analysed the impacts of a reduction in primary and final energy consumption in Portugal. To simulate the impacts of energy efficiency targets, we took into account the energy savings achieved to date because of the implementation of the NEEAP. In particular, the 11% primary energy saving achieved in 2013 (PNAEE, 2017) falls 14 percentage points short of the set 25% primary energy saving (RCM 20/2013). Hence, an additional reduction of 14% is needed to comply with the national target. Assuming that no further efficiency improvements occur as a result of the NEEAP, the impacts of a 14% reduction in energy consumption represent the costs to assure the compliance with the national environmental targets. In addition, we simulated the extreme scenario where NEEAP measures did not take place (or, alternatively, a strong economic recovery took place) and, thus, corresponds with a 25% reduction in energy consumption. Given the RES and GHG emissions components of policies underlying our analysis, the energy consumption reduction scenarios are defined for reductions in primary or final energy consumption of fossil/fossil-fuelled or all energy products. In particular, we simulated the scenarios presented in Table 6.2.

Table 6.2. Simulated energy saving target scenarios

Scenario		Policy target (% energy saving)	Policy variable
Scenario PE	PE_14	-14% primary energy consumption	Energy savings in primary energy (PE) consumption of fossil fuels (coal, natural gas and refined petroleum products)*
	PE_25	-25% primary energy consumption	
Scenario FE_Fossil	FE_Fos_14	-14% final energy consumption	Energy savings in final energy (FE) consumption of fossil-fuelled energy products (natural gas, refined petroleum products and fossil-fuelled electricity)
	FE_Fos_25	-25% final energy consumption	
Scenario FE_All	FE_All_14	-14% final energy consumption	Energy savings in final energy (FE) consumption of all energy products (natural gas, refined petroleum products and electricity [from fossil and renewable sources])
	FE_All_25	-25% final energy consumption	

* Note: Imports of electricity are not taxed because: i) fossil and renewable sourced electricity imports are indistinguishable; and ii) electricity imports represent a negligible part of primary energy consumption in Portugal (see (DGEG, 2016d)).

The goal of this paper is to assess the economic impacts of complying with energy efficiency targets that may be defined in different ways and scenarios. All of them will generate direct extra costs for economic activities (and opportunity costs) that will drive substitution effects among inputs and changes in consumption behaviour. Accordingly, the hybrid CGE model will simulate the energy saving targets scenarios through a tax on primary/final consumption of fossil/all energy products that are, in turn, recycled via a reduction in indirect taxes on the final consumption of non-energy goods and services such that the fiscal revenue associated with the tax does not affect the public budget. The rationale considered to follow this methodology is twofold. On the one hand, the tax will capture the extra costs (direct or opportunity costs) associated with any specific measure on energy consumption to attain the energy savings targets. On the other hand, the tax provides desirable outcomes, such as “static efficiency” (i.e. identifying the cheapest compliance option (OECD, 2016)).

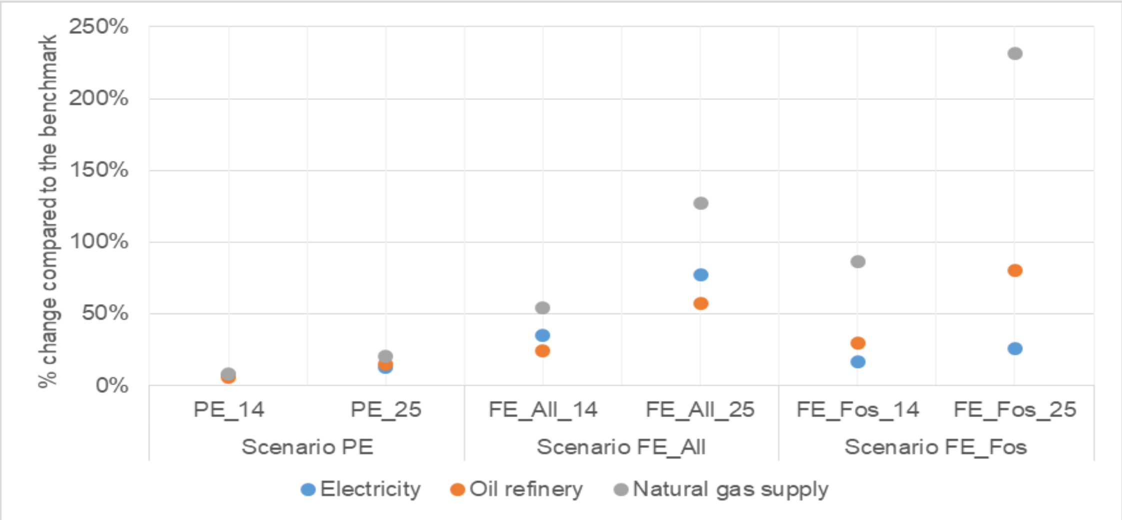
6.4. Results and discussion

This section presents and discusses the main results of the simulated policies from a sectoral, macroeconomic and environmental perspective.

6.4.1. Impacts on the energy sector

Achieving energy savings targets leads to demand price hikes in energy products – in particular if the policy target is attained via a tax on final energy consumption (scenarios FE_All and FE_Fos; Figure 6.5). The largest price increase occurs for natural gas, due to the higher ktoe content per euro (price) of natural gas (1.48 ktoe/M€) than other fossil fuels (e.g. 0.66 ktoe/M€ for refined oil products) – explained by the lower international prices per ktoe and the lower domestic fiscal burden on natural gas as compared to the other fossil fuels. Results for coal (prices and output levels) are not reported because there is no production of coal in Portugal and all consumption relies on imports (almost entirely for electricity generation).

Figure 6.5. Impacts of energy saving targets' scenarios, aiming a 14% (_14) and 25% (_25) reduction in energy consumption, on energy demand prices (% change as compared to the benchmark)

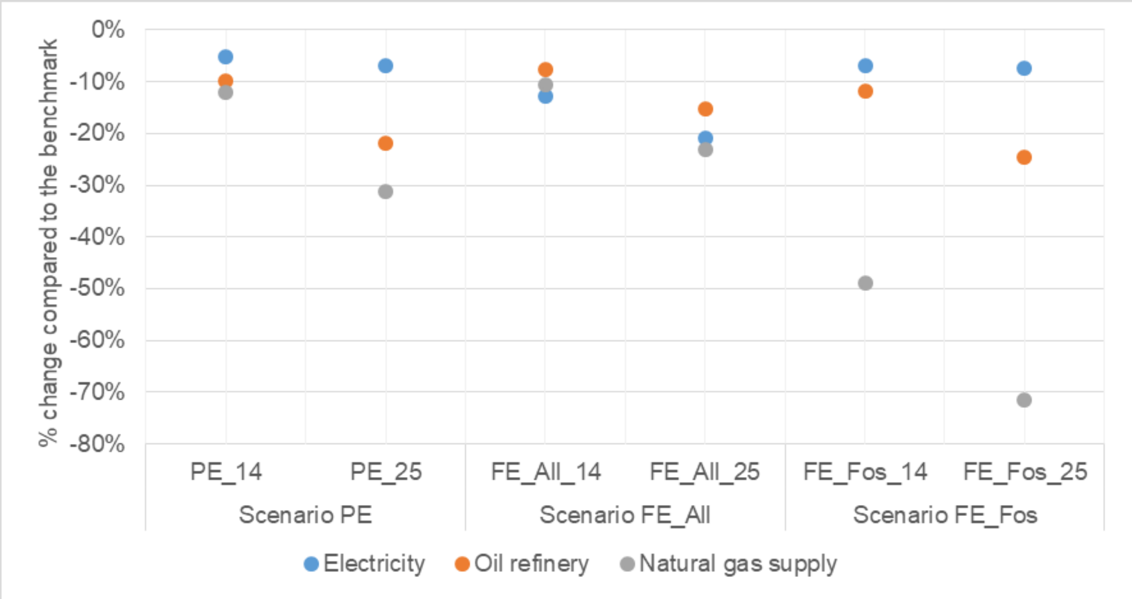


Constraining energy consumption induces a generalized decrease in output levels of the energy sectors. Natural gas records the strongest impacts (Figure 6.6), which is related to the above mentioned strong impacts on prices and to the below explained changes in the electricity mix (electricity is the main Portuguese consumer of natural gas).

Despite the strong impacts recorded in activity levels (Figure 6.6), there are no significant changes in the economy's energy mix[14]. The share of refined petroleum products (48% in the benchmark) ranges between 45% in the FE_Fos_25 scenario and 49% in the FE_All scenarios (_14 and _25). The share of electricity (28% in the benchmark) increases by up to 34% in the FE_Fos_25 scenario, while it remains constant in the PE and FE_All scenarios. Finally, the share of natural gas (7% in the benchmark) decreases to 4% in the FE_Fos_25 scenario. Note that the low shares of fossil fuels in the FE_Fos_25 scenario are offset by renewable-sourced electricity.

[14] Heat, waste and renewables, except electricity, were not included in the CGE model. Their share in the benchmark (17% of final energy consumption) is assumed to be kept constant in all scenarios.

Figure 6.6. Impacts of energy saving targets' scenarios, aiming a 14% (_14) and 25% (_25) reduction in energy consumption, on the activity levels of energy sectors (% change compared to the benchmark)



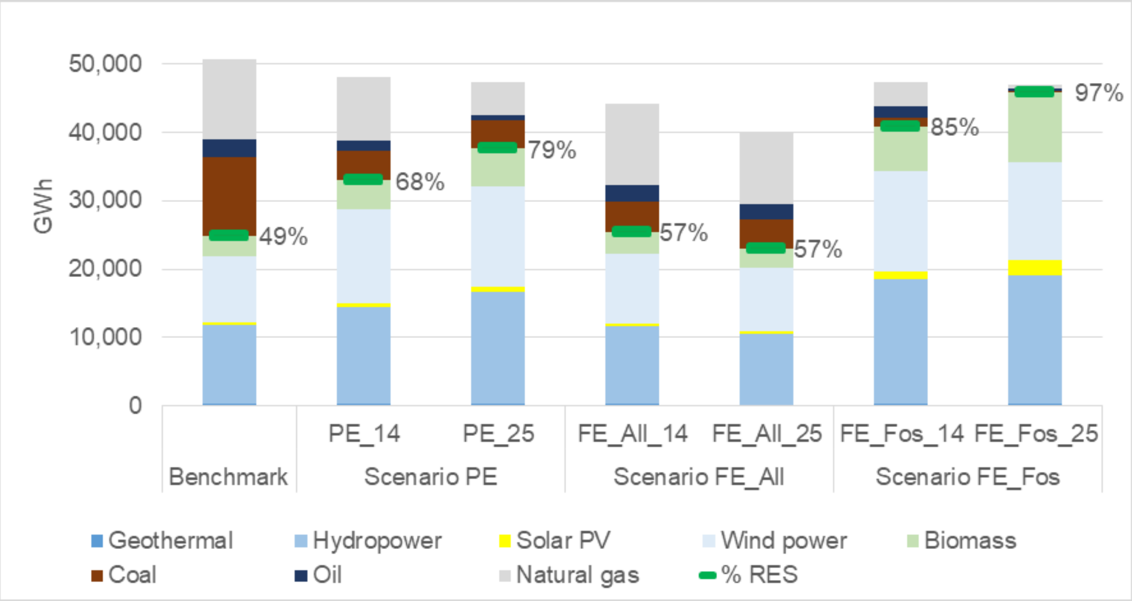
Focusing on the electricity sector, results show that achieving the policy target through energy savings in the final consumption of all energy products (scenario FE_All) implies that changes in electricity generation are mostly explained by each technology's cost-effectiveness and maximum capacity. By contrast, achieving the policy target via energy savings in the consumption of fossil fuels only (scenarios PE and FE_Fos) provides advantages for renewable-sourced electricity generation (Figure 6.7). This result derives from the fact that electricity is a homogeneous good and, thus, generation technologies are treated as quasi-perfect substitutes[15]. Hence, as fossil-fuelled generation becomes more expensive due to the tax on energy inputs, renewable technologies increase their activity levels to offset the decrease in fossil generation.

Compared to the benchmark, the electrical mix becomes dominated by renewable technologies when energy saving targets are achieved by limiting fossil fuels consumption (scenarios PE and FE_Fos; Figure 6.7). Under a 14% reduction in energy consumption, wind and hydropower output increase, respectively, by up to 42% and 22% in the PE scenario, and by up to 54% and 61% in the FE_Fos scenario. Under the energy saving target of 25%, wind and hydropower output increase, respectively, by up to 54% and 44%

[15] We assume that the elasticity of substitution between technologies is 10, following (Wing, 2006), as to prevent corner solutions (i.e. all electricity is generated by the cheapest technology).

in the PE scenario, and by 54% and 71% in the FE_Fos scenario. In the last two scenarios it represents the maximum technical potential of wind power and, for the FE_Fos scenario, the maximum technical potential for hydropower under average hydrologic conditions (see (APA, 2012)). If the energy saving target covers final consumption of all energy products (scenario FE_All), renewables do not have a comparative advantage over fossils. As a result, the electrical mix is not so significantly different from the benchmark.

Figure 6.7. Electricity generation mix per energy saving targets' scenario, aiming a 14% (_14) and 25% (_25) reduction in energy consumption (GWh and share of RES)



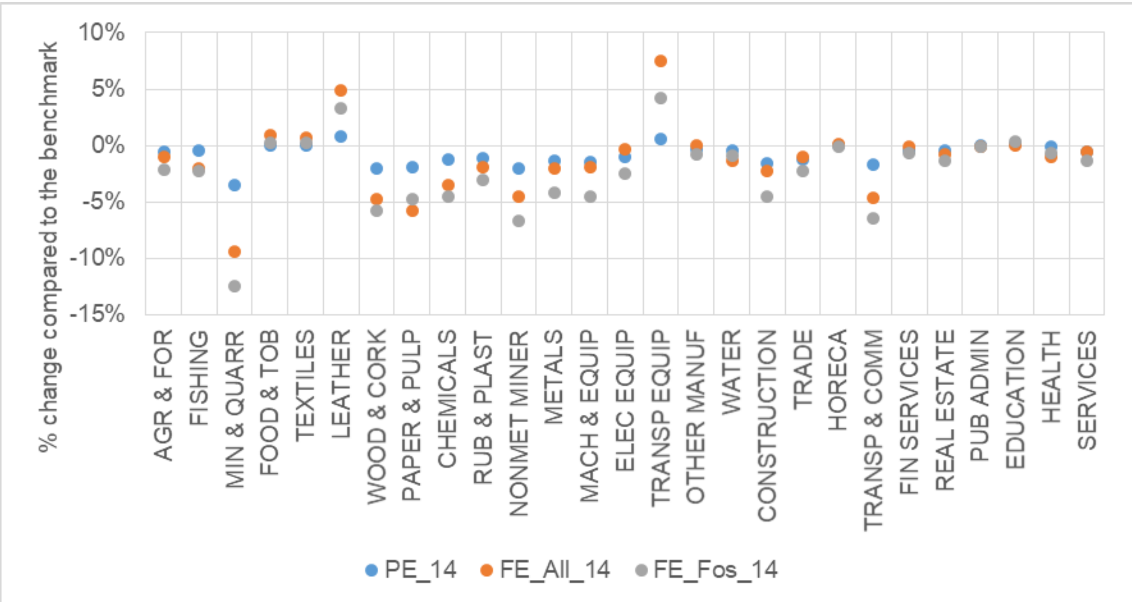
6.4.2. Impacts on the non-energy sectors

As to the non-energy sector activity levels, smaller variations occur if the energy saving target is achieved through reductions in primary energy consumption (Figure 6.8[16]). Results show a generalized decrease in activity level in almost all cases. Service sectors (namely public, financial and other personal services) maintain their activity levels, as their production costs are barely affected given their low levels of energy consumption. Sectors with relevant levels of energy consumption (such as accommodation and food service

[16] Results for policies aiming at a 25% reduction in energy consumption lead, in almost all sectors and scenarios, to impacts that are twofold the ones obtained for a 14% reduction. Hence, those former results are not presented.

activities, and manufacturing of food and textiles) also maintain their activity levels as the effect of the energy tax is mitigated via fiscal revenue recycling (reduction of indirect taxes on goods and services). Sectors with relatively lower energy consumption and higher indirect taxation, such as the manufacturing of leather products and transport equipment, manage to increase their output levels in the presence of energy taxes. Within the mechanism adopted, it turns out that the effect of energy taxation on production costs is counterbalanced by a reduction in the tax burden in the final consumption of goods and services supplied by these sectors and, hence, results in moderate changes in consumer prices and reasonable inflation rates for all scenarios (see also Section 6.4.3). By contrast, energy intensive sectors record noticeable reductions in their production levels (e.g. between -2.0% and -6.7% for non-metallic mineral products). This negative effect derives, first, from the preponderance of energy inputs in the production function (increasing production costs) and, second, from the fact that this effect could not be completely offset via fiscal revenue recycling (thus resulting in increasing prices and reducing activity levels). Overall, the most affected sectors represent around 17% of GDP in the benchmark and simulated scenarios and, therefore, none of the simulated policies induces significant structural changes in the national economy.

Figure 6.8. Sectoral impacts of energy saving targets' scenarios, aiming a 14% reduction in energy consumption, on output levels of non-energy sectors (% change compared to the benchmark)



6.4.3. Macroeconomic impacts

Results show that the macroeconomic impacts of achieving energy saving targets are broadly negative, irrespective of the tax base (Table 6.3). The energy tax increases energy prices and production costs and, thus, reduces profits. Accordingly, producers rearrange production processes – in particular the use of energy and other inputs (notably capital and labour) as to minimize the impacts on production costs. Simultaneously, sectoral activity levels contract and, as a consequence, demand for inputs and labour decrease, and involuntary unemployment increases. Still, the impacts of taxing primary energy consumption (scenario PE) are the less severe.

The fiscal revenue recycling mechanism implies that consumer prices do not increase considerably following the increase in production costs and, thus, the aggregate effects on final consumption of non-energy products are negligible. Though inflation is moderate, its combined effect with lower nominal wages results in a slight decrease in real wages. Moreover, this decrease in real wages is associated with an increase in the rate of involuntary unemployment. Overall, this leads to a decrease in real GDP in all scenarios.

From a macroeconomic perspective, attaining the energy saving targets by taxing primary energy consumption (scenario PE) is most appropriate as it results in smaller reductions in GDP and lower inflation rates, while the effects in unemployment and real wages are limited. Comparison of the FE_ scenarios shows that the most cost-effective solution is to make no distinction between fossil and renewable sources (scenario FE_All). This is related to the fact that taxing all energy consumption implies that the tax burden is spread across a larger tax base (which reduces the tax rate to achieve a certain energy saving) and, thus, the resulting economic distortions are smaller.

Table 6.3. Macroeconomic impacts of simulated energy saving targets' scenarios, aiming a 14% (_14) and 25% (_25) reduction in energy consumption (% change compared to the benchmark)

Macroeconomic variable	Scenario PE		Scenario FE_All		Scenario FE_Fos	
	PE_14	PE_25	FE_All_14	FE_All_25	FE_Fos_14	FE_Fos_25
Real GDP at market prices	-0.5	-1.1	-2.3	-5.1	-2.6	-6.2
Consumer Price Index	0.3	0.5	0.5	1.3	1.1	2.5
Welfare (HEV)	0.0	0.0	0.0	0.0	0.0	0.1
Real wage	-0.2	-0.2	0.0	0.0	-0.2	-0.3
Unemployment rate	1.3	2.6	0.0	0.0	1.3	3.9

6.4.4. Impacts on energy security

The reduction in energy consumption leads to an improvement in the energy trade balance for all scenarios (i.e. to a lower deficit, as Portugal is a net energy importer; Table 6.4). The smallest deficit reduction occurs for the PE scenario, where national energy needs are increasingly satisfied by imports of final energy products and electricity due to the larger impacts on primary energy prices that rise production costs of the energy sectors and reduce their activity levels. The largest deficit reduction occurs in the FE_Fos scenario, where the electricity trade balance deteriorates in response to the lower activity level of the fossil-fuelled energy sectors – further intensified by the reduction in domestic power generation (between -6.9% and -7.6%; Figures 6.6 and 6.7).

The energy saving targets scenarios assessed improve, also, energy security, measured by the dependence on net imports (Table 6.4), due to the simultaneous reduction in energy consumption and increase in endogenous renewable-sourced energy. Scenario FE_All presents the smallest progress because the incentive to shift from imported to renewable domestic energy sources is limited given that all energy products are taxed.

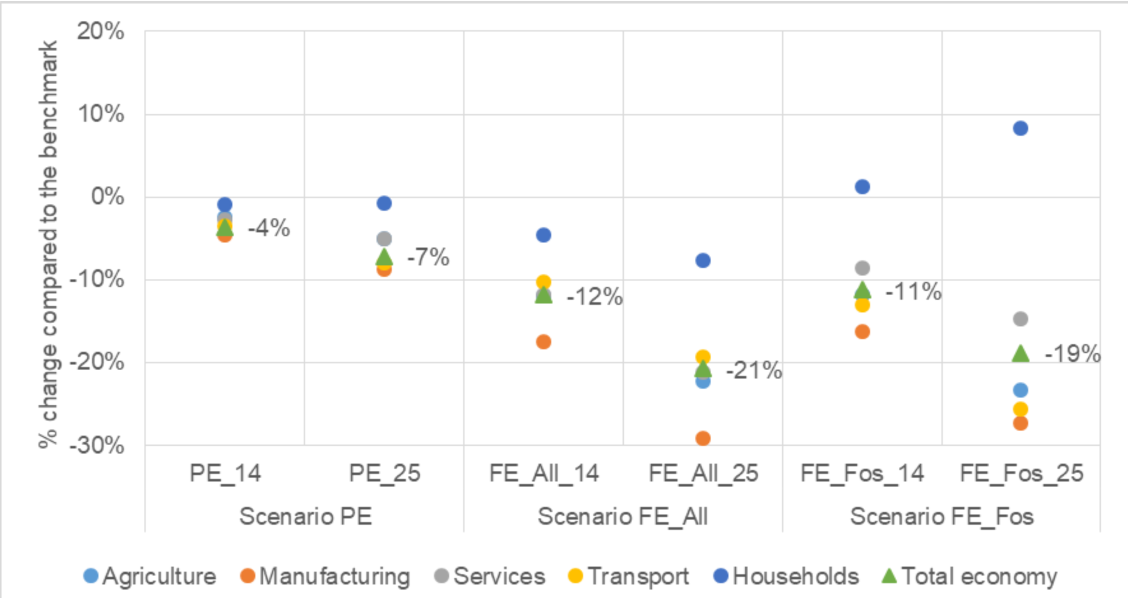
Table 6.4. Impacts of energy saving targets' scenarios, aiming a 14% (_14) and 25% (_25) reduction in energy consumption, on energy trade balance (% change compared to the benchmark) and on energy indicators

	Benchmark (M€)	Scenario PE		Scenario FE_All		Scenario FE_Fos	
		PE_14	PE_25	FE_All_14	FE_All_25	FE_Fos_14	FE_Fos_25
Energy trade balance							
Mining of coal; extraction of crude petroleum and natural gas	-7,478.22	-13.4%	-26.5%	-10.8%	-18.7%	-21.1%	-35.1%
Refined petroleum products	-679.93	88.1%	203.6%	-7.6%	-14.9%	-8.1%	-19.7%
Electricity	-636.77	18.2%	35.6%	-6.2%	-17.5%	49.8%	89.6%
Natural gas	-0.12	93.4%	183.5%	-10.7%	-23.1%	-47.1%	-69.4%
Total	-8,795.04	-3.3%	-4.2%	-10.2%	-18.3%	-14.9%	-24.9%
Energy indicators							
Energy dependence (%)	76.3%	70.9%	65.7%	74.7%	74.8%	64.9%	57.8%
Share of energy in total trade (%)	10.7%	10.0%	9.4%	9.9%	9.1%	9.5%	8.6%
Energy trade balance (% GDP)	-5.1%	-5.0%	-4.9%	-4.7%	-4.3%	-4.4%	-4.0%

6.4.5. Impacts on energy intensity

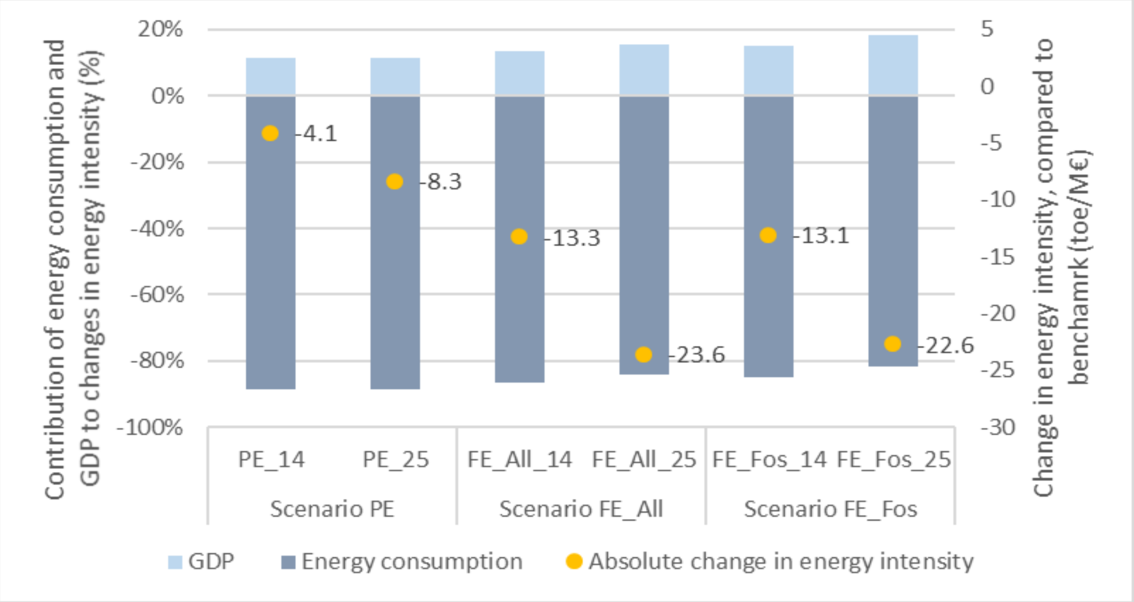
Final energy intensity falls in all scenarios (Figure 6.9). As expected, the largest decreases are observed for the most energy intensive sectors (in particular manufacturing and transport). Scenarios FE_All and FE_Fos lead to similar changes in total energy intensity, despite sectoral differences, which are explained by the incidence base of energy saving targets (all energy products and fossil fuels, respectively) and the sectoral energy mix. Accordingly, the services and households sectors, which consume mainly electricity, record largest reductions within the FE_All scenario.

Figure 6.9. Impacts of energy saving targets' scenarios, aiming a 14% (_14) and 25% (_25) reduction in energy consumption, on intensity of final energy consumption (% change compared to the benchmark)



The decomposition of aggregate energy intensity changes into the contribution of changes on energy consumption and GDP (Figure 6.10) shows that improvements are mostly due to a reduction in energy consumption. Thus, energy intensity improvements derive, mainly, from energy efficiency gains (i.e. from lower energy needs per output) and, less so, from structural changes in the economy at the aggregate level (i.e. from a shift to tertiary sector activities with lower energy consumption) as the sectoral GVA structure is kept relatively unchanged between scenarios.

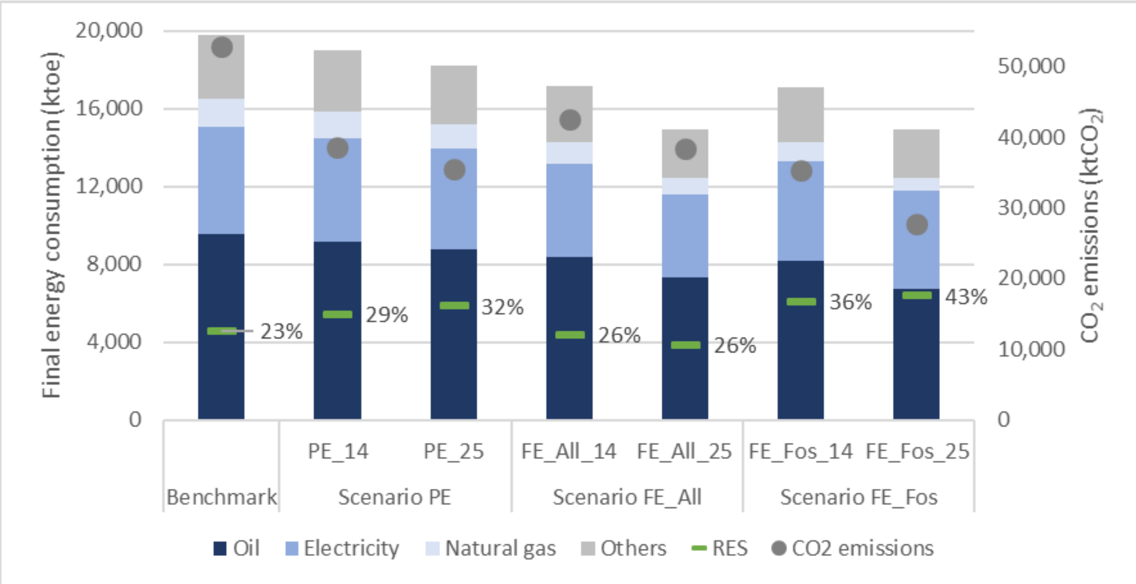
Figure 6.10. Decomposition of energy intensity changes into components per energy saving targets' scenario, aiming a 14% (_14) and 25% (_25) reduction in energy consumption



6.4.6. Progress towards policy goals for renewables and CO_2 emissions

Results highlight the effectiveness of energy savings targets focused on the consumption of fossil fuels in strengthening the role of RES in final energy consumption (Figure 6.11). Lowest levels of fossil fuel consumption and largest shares of RES in the electrical mix produce noticeable reductions in CO_2 emissions. In the context of a 14% reduction in energy consumption, CO_2 emissions decrease by between 32% (FE_All scenario) and 43% (FE_Fos scenario); in the extreme scenario of a 25% energy saving, CO_2 emissions decrease by between 38% and 55%, respectively (Figure 6.11). The environmental benefits of the FE_All scenario are the smallest because fossil and renewable energy sources are indistinctly treated and, thus, the CO_2 emitting sectors maintain a prevailing role in the national energy mix. Hence, our results confirm that promoting energy savings via energy taxes is an effective policy to decouple energy and CO_2 from GDP growth.

Figure 6.11. Final energy consumption and CO_2 emissions per energy saving targets' scenario, aiming a 14% (_14) and 25% (_25) reduction in energy consumption (ktoe and share of RES)

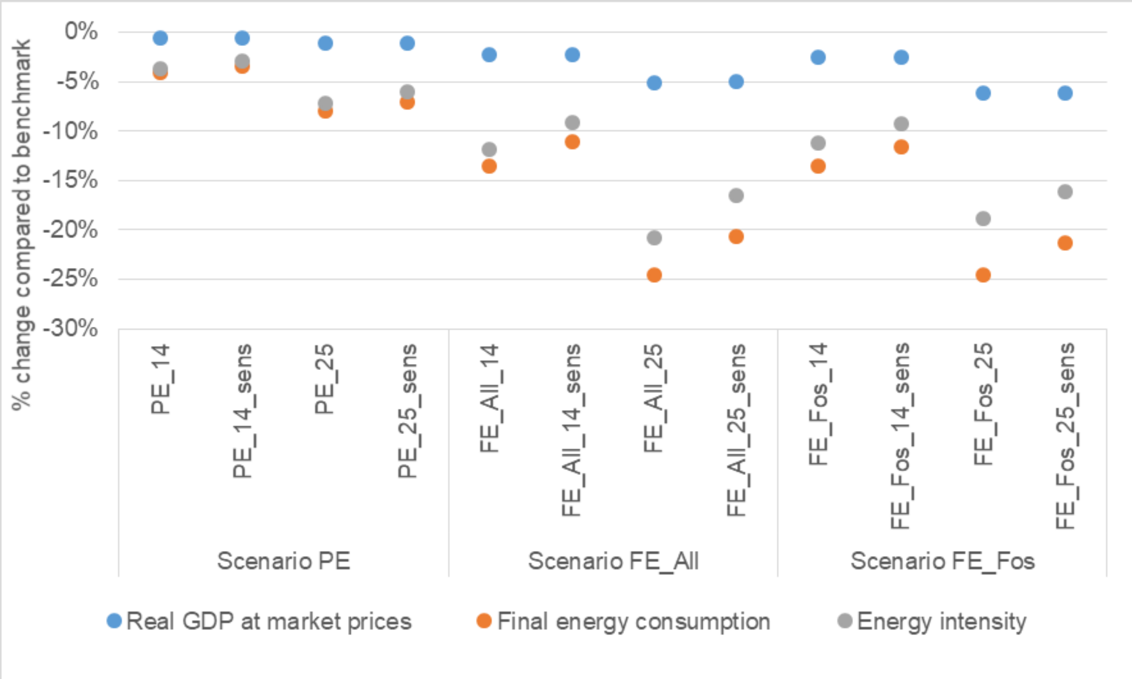


Note that the 14% and 25% reduction in final energy consumption (scenarios FE_All and FE_Fos) correspond to smaller reductions in primary energy consumption for scenario FE_All (-12% and -20% primary energy consumption, respectively), but to larger reductions for scenario FE_Fos (-21% and -32% primary energy consumption, respectively). The largest difference recorded in the FE_Fos scenario is explained by the dominant role of renewable-sourced electricity and the modelling assumption that all renewable primary energy consumption for power generation is transformed into electricity without any efficiency losses – hence tightening the gap between primary and final energy consumption (i.e. increasing the efficiency of the energy system).

6.4.7. Sensitivity analysis

The robustness of the model results is assessed through a sensitivity analysis, simulating the described scenarios with alternative elasticities of substitution available in literature ((Aguiar, Narayanan, & McDougall, 2016; EC, 2013b; Okagawa & Ban, 2008); Appendix 6.4). The impacts on key variables are broadly similar, though smaller, as compared to those obtained for the reference elasticities (Figure 6.12). Differences in real GDP are less than 0.2 p.p.; differences in final energy consumption vary between 0.6p.p. (PE_14 scenario) and 3.9 p.p. (FE_All_25 scenario); and differences in energy intensity vary between 0.7 p.p. (PE_14 scenario) and 4.2 p.p. (FE_All_25 scenario). Thus, overall reported changes are coherent between our central results and this sensitivity analysis – confirming the robustness of our model.

Figure 6.12. Sensitivity analysis - Economic impacts of simulated energy saving targets' scenarios (% change compared to the benchmark)



6.5. Conclusions and policy implications

Public policies fostering sustainability encompass, without exception, concerns with dematerialization and resource efficiency, as these are key factors to decouple economic growth from resources use. This issue becomes particularly relevant with regard to energy, given its crucial role in modern economies. Such relevancy is patent in the international framework of climate policies and in all current and upcoming EU energy and climate policies and their transposition to EU Member States legislation. The European Union has defined global energy and climate targets for 2020 and 2030, and Member States cannot overlook those targets as these constitute the key to test EU's commitment with climate change mitigation. Accordingly, the objective of this paper is to assess the sectoral, economic and environmental impacts of energy efficiency targets, using Portugal as a case study. Our point of departure was the national energy efficiency target (25% reduction in primary energy consumption) and the respective progress achieved until now (in 2013, Portugal had reduced primary energy consumption by 11%). Based on these premises, we calculated the existing gap that may have to be filled with additional policies to ensure that Portugal will meet the defined targets.

The three simulated policies consist in achieving energy efficiency targets through reductions in primary or final energy consumption of fossil fuels or all energy products. Following energy taxation, activity levels of the energy sectors as well as the outputs of the most energy intensive sectors (notably manufacturing) are reduced – culminating in a reduction in real GDP in all cases. Other macroeconomic impacts encompass a slight increase in unemployment rates and a reduction in production factor remuneration. Furthermore, given that Portugal is a net energy importer, gains in energy savings lead to lower energy trade deficits. This increases the role of renewable electricity, especially in the case of energy savings in fossil-fuelled energy. Such a mix contributes to attain the RES share target set by the country and leads to significant reductions in CO_2 emissions – even if our results may be rather conservative, as we do not model biomass and other renewable energy consumption except in the power sector (it is assumed that the share of renewable energy by end use sectors, except in power sector, remains constant in all scenarios). Nonetheless, such a mix may pose additional challenges concerning energy security issues due to the variability and uncertainty of renewable electricity. Finally, an overall reduction in energy intensity is foreseen, mostly due to a reduction in energy consumption – reinforcing the idea that the underlying policies promote the decoupling of economic growth and energy use.

Our results suggest that achieving the energy efficiency policy target via energy savings in primary energy consumption of fossil fuels is the most cost-effective of the simulated policies as it generates lowest macroeconomic costs to attain the policy targets and simultaneously induces the smallest reduction in final energy consumption (the only relevant energy for firms and households). This result is explained by two simultaneous effects of the energy tax on primary energy consumption: (i) it produces strong incentives to improve the efficiency of the energy producers (supplying final energy to the markets) thus reinforcing the efficiency of the energy system (as these incentives are greater for those technologies exhibiting lower efficiencies); (ii) it is more beneficial from an economic perspective because most economic activities are final consumers of energy (and therefore not directly liable for the energy tax).

Results also show that fiscal policies burdening consumed energy quantities (ktoe) may have unexpected effects on energy markets and undesired consequences from an environmental perspective. Natural gas records the strongest impacts, as compared to refined petroleum products and electricity inputs. This is due to the greater ktoe to euro ratio of natural gas than, for instance, refined petroleum products, which results in a greater relative weight of the energy tax on the price of natural gas. As a result, any policy aiming energy savings by taxing the energy content (e.g. ktoe) will produce greater distortions on natural gas markets (on the price and consumption levels) and will penalise relatively more an energy product with lower environmental impacts (lower than refined petroleum products, for example). This outcome highlights that the relationship between improvements in energy savings and reductions in GHG emissions is not straightforward – suggesting that mitigation policies (e.g. carbon taxation) may be coupled with energy efficiency policies in order to avoid undesirable results. Another counterintuitive result is that the larger impacts on electricity prices and outputs are linked to the taxation of final consumption of all energy products, which spreads the fiscal burden across a larger tax basis (i.e. implies lower ktoe tax rates) and, therefore, should produce lower distortions in energy markets.

Our analysis presents some caveats. First, we use a static general equilibrium model which only allows for a comparative-static analysis, not capturing the economy's adjustment path towards the policy targets. Second, the model does not simulate final renewable energy consumption (except for the consumption of renewable electricity), implying that our results may be conservative in the case of RES targets. Third, the economic effects of the implemented policies envisaging energy savings (i.e. energy efficiency, in the EU policy jargon) are the outcome of exogenous elasticities of substitution estimated from historical data. However, the sensitivity analysis confirmed the robustness of our results. Despite these limitations, this paper fills a gap in literature regarding the quantification of the real impacts of binding energy saving targets set by public policies and provides some insight on unexpected outcomes that may be considered in any climate/energy policy-making process in the international context. Furthermore, it constitutes the first quantitative assessment of the economic impacts that energy efficiency targets may pose to the Portuguese economy and presents sectoral detail that allows for the design of fine-tuned public policies. Hence, the approach can be replicated in other countries and regions that are committed to energy efficiency targets, as these necessarily imply a trade-off between economic growth and environmental goals.

Appendix 6.1. Model description

A full description of the production and consumption functions is provided below (see Figures 6.1 to 6.4 in the text for a depiction of production and consumption structures). They represent constant elasticity of substitution (CES) functions except for equations 1 and 14, which correspond to Leontief functions, and equation 17, which is a Cobb–Douglas function.
There are 31 production sectors, denoted by i, which are described in detail in Appendix 6.2. Greek letters stand for scale parameters {α, λ, γ, φ} and elasticity of substitution {σ}. Latin letters stand for share parameters in the production and consumption functions {a, b, c, d, s}. Subscripts A and H stand for production activity and households, respectively.

Production

Non-electricity production sector

$$Output_i = \min\left(\frac{KLE_i}{c_{0i}}, \frac{CID_{1i}}{c_{1i}}, ..., \frac{CID_{ni}}{c_{ni}}\right)$$

Eq. 1 - Output from sector i {KLE + intermediate inputs}

$$KLE_i = \alpha_i \left(a_i KL_i^{\frac{\sigma_i^{KLE}-1}{\sigma_i^{KLE}}} + (1-a_i) E_i^{\frac{\sigma_i^{KLE}-1}{\sigma_i^{KLE}}} \right)^{\frac{\sigma_i^{KLE}}{\sigma_i^{KLE}-1}}$$

Eq. 2 - KLE_i {composite input KL + Energy (E)}

$$KL_i = \alpha_{iKL} (a_{iKL} L_i^{\frac{\sigma_i^{KL}-1}{\sigma_i^{KL}}} + (1-a_{iKL}) K_i^{\frac{\sigma_i^{KL}-1}{\sigma_i^{KL}}})^{\frac{\sigma_i^{KL}}{\sigma_i^{KL}-1}}$$

Eq. 3 - KL_i {composite input Capital (K) + Labour (L)}

$$E_i = \alpha_{iE} \left(a_{iE} ELEC_{iA}^{\frac{\sigma_i^{E}-1}{\sigma_i^{E}}} + (1-a_{iE}) PE_i^{\frac{\sigma_i^{E}-1}{\sigma_i^{E}}} \right)^{\frac{\sigma_i^{E}}{\sigma_i^{E}-1}}$$

Eq. 4 - E_i {composite input Electricity (ELEC) + Primary energy (PE)}

$$PE_i = \alpha_{iPE} \left(a_{iPE} COAL_{iA}^{\frac{\sigma_i^{PE}-1}{\sigma_i^{PE}}} + (1-a_{iPE}) HYDRO_i^{\frac{\sigma_i^{PE}-1}{\sigma_i^{PE}}} \right)^{\frac{\sigma_i^{PE}}{\sigma_i^{PE}-1}}$$

Eq. 5 - PE_i {composite input COAL + Hydrocarbons (HYDRO)}

$$HYDRO_i = \alpha_{iPET} \left(a_{iPET} REF_{iA}^{\frac{\sigma_i^{PET}-1}{\sigma_i^{PET}}} + (1-a_{iPET}) GAS_{iA}^{\frac{\sigma_i^{PET}-1}{\sigma_i^{PET}}} \right)^{\frac{\sigma_i^{PET}}{\sigma_i^{PET}-1}}$$

Eq. 6 - $HYDRO_i$ {composite input Refined oil products (REF) + Natural Gas (GAS)}

Electricity production sector

$$ELECTRICITY = \alpha_{TECH} \left(\sum_{t=1}^{n} s_t ELECT_t^{\frac{\sigma^{TECH}-1}{\sigma^{TECH}}} \right)^{\frac{\sigma^{TECH}}{\sigma^{TECH}-1}} , \sum_{t=1}^{n} s_t = 1$$

Eq. 7 - Composite of ELECTRICITY (aggregate of n generation technologies)

$$ELECT_t = \alpha_t \left(a_t KLE_t^{\frac{\sigma_t^M - 1}{\sigma_t^M}} + \sum_{j=1}^{n} b_{jt} \left(D_{tj}\right)^{\frac{\sigma_t^M - 1}{\sigma_t^M}} \right)^{\frac{\sigma_t^M}{\sigma_t^M - 1}}, \sum_{j=1}^{n} b_{jt} = \left(1 - a_t\right)$$

Eq. 8 - Output from technology t {KLE + intermediate inputs (D_{it})}

$$KLE_t = \alpha_t \left(a_t KL_t^{\frac{\sigma_t^{KLE} - 1}{\sigma_t^{KLE}}} + (1 - a_t) E_t^{\frac{\sigma_t^{KLE} - 1}{\sigma_t^{KLE}}} \right)^{\frac{\sigma_t^{KLE}}{\sigma_t^{KLE} - 1}}$$

Eq. 9 – KLE_t {composite input KL + Energy (E)}

$$KL_t = \alpha_{tKL} (a_{tKL} L_t^{\frac{\sigma_t^{KL} - 1}{\sigma_t^{KL}}} + (1 - a_{tKL}) K_t^{\frac{\sigma_t^{KL} - 1}{\sigma_t^{KL}}})^{\frac{\sigma_t^{KL}}{\sigma_t^{KL} - 1}}$$

Eq. 10 – KL_t {composite input capital (K) + labour (L)}

Foreign trade

$$A_i = \lambda_i \left(b_i Output_i^{\frac{\sigma_i^A - 1}{\sigma_i^A}} + (1 - b_i) IMP_i^{\frac{\sigma_i^A - 1}{\sigma_i^A}} \right)^{\frac{\sigma_i^A}{\sigma_i^A - 1}}$$

Eq. 11 - Armington nest for total supply {Domestic output (OUTPUT) + Imports (IMP)}

$$A_i = \gamma_i \left(d_i D_i^{\frac{\sigma_i^\varepsilon + 1}{\sigma_i^\varepsilon}} + (1 - d_i) EXP_i^{\frac{\sigma_i^\varepsilon + 1}{\sigma_i^\varepsilon}} \right)^{\frac{\sigma_i^\varepsilon}{\sigma_i^\varepsilon + 1}}$$

Eq. 12 - Armington nest for total demand {Domestic demand (D) + Exports (EXP)}

Consumption

$$W = \left(s_{UB} LEISURE^{\frac{\sigma^{UB} - 1}{\sigma^{UB}}} + (1 - s_{UB}) UA^{\frac{\sigma^{UB} - 1}{\sigma^{UB}}} \right)^{\frac{\sigma^{UB}}{\sigma^{UB} - 1}}$$

Eq. 13 – Welfare function {Leisure + Consumption (UA)}

$$UA = \min\left(\frac{SAV_{CONS}}{s_{UA}}, \frac{FCHOU}{(1 - s_{UA})} \right)$$

Eq. 14 – UA composite good {savings (SAV) + Final consumption (FCHOU)}

$$FCHOU = \varphi_{FCH} \left(s_{EH} EHOU^{\frac{\sigma^{FCH} - 1}{\sigma^{FCH}}} + s_{FH} FUELOIL^{\frac{\sigma^{FCH} - 1}{\sigma^{FCH}}} + (1 - s_{EH} - s_{FH}) NEG^{\frac{\sigma^{FCH} - 1}{\sigma^{FCH}}} \right)^{\frac{\sigma^{FCH}}{\sigma^{FCH} - 1}}$$

Eq. 15 – FCHOU {composite good of Energy for home (EHOU) + Energy for transport (FUELOIL) + Non-energy goods (NEG)}

$$EHOU = \varphi_{EH}\left(s_{EH} ELEC_H^{\frac{\sigma^{EH}-1}{\sigma^{EH}}} + (1-s_{EH}) PEHOU^{\frac{\sigma^{EH}-1}{\sigma^{EH}}} \right)^{\frac{\sigma^{EH}}{\sigma^{EH}-1}}$$

Eq. 16 – EHOU {composite good of Electricity (ELEC) + Primary energy (PEHOU)}

$NEG = \prod_{i=1}^{n} D_{iH}^{SO_i}$, where i ≠ energy products

Eq. 17 – NEG {composite consumption of non-energy goods}

$$PEHOU = \varphi_{NEH}\left(s_C COAL_H^{\frac{\sigma^{NEH}-1}{\sigma^{NEH}}} + s_G GAS_H^{\frac{\sigma^{NEH}-1}{\sigma^{NEH}}} + (1-s_C-s_G) REF_H^{\frac{\sigma^{NEH}-1}{\sigma^{NEH}}} \right)^{\frac{\sigma^{NEH}}{\sigma^{NEH}-1}}$$

Eq. 18 – PEHOU {composite good of Coal + Gas + Refined petroleum products (REF)}

Appendix 6.2. Production sectors

Sector	Description
AGR&FOR	Agriculture and forestry
FISHING	Fishing and aquaculture
MIN&EXTRACT_FUELS	Mining of coal; extraction of crude petroleum and natural gas
MIN&QUARR	Other mining and quarrying
FOOD&TOB	Manufacture of food, beverages and tobacco products
TEXTILES	Manufacture of textiles products
LEATHER	Manufacture of leather products
WOOD&CORK	Manufacture of wood and cork products
PAPER&PULP	Manufacture of paper and paper products; printing
REFPET	Manufacture of coke and refined petroleum products
CHEMICALS	Manufacture of pharmaceutical and chemical products
RUB&PLAST	Manufacture of rubber and plastic products
NONMET_MINER	Manufacture of non-metallic mineral products
METALS	Manufacture of basic metals and metal products
MACH&EQUIP	Manufacture and repair of machinery and equipment
ELEC_EQUIP	Manufacture of electric and electronic products
TRANSP_EQUIP	Manufacture of transport equipment
OTHER_MANUF	Other manufacturing
ELECT	Electricity, steam and air conditioning supply
GAS	Natural gas supply
WATER	Water collection, treatment and supply
CONSTRUCTION	Construction
TRADE	Trade and repair
HORECA	Accommodation and food service activities
TRANSP&COMM	Transport and communications
FIN_SERVICES	Financial and insurance activities
REAL_ESTATE	Real estate and rental activities
PUB_ADMIN	Public administration
EDUCATION	Education
HEALTH	Human health activities
SERVICES	Other professional and personal services

Appendix 6.3. Elasticities of substitution

Production sector	Production substitution elasticities					International trade elasticities	
	Capital, labour and energy	Electricity vs. Fossil fuels	Capital vs. Labour	Coal vs. Oil and gas	Oil vs. Gas	Armington substitution between domestic and imports	Armington transformation between domestic and exports
	σ_{KLE}(a)	σ_{E}(b)	σ_{KL}(c)	σ_{COG}(b)	σ_{OG}(b)	σ_{A}(c)	σ_{i}^{E}(d)
AGR&FOR	0.5	0.3	0.56	0.5	0.5	2.2	3.9
FISHING	0.5	0.3	0.56	0.5	0.5	2.2	3.9
MIN&EXTRACT_FUELS	0.5	0.3	1.26	0.5	0.5	2.8	2.9
MIN&QUARR	0.96	0.3	1.26	0.5	0.5	1.9	2.9
FOOD&TOB	0.5	0.3	1.26	0.5	0.5	2.8	2.9
TEXTILES	0.8	0.3	1.26	0.5	0.5	2.8	2.9
LEATHER	0.8	0.3	1.26	0.5	0.5	2.8	2.9
WOOD&CORK	0.8	0.3	1.26	0.5	0.5	2.8	2.9
PAPER&PULP	0.8	0.3	1.26	0.5	0.5	2.8	2.9
REFPET	0.5	0.3	1.12	0.5	0.5	2.8	2.9
CHEMICALS	0.96	0.3	1.26	0.5	0.5	1.9	2.9
RUB&PLAST	0.8	0.3	1.26	0.5	0.5	2.8	2.9
NONMET_MINER	0.96	0.3	1.26	0.5	0.5	1.9	2.9
METALS	0.8	0.3	1.26	0.5	0.5	2.8	2.9
MACH&EQUIP	0.8	0.3	1.26	0.5	0.5	2.8	2.9
ELEC_EQUIP	0.8	0.3	1.26	0.5	0.5	2.8	2.9
TRANSP_EQUIP	0.8	0.3	1.26	0.5	0.5	2.8	2.9
OTHER_MANUF	0.96	0.3	1.26	0.5	0.5	1.9	2.9
ELECT	0.5	0.3	1.26	0.5	0.5	2.8	2.9
GAS	0.5	0.3	1.12	0.5	0.5	2.8	2.9
WATER	0.5	0.3	1.26	0.5	0.5	2.8	2.9
CONSTRUCTION	0.5	0.3	1.4	0.5	0.5	1.9	0.7
TRADE	0.5	0.3	1.68	0.5	0.5	1.9	0.7
HORECA	0.5	0.3	1.68	0.5	0.5	1.9	0.7
TRANSP&COMM	0.5	0.3	1.68	0.5	0.5	1.9	0.7
FIN_SERVICES	0.5	0.3	1.68	0.5	0.5	1.9	0.7
REAL_ESTATE	0.5	0.3	1.68	0.5	0.5	1.9	0.7
PUB_ADMIN	0.5	0.3	1.68	0.5	0.5	1.9	0.7
EDUCATION	0.5	0.3	1.68	0.5	0.5	1.9	0.7
HEALTH	0.5	0.3	1.68	0.5	0.5	1.9	0.7
SERVICES	0.5	0.3	1.68	0.5	0.5	1.9	0.7

Final demand substitution elasticities		
Consumption vs. Leisure*	σ_{LC}	1.45
Consumption of energy for transport, energy for home and non-energy goods(e)	σ_{EOG}	0.1
Consumption of electricity vs. fossil energy products(e)	σ_{EH}	1.5
Consumption of fossil energy products(e)	σ_{FF}	1

Electricity sector substitution elasticities		
Between generation technologies(f)	σ_{TECH}	10
Between intermediate goods and KLE aggregate(g)	σ_{M}	0.2
Between capital, labour and energy(g)	σ_{KLE}	0.25
Between capital and labour(g)	σ_{KL}	1.26

Source: (a) (Kemfert & Welsch, 2000); (b) (C. Böhringer et al., 1998); (c) (Hertel, 1997); (d) (Melo & Tarr, 1992); (e) (Labandeira, Labeaga, et al., 2009); (f) (Wing, 2006); (g) (EC, 2013b).
Note: *σ_{LC} was calibrated so that the model reproduced the uncompensated labour supply elasticity of 0.4 available in literature (see (Labandeira, Labeaga, et al., 2009)).

Appendix 6.4. Elasticities of substitution used in sensitivity analysis

Production sector	σ_{KEL} [(a)]	σ_{E}[(b)]	σ_{KL}[(a)]	σ_{COG}[(b)]	σ_{OG}[(b)]	σ_{A}[(c)]	σ_{I}^{E}[(c)]
AGR&FOR	0.516	0.16	0.26	0.07	0.25	2.5	1.25
FISHING	0.516	0.16	0.2	0.07	0.25	2.5	1.25
MIN&EXTRACT_FUELS	0.553	0.16	0.2	0.07	0.25	10.4	5.2
MIN&QUARR	0.553	0.16	0.2	0.07	0.25	5.9	2.95
FOOD&TOB	0.395	0.16	1.12	0.07	0.25	2.3	1.15
TEXTILES	0.637	0.16	1.26	0.07	0.25	7.5	3.75
LEATHER	0.637	0.16	1.26	0.07	0.25	7.5	3.75
WOOD&CORK	0.456	0.16	1.26	0.07	0.25	7.5	3.75
PAPER&PULP	0.211	0.16	1.26	0.07	0.25	5.9	2.95
REFPET	0.256	0.16	1.26	0.07	0.25	4.2	2.1
CHEMICALS	0	0.16	1.26	0.07	0.25	6.6	3.3
RUB&PLAST	0	0.16	1.26	0.07	0.25	6.6	3.3
NONMET_MINER	0.411	0.16	1.26	0.07	0.25	5.9	2.95
METALS	0.644	0.16	1.26	0.07	0.25	7.5	3.75
MACH&EQUIP	0.292	0.16	1.26	0.07	0.25	8.1	4.05
ELEC_EQUIP	0.524	0.16	1.26	0.07	0.25	8.8	4.4
TRANSP_EQUIP	0.519	0.16	1.26	0.07	0.25	8.6	4.3
OTHER_MANUF	0.529	0.16	1.26	0.07	0.25	7.5	3.75
ELECT	0.256	0.16	1.26	0.07	0.25	5.6	2.8
GAS	0.256	0.16	1.26	0.07	0.25	5.6	2.8
WATER	0.256	0.16	1.26	0.07	0.25	5.6	2.8
CONSTRUCTION	0.529	0.16	1.4	0.07	0.25	3.8	1.9
TRADE	0.784	0.16	1.68	0.07	0.25	3.8	1.9
HORECA	0.784	0.16	1.26	0.07	0.25	3.8	1.9
TRANSP&COMM	0.281	0.16	1.26	0.07	0.25	3.8	1.9
FIN_SERVICES	0.32	0.16	1.26	0.07	0.25	3.8	1.9
REAL_ESTATE	0.32	0.16	1.26	0.07	0.25	3.8	1.9
PUB_ADMIN	0.32	0.16	1.26	0.07	0.25	3.8	1.9
EDUCATION	0.32	0.16	1.26	0.07	0.25	3.8	1.9
HEALTH	0.32	0.16	1.26	0.07	0.25	3.8	1.9
SERVICES	0.784	0.16	1.26	0.07	0.25	3.8	1.9

Source: (a) (Okagawa & Ban, 2008); (b) (Aguiar et al., 2016); (c) (EC, 2013b).

CHAPTER 7

ASSESSING THE IMPACTS OF CLIMATE CHANGE ON HYDROPOWER GENERATION AND THE POWER SECTOR IN PORTUGAL: A PARTIAL EQUILIBRIUM APPROACH*

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Abstract

Hydropower plays a major role in the Portuguese electrical mix. Given the projected impacts of climate change on the availability of water resources, effects on hydropower generation are widely recognized though scantily quantified in literature. Considering projected climate change impacts on water resources in Portugal, we use a partial equilibrium bottom-up optimization model (TIMES_PT) to assess the effects of climate change on the Portuguese electrical system by 2050 – particularly focusing on the impacts on water resources availability and hydropower generation. Results show that hydropower generation may decrease by 41% in 2050. Hydropower will remain one of the most cost-effective technologies in the power sector, though it will lose as compared to other renewable energy sources (solar PV and wind power) due to, not only, the almost fully exploited endogenous hydropower potential, but also, due to climate change impacts. This will result in higher electricity prices (up to a 17% increase). Moreover, the stronger the climate change impacts the higher the levels of greenhouse gas emissions (up to 7.2% increase) – thus demanding stronger political action to comply with EU climate goals for 2050.

7.1. Introduction

Energy plays a vital role in human lives and economic development. Simultaneously, the energy sector is the main source of greenhouse gas (GHG) emissions and, consequently, of climate change (INAG, DGEG, & REN, 2007; IPCC, 2011). Energy issues are, therefore, a key factor for sustainability. Accordingly, the tight relationship between energy, economy and environment (the so-called E3 system) is currently one of the hot topics in scientific research and on political agendas (IPCC, 2014c).

On the other hand, the energy system will be one of the economic sectors most affected by climate change, both at demand and supply sides (Ciscar & Dowling, 2014). On the demand side, we should expect major changes in heating and cooling needs (e.g. (Eskeland & Mideksa, 2009; Giannakopoulos et al., 2009; Mideksa & Kallbekken, 2010)). On the supply side, climate change will affect: i) the technical efficiency of thermal power systems, namely due to deviations in cooling water temperature, ii) the yield of renewable energy systems, due to the sensitivity towards environmental parameters (e.g. solar irradiance), and iii) the availability of renewable energy sources, in particular water resources (e.g. (Golombek et al., 2012; IPCC, 2011; Santos et al., 2002; Tarroja, AghaKouchak, & Samuelsen, 2016; van Vliet, van Beek, et al., 2016)).

Given the critical character of energy issues in the economy and the growing concerns about climate change and its multiple impacts, quantitative analyses have been essential to provide scientists and policymakers with accurate information on these subjects. Two types of analytical approaches have been used in energy-economic models: top-down and bottom-up (Böhringer & Rutherford, 2008; Nakata et al., 2011). The top-down approach has been dominated by computable general equilibrium (CGE) models (see (Hourcade et al., 2006)), which are oriented by an economic reasoning to compute the equilibrium across all markets (of factors and goods). Usually in these models, the energy sector is represented by an aggregate production function (similarly to the remainder of sectors), which captures substitution and transformation possibilities of inputs through constant elasticities of substitution and transformation. This is done in a simplified form that does not include detailed information on current and prospective technologies; see e.g. (Böhringer & Rutherford, 2008, 2010; Cai & Arora, 2015; Saveyn, Van Regemorter, & Ciscar, 2011).

The bottom-up approach has an engineering character, including a detailed representation of energy sector sources and technologies though neglecting the interaction between the energy system and the rest of economy (Nakata, 2004; Nakata et al., 2011; Pandey, 2002). These models are typically translated into optimization problems (Böhringer & Rutherford, 2008) as to explore different energy futures based on optimal decisions – thus helping policymakers to understand how future energy systems may unfold in the face of climate change (Vaillancourt et al., 2014). Bottom-up models are extensively used in energy-sector studies, regarding technological evolution and efficiency improvements (e.g. (Criqui, Mima, Menanteau, & Kitous, 2015; Fortes, Alvarenga, Seixas, & Rodrigues, 2015; Leibowicz, Krey, & Grubler, 2016; Nguene, Fragnière, Kanala, Lavigne, & Moresino, 2011; Vaillancourt et al., 2014)), and the cost-effectiveness of economic instruments and environmental policies (e.g. (Fernandes & Ferreira, 2014; Labriet, Cabal, Lechón, Giannakidis, & Kanudia, 2010; Simões, Cleto, Fortes, Seixas, & Huppes, 2008)).

Few studies perform a broad analysis of climate change impacts on the energy system, from the effects on climate parameters (e.g. temperature and precipitation) to the resulting technological structure, inherent financial costs and GHG emissions. Climate change impacts on natural resources, and also on hydropower, are often analyzed through climate and hydrological models (whose character is eminently biophysical) and/or electrical grid models (Majone, Villa, Deidda, & Bellin, 2016; Tarroja et al., 2016; van Vliet, Wiberg, Leduc, & Riahi, 2016). Economic impacts of climate change on the energy sector are mainly assessed through bottom-up technological models that rely on techno-economic data, but disregard the biophysical component. An exception is the study from (Seljom et al., 2011) that use ten climate experiments and a bottom-up energy model to analyse the impacts of climate change on energy demand and supply, considering the effects on hydro- and wind power potential for Norway by 2050. They find that climate change will increase precipitation and hydropower potential.

The goal of this paper is to assess the effects that a reduction in water availability for hydropower generation (resulting from climate change) will have on the Portuguese electrical system by 2050. Portugal emerges as our case study for two main reasons: i) climate change is expected to negatively impact precipitation, runoff and water resources availability, given its Mediterranean climate conditions (Köppen-Geiger classification; see (Kottek et al., 2006)); and ii) the likely decrease in water resources availability will impact hydropower generation, which represents more than 20% of total electricity generation in an “average” year, increasing to almost 40% in a “wet” year (DGEG, 2016c; REN, 2015). This paper provides evidence about the impacts of climate change in a Mediterranean region that may diverge from those projected for a cold climate country (Seljom et al., 2011), thus highlighting the relevance of the regional dimension in the study of climate change impacts. The analysis is restricted to the impacts of climate change on water resources, supported by the low magnitude of projected impacts on wind, biofuels, solar irradiance and geothermal resources (see (IPCC, 2011)).

To this end, we use the partial equilibrium bottom-up optimization model TIMES_PT (Loulou & Goldstein, 2005) with data on future water resources availability in Portugal, as projected by hydrological models such as Temez (Santos et al., 2002), VIC (van Vliet, Donnelly, Strömbäck, Capell, & Ludwig, 2015), and SWAT (Santos, 2014) - thus implementing the improvements for future research on sustainability pointed out by (Pollitt et al., 2010). The added value of using a bottom-up model to study climate change impacts on the power sector is that the model adjusts not only hydropower production to water availability, but also adapts the whole energy system to new conditions by selecting the most cost-effective technologies to satisfy energy services demand. Alongside the new electrical and energy mixes, the model provides information on resulting electricity prices and GHG emissions.

The remainder of this paper is organized as follows. Section 7.2 reviews the climate change impacts on water resources and hydropower generation in Portugal. Section 7.3 describes the TIMES_PT model, the modelling assumptions and climate change scenarios considered in our analysis. Section 7.4 presents the simulations results. Section 7.5 provides a discussion on the policy implications of the presented results and concludes.

7.2. Overview of climate change impacts on water resources and hydropower generation in Portugal

Climate change impacts are expected to interfere with the availability, timing and variability of water resources endowments. They will therefore affect numerous domains of life and economic sectors, especially water-dependent activities. This section reviews the main impacts of climate change on water resources and hydropower generation in Portugal.

7.2.1. Water resources

Climate conditions in Portugal are Mediterranean (Kottek et al., 2006), characterized by those that generally describe Southern Europe and the Mediterranean basin – the latter being identified as ‘hot spot’ region for climate change (Giorgi, 2006). Several studies project severe impacts of climate change for these regions, namely higher temperatures, higher potential evaporation, a decrease in annual precipitation (with increased asymmetry in seasonal and spatial distribution), more frequent and severe droughts, a gradual decline in the average streamflow, and changes in river regimes that lead to a decrease in runoff (e.g. (Cunha et al., 2007; Flörke, Laaser, et al., 2011; García-Ruiz et al., 2011; IPCC, 2007b; van Vliet et al., 2015)).

Regarding temperature, the IPCC Special Report on Emissions Scenarios (SRES) simulations point towards an increase in annual mean temperatures in Portugal (Christensen, 2005; Cunha et al., 2007). (Cunha et al., 2007) foresee an increase in temperature of between 2.0°C and 3.0°C by 2050, and of between 3.5°C and 5.0°C by 2100. This increase is expected to be even larger in summer: +3.0°C to +5.0°C by 2050 and +5.0°C to +7.0°C by 2100.

Precipitation is expected to decrease in Portugal, with important impacts for future water availability (APA, 2013; Cunha et al., 2007; Giorgi, 2006; Pulquério et al., 2014). However, precipitation changes are expected to be unevenly spread between Portuguese regions, with increases in the Northern region (with Atlantic influence) and reductions in the Southern region (with Mediterranean influence) (APA, 2013). As compared to 1964-1990 average values, different climate models forecast an overall decrease in precipitation for Portugal by 2050 (Santos et al., 2002; Santos & Miranda, 2006)[17]. At the regional level, projections range from -28% in the South to +11% in the North. Across seasons, reductions in precipitation are expected for all seasons except winter. The projected seasonal variability is in accordance with (López-Moreno et al., 2010; Luis, González-Hidalgo, Longares, & Stepánek, 2009; Rodrigo & Trigo, 2007) that highlight a decreasing trend in precipitation in the Iberian Peninsula. Similarly, the PRUDENCE project (Christensen, 2005) estimates, for Portugal, an annual decrease in precipitation of 6.1% per degree of global warming – resulting from a generalized declining trend in all seasons

[17] The main source of projections for precipitation and runoff in Portugal referred to in this text follow the SIAM project results (Santos et al., 2002; Santos & Miranda, 2006) which, to date, is the most comprehensive analysis of climate change impacts carried out for Portugal.

except winter (+1.5% in winter against -11.6% in spring, -19% in summer and -9.2% in autumn by 2100).

The runoff regime in Portugal is strongly influenced by the seasonal and spatial variability of precipitation and, hence, highly variable across regions as the wet northern coastal river basins contrast with the dry inland southern basins (Santos et al., 2002). All models show a generalized decrease in runoff across regions and seasons, despite the spatial and seasonal differences (see Table 7.1; (Cunha et al., 2007; Santos et al., 2002; Santos & Miranda, 2006)).

Table 7.1. Projected annual and seasonal changes in precipitation and runoff in Portugal by 2050 as compared to 1964-1990 (based on HadCM3 model)

	Region	Annual	Spring	Summer	Autumn	Winter
Precipitation	North	0% to +11%	n.a.	n.a.	1%	0%
	Centre	-18% to +6%	n.a.	n.a.	n.a.	n.a.
	South	-28% to +6%	n.a.	n.a.	9%	-25%
	Portugal	n.a.	-12% to -25%	-25%	-12% to -33%	+10% to +18%
Runoff	North	<-10%	-15% to -20%	-20% to -40%	<-20%	n.a.
	Centre	-15% to -20%	n.a.	n.a.	-30% to -60%	n.a.
	South	-20% to -50%	-30% to -60%	n.a.	-50% to -90%	0% to -40%

Source: Own elaboration based on (Cunha et al., 2007; Santos et al., 2002; Santos & Miranda, 2006).

Note: n.a. = not available.

These results are coherent with studies focusing on specific Portuguese river basins. (Nunes et al., 2008) compared the Alentejo and Ribatejo basins under different scenarios of precipitation change by 2100. In both regions surface and subsurface runoff were projected to decrease by more than 60% and 80%, respectively, due to the diminished availability of water from precipitation. (Mourato et al., 2014) studied the Cobres basin, whose climate is representative of the climate conditions in southern Portugal. All scenarios project a decrease in runoff for the period 2071-2100, with annual runoff variations ranging from -35% to -80% as compared to 1961-1990. At the seasonal level, projections range between -61% to -96% in autumn, -21% to -77% in winter, -40% to -99% in spring and -45% to -91% in summer. (Kilsby, Tellier, Fowler, & Howels, 2007) simulated the impacts in mean monthly streamflow for the Tagus and Guadiana basins, projecting a change that ranges between -49% and -20% for the Tagus and between -26% and -21% for the Guadiana by 2100 as compared to 1973-1990 and to 1961-1990 streamflow data, respectively. Finally, (Falloon & Betts, 2006) forecast a decrease of 40% to 55% in annual flow for the river Douro by 2080 as compared to 1961-1990.

Considering that the larger Portuguese river basins are transboundary, climate conditions in Spain are also determinant for the Portuguese hydrological regime (Cunha et al., 2007). Therefore, reduced runoff from the Spanish sub-basins may lead to a larger reduction in water availability in the Portuguese sub-basins. In addition, the likely retention of water in the Spanish parts of the river basins will deepen the negative change in water availability across the Portuguese sub-basins (APA, 2013; Cunha et al., 2007). Consequently, it is plausible that competition for water resources between Portugal and Spain will be intensified in a climate change scenario and, thus, constitute an increasing challenge for policymakers.

7.2.2. Hydropower generation

Given the unconditional dependence of hydropower on water resources, the correlation between water availability and electricity generation is significant (Rübbelke & Vögele, 2012). Water availability is highly determined by precipitation, which influences hydropower generation in different ways (Tapiador et al., 2011): i) through changes upstream in river flow and storage, which influence energy produced downstream; ii) through river flow, which depends on current and past precipitation; and iii) through climate variability. Precipitation levels and regularity are thus crucial factors for electrical generation (Costa et al., 2012) and, hence, hydropower is probably one of the Renewable Energy Sources (RES) that is most affected by climate change (Ciscar & Dowling, 2014). Climate change impacts on water resources may lead to two different types of impacts on hydropower generation (APA, 2013; Mukheibir, 2013): i) direct climate-induced impacts, such as changes in hydro-meteorological variables, that directly affect the availability of water for power generation; and ii) indirect impacts, such as increased competition for water resources, that are a result of the amplified scarcity of the natural resource and lead to changes in social and economic activities.

Direct impacts

The main mechanisms through which climate change can directly affect hydropower generation are changes in precipitation, melting of freshwater glaciers, changes in river flows, changes in evaporation, sedimentation and dam safety (Chandramowli & Felder, 2014; Gaudard & Romerio, 2014; Mideksa & Kallbekken, 2010). The projected increase in intensity and frequency of extreme weather events (intense rainfall leading to flooding and longer dry periods leading to droughts) can also adversely affect hydropower systems and increase the risks associated with critical situations for electricity generation (APA, 2013; Mideksa & Kallbekken, 2010). In addition, climate change impacts on hydropower generation will vary according to the infrastructure type. Hydropower plants with storage capacity are less vulnerable to short-term variations than run-of-river power plants, as reservoirs allow for a better management of flash-flow events and river flow variability (Gaudard & Romerio, 2014; Lehner et al., 2005). Also, deep dams with smaller surface areas will likely be less affected by climate change impacts than those with large surface areas given their larger evaporation potential (Mukheibir, 2013). While the impact of climate change on evaporation has been widely acknowledged (see (Mekonnen & Hoekstra, 2012), the impacts of water evaporation on hydropower generation are usually not quantified (see (Bakken, Engeland, Killingtveit, Alfredsen, & Harby, 2013)). Concerning Portugal (Table 7.2), changes in precipitation regimes and resulting accrued seasonal/spatial asymmetries in river flows and reduced runoff are expected to decrease hydropower production and widen inter-annual output (APA, 2013; Lehner et al., 2005; Pereira-Cardenal et al., 2014). Very few studies project neutral or positive impacts of climate change on hydropower generation in Portugal (APA, 2013; EC, 2009; Hamududu & Killingtveit, 2012), and these are refuted by several examples. (Lehner et al., 2005) estimated a reduction by between 6% and 18% in gross hydropower potential and by between 22% and 44% in developed hydropower potential by 2070 as compared to 1961-1990[18]. This means that Portugal is among the European countries most prone to a reduction in hydropower potential (Lehner et al., 2005). As both high and low flows are expected to become more extreme, the impact on run-of-river plants may be stronger than in reservoir plants (-25% and -15%, respectively; (Lehner et al., 2005)). Projections by (Cleto, 2008) point to a 7% gap in hydropower generation in Portugal in the presence of strong or weak climate change impacts by 2050, whereas (Alves, 2013) concludes that hydropower generation in Portugal will decrease by 7% in a climate change scenario by 2050 as compared to 2010. These results for the particular case of Portugal align with

[18] ‘Gross hydropower potential’ is defined as “the annual energy potentially available if all natural runoff at all locations were to be harnessed down to the sea level without any energy losses”. ‘Developed hydropower potential’ corresponds to “a country’s supplied electricity by hydropower” (B. Lehner et al., 2005). Hydropower potential is, by convention, forecast-based on the 90 % dependable river flow (Jain & Singh, 2003).

projections for southern European countries (e.g. (IPCC, 2007b; Jochem & Schade, 2009)) and the Iberian Peninsula (e.g. (Pereira-Cardenal et al., 2014)).

Table 7.2. Geographical distribution of hydropower plants in Portugal

Region	Nº of hydropower plants			Hydropower installed capacity		
	Large-scale ≥ 10 MW	Small-scale < 10 MW	Total	Large-scale ≥ 10 MW	Small-scale < 10 MW	Total
North	23	58	81	5,041.2	343.1	5,384.3
Centre	15	66	81	949.1	56.8	1,005.9
South	6	16	22	500.0	23.8	523.8
Portugal	44	140	184	6,490.3	423.7	6,914.0

Source: Own elaboration based on (E2p energias endógenas de Portugal, 2017).

Indirect impacts

Climate change can indirectly affect hydropower generation through increased competition among economic sectors, whose performance rely on water resources availability (such as the energy sector or agriculture; (Ebinger & Vergara, 2011)), and across countries that share common river catchments. Concerning competition between economic sectors, climate change consequences, such as reduced runoff and increased irrigation needs, will likely diminish water availability for hydropower generation when compared to competing end-users – namely agriculture, industry and domestic consumption. (Pereira-Cardenal et al., 2014), for example, show that lower inflows and higher irrigation demands will lead to an increase in water values and may reduce hydropower generation. Therefore, increased competition for water uses in a situation of water stress will likely become more frequent and intense.

Regarding competition across countries, it is expected that climate change will exacerbate the existing complexity of transboundary water management. Any change in the upstream country affects the availability and quality of water resources in the downstream country. Thus, in the context of climate change, if the upstream country increases its water withdrawals, the downstream country will face increased water scarcity – impairing the production of water dependent-economic activities like agriculture and energy (Flörke, Laaser, et al., 2011). In Portugal, the main river basins are transboundary and, hence, competition is likely to intensify in a context of greater water scarcity induced by climate change. Moreover, competitive energy companies pursue their own interests and profits and, thus, their management strategies do not encompass global optimization criteria for the sector (e.g. benefiting from cascade effects; (APA, 2013)). The Portuguese hydropower system is likely to be negatively affected, given its high dependence on the Douro, Tagus and Guadiana rivers that are downstream of relevant Spanish hydropower plants and irrigation systems.

7.3. Methodology

We use the bottom-up model TIMES_PT to quantify the impacts of climate change, via water resources availability, on the Portuguese power sector by 2050. This section describes the model, the modelling assumptions and the climate change scenarios considered.

7.3.1. TIMES_PT model

TIMES is a dynamic linear optimization bottom-up model generator for energy systems which provides a technology-rich basis for estimating energy dynamics over a long-term horizon. The objective of TIMES is to minimize the net present value (NPV) of total costs subject to technological, physical and policy constraints in such a way that demand of energy services is satisfied at the minimum total system cost, such that: (Loulou & Goldstein, 2005).

$$Min\ NPV = \sum_{r=1}^{R}\sum_{t=0}^{T}\left(1 + d_{(r,t)}\right)^{refy-t} * ANNCOST_{(r,t)}$$

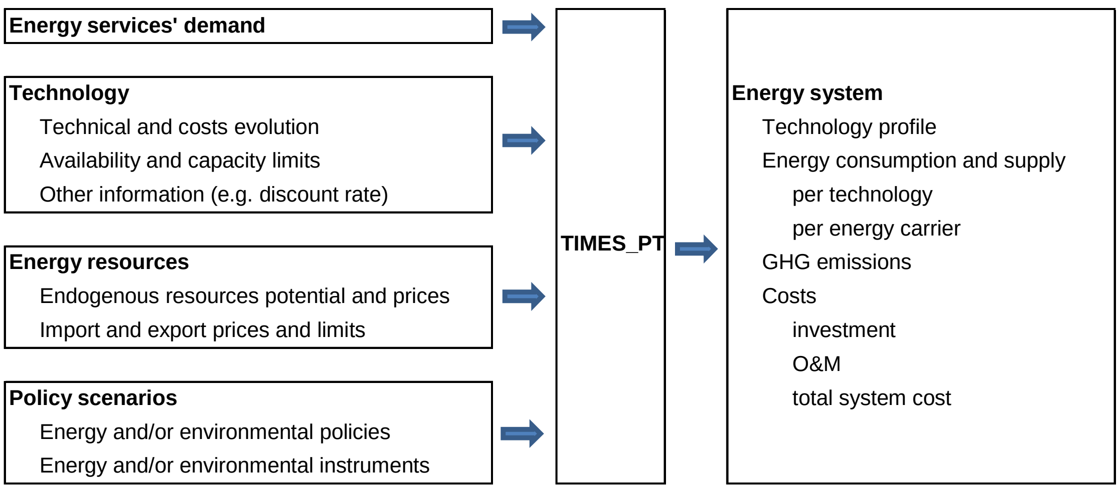
with $ANNCOST = K + O\&M + M - X + D + Tax - S - SM - SV + WL$

being R the set of regions and T the set of years, and where d is the discount rate and refy is the reference year for discounting. While dropping regional and time notation (r and t, respectively), ANNCOST is the total annual cost, K are the capital costs incurred in investment or dismantling processes, O&M are the fixed and variable operation and maintenance costs, M are the costs incurred for imports and domestic resource production, X are the revenues from exports, D are the delivery costs for required commodities consumed by processes, Tax are taxes, S are subsidies, SM is the recuperation of sunk material, SV is the salvage value of processes and embedded commodities, and WL is the welfare loss (i.e., the negative of consumer surplus) resulting from reduced end-use demands if an elastic demand is assumed.

The equilibrium between supply and demand is achieved for the energy sector (partial equilibrium) at prices computed by the model and, hence, energy suppliers produce exactly the amounts that consumers are willing to buy. This equilibrium is a result of simultaneous decisions concerning technology investment and operating costs, primary energy supply and energy trade, assuming perfect market foresight (Loulou & Goldstein, 2005).

The TIMES_PT model uses the TIMES equations to represent the Portuguese energy system from 2005 to 2050. The model includes imports, primary energy supply and electricity generation, energy transformation and distribution, exports and final consumption in five end-use sectors (industry, residential, services, agriculture and transport) that group more than 60 energy service demand categories (Figure 7.1).

Figure 7.1. TIMES_PT structure: inputs and outputs



Source: (Fortes et al., 2015)

TIMES_PT inputs are the following (Loulou & Goldstein, 2005): i) technological data provided by a comprehensive database on technical and economic data that characterizes existing and future technologies (in terms of efficiency, capacity, availability, lifetime, emission factors, investment, and operation and maintenance costs); ii) resource potentials and prices for present and future sources of primary energy supply, including imported energy carriers prices; iii) policy constraints; and iv) energy services, materials and mobility end-use demand which are quantified exogenously through the evolution of specific socio-economic indicators (e.g. population, GDP, sector production, private consumption) and demand elasticities ((Fortes et al., 2015) shows energy services equation). TIMES_PT outputs encompass: i) energy flows; ii) installed capacity and activity per technology; iii) inherent GHG emissions; iv) final energy prices; and v) the energy system cost.

7.3.2. Modelling assumptions

The scenarios assessed in this paper are based on specific modelling assumptions regarding energy services demand, policy options, technologies, techno and economic evolution including technical potential of renewable energy technologies, discount rates, fossil fuel import prices and electricity trade.

The socio-economic evolution and the associated energy services demand projections are the driving forces of the whole energy system modelled in TIMES_PT. As expected, the stronger the socio-economic development, the higher is energy services demand. Energy *services' demand* follows International Monetary Fund projections (IMF, 2013) for economic evolution until 2020, which include the recent financial and economic crisis effects and the consequential perspectives for the short-term. After 2020, a single socio-economic scenario is considered, which assumes average growth rates of population and GDP between the 'Low' and 'High' scenarios adopted by the Portuguese National Program on Climate Change (PNPCC) (APA, 2015). Table 7.3 summarizes the main socio-economic drivers considered in this paper.

Policy assumptions considered include: i) no nuclear energy over the modelling horizon; ii) no conventional coal power plants after the decommissioning of existing units by 2020 (following the National Action Plan for Renewable Energy 2020; (RCM 20/2013)); iii) minimum installed capacity of hydropower as projected in the National Plan for High Potential Hydropower Infrastructures (INAG et al., 2007), with some adjustments to reflect the current situation and prospects (following the assumptions of the Portuguese National Program on Climate Change 2020-2030; (APA, 2015)); iv) extension of the EU Emissions Trading System (ETS) up to 2050 considering an ETS price according to the EU

Reference Scenario 2013, which sets a value of 100€$_{2010}$/tCO_2 by 2050 (EC, 2013a); v) neither subsidies nor feed-in tariffs; and vi) no GHG emissions target.

Table 7.3. Socio-economic drivers of the model

Year	GDP		Population	
	M€$_{2011}$	Annual growth rate (%)[A]	Inhabitants (10^3)	Annual growth rate (%)[B]
2010	165,549.3		10,503	
2020	172,063.8	-0.8%	10,566	0.4%
2030	210,653.4	2.1%	10,441	-0.1%
2040	258,515.7	2.1%	10,318	-0.1%
2050	317,252.8	2.1%	10,196	-0.1%

Notes:
[A] PNPCC assumes for GDP an annual growth rate of 1.5% and 3% in Low and High scenarios respectively
[B] PNPCC assumes for population an annual growth rate of -3% and 0.1% in Low and High scenarios respectively

Technical potential of Portuguese renewable energy is based on national studies and expert opinion concerning current and future technologies (Table 7.4; (APA, 2015)). The TIMES_PT technological database contains an extended list (more than two thousand (Fortes et al., 2015)) of mature and emergent energy-related technologies from both supply and demand. The database comprises technical (e.g., efficiency, lifetime, availability, emission factors) and economic data (e.g., investment, operation and maintenance costs) and their respective evolution over time. In Appendix 7.1 we present a summary table with techno-economic data of selected power generation technologies from TIMES_PT database.

Table 7.4. National primary energy potential by type in 2015 and 2050

Primary energy	Unit	Current potential	Projected potential
		2015	2050
Hydro	GW	6.054	9.834
Onshore wind	GW	5.034	7.500
Offshore wind	GW	0	10.000
Wave	GW	0	7.700
Solar PV	GW	0.451	9.300
CSP	GW	0	
Biomass, biogas and waste	PJ	0.726	53.120
Geothermal	GW	0.029	0.980
Crops for ethanol production	PJ	0	19.500
Crops for biodiesel production	PJ	0	9.990

Source: (DGEG, 2016c; E2p energias endógenas de Portugal, 2017; Seixas et al., 2012)

Time discount rates are defined per sector, namely: 9% for centralized electricity generation; 8% for buses and trains; 12% for commercial, industry, decentralized electricity generation, combined heat and power and freight transport; and 17.5% for residential, cars and motorcycles. These discount rates follow the EU Energy Roadmap 2050 (EC, 2011b) PRIMES model, and involve a risk averseness and various risk factors of sectors and agents.

Fossil fuel import prices were adopted from the 4DS Scenario of Energy Technology Perspectives 2015 (Table 7.5; (OECD/IEA, 2015b))[19].

Electricity trade under the Iberian Electricity Market (MIBEL) was not considered (given that TIMES_PT is not featured to accommodate market decisions like those that support MIBEL), and a zero net electricity trade balance was assumed from 2015 onwards (following (APA, 2015)).

Table 7.5. Fossil fuel prices between 2013 and 2050 under Scenario 4DS

Fossil fuel	Oil	Coal	Gas
Unit	2013 USD/barrel	2013 USD/tonne	2013 USD/Mbtu
2013	106	86	10.6
2020	112	101	11.1
2025	118	105	11.6
2030	123	108	12.1
2035	128	110	12.4
2040	132	112	12.7
2045	135	114	13.0
2050	137	116	13.2

Source: (OECD/IEA, 2015b)

7.3.3. Climate change scenarios

Provided the expected negative impacts of climate change on precipitation, runoff and water resources availability and the expected low negative impacts of climate change on wind, biofuels, solar irradiance and geothermal resources (IPCC, 2011; Santos et al., 2002), the analysis is restricted to the impacts of climate change on water resources. The

[19] We assume identical fossil fuel international prices in all scenarios to quantify the individual contribution of the climate assumptions on the energy system. Thus, the fossil fuel prices do not match with the assumptions underpinning the considered climate change scenarios A2c, B2a, RCP4.5 and RCP8.5.

most common methodological approach to evaluate climate change impacts on hydropower generation potential consists in translating long-term climate variables into runoff (Ebinger & Vergara, 2011; Schaeffer et al., 2012). Following this methodology, we explore four climate change scenarios which reflect differentiated runoff variations in Portugal by 2050 (see (Cleto, Simões, Fortes, & Seixas, 2008; Santos, 2014; Santos et al., 2002; van Vliet et al., 2015)). The scenarios were built through the downscaling of the SRES A2 and B2 scenario family (IPCC, 2000) and the Representative Concentration Pathways (RCPs) 4.5 and 8.5 (van Vuuren, Edmonds, et al., 2011), representing a diverse range of runoff projected variations for Portugal (RV), available in literature:

- No_CC scenario: This reference scenario, with no climate change, reflects the key assumptions in the evolution of the Portuguese energy sector from 2013 up to 2050 and constitutes the baseline to which each climate scenario is compared.
- RV_A2c scenario: This scenario relies on the key assumptions of the SRES A2c scenario, which describes a heterogeneous world, with high population growth and regional differences in economic performance, slow technological change, intensive energy use and low environmental concerns (IPCC, 2000). Runoff projections for the RV_A2c scenario were taken from (Cleto et al., 2008).
- RV_B2a scenario: This scenario relies on the key assumptions of the SRES B2a scenario, which describes a world with moderate population and GDP growth, medium technological change and considerable concerns on social, economic and environmental issues (IPCC, 2000). This scenario encompasses weaker impacts of climate change vis-à-vis the RV_A2c scenario. Runoff projections were taken from (Cleto et al., 2008).
- RV_RCP4.5 scenario: This scenario relies on the key assumptions of the RCP4.5, which is a stabilization situation where mitigation policies are such that radiative forcing reaches 4.5 W/m^2 by 2100 without overshooting this limit (Thomson et al., 2011). This scenario corresponds to an intermediate low-emissions scenario, being similar to the SRES B1 scenario (San José et al., 2015). Runoff projections were adapted from (Santos, 2014).
- RV_RCP8.5 scenario: This scenario relies on the key assumptions of the RCP8.5, which does not consider any specific climate mitigation target, thus leading to an increase in GHG emissions over time. This scenario's drivers and development path is based on the SRES A2r scenario (Riahi et al., 2007, 2011). Runoff projections for RV_RCP8.5 were taken from (van Vliet et al., 2015).

The RV_A2c and RV_RCP8.5 scenarios imply the strongest impacts of climate change on water resources availability when compared to the RV_B2a and RV_RCP4.5 scenarios.

Considering these climate change scenarios, we calculate the Hydropower Capacity Factor (HCF)[20] projected for Portugal by 2050. The HCF is a TIMES_PT input, which considers the seasonal hydrological conditions and thus allows determining the likely impacts of different water availability conditions on the Portuguese power sector. To do so, we consider the projected runoff variations by 2050 under each of the abovementioned climate scenarios. TIMES_PT model embodies a temporal component (through twelve time-slices, four seasons, day, night and peak), but does not allow for a spatial differentiation. To obtain the national HCF, the following methodology is applied:

Step 1. Based on the regional projections (see Section 7.2.1), we compute the weighted national average change in runoff per season. For the RV_A2c and RV_B2a scenarios, we use the hydropower installed capacity per region to obtain the national weighted average of projected runoff variations per season, following (Cleto et al., 2008)[21]. For the RV_RCP4.5 scenario, we use the seasonal projections for the Vez river basin in the North region (Santos, 2014) – the only RCP scenario runoff projections, to date, available for Portugal. As to obtain runoff projections for Portugal under RCP4.5, we perform a linear regression between these runoff projections in the North region and those for the remainder of the regions – assuming that regional differences captured by the RV_A2c and RV_B2a scenarios remain valid for RV_RCP4.5. The estimated coefficients are then used to calculate regional runoff variations per season by 2050. The RV_RCP8.5 scenario directly considers the national runoff variation available from (van Vliet et al., 2015), while deriving the seasonal variation using the projections by (Santos, 2014).

Step 2. Given the seasonal breakdown of precipitation in Portugal for each scenario's control period, as taken from (Belo-Pereira, Dutra, & Viterbo, 2011), we compute the weighted annual average of projected runoff variations.

Step 3. Finally, considering that (Kao et al., 2015) show that there is a strong linear relationship between runoff and annual hydropower generation, given by:

$$G/G_0 = a\ R/R_0 + b \qquad \text{Eq. (1)}$$

[20] The Hydropower Capacity Factor (HCF) is around 1 in an "average year", smaller than 1 in a "dry year", and greater than 1 in a "wet year".
[21] The authors assume that the share of installed capacity by region will remain stable over time, which is coherent with the long-term national policy for the hydropower sector.

where G is the variable annual generation, G_0 is the average annual generation, G/G_0 corresponds to the HCF, R is the variable annual runoff, R_0 is the average annual runoff, and where a and b are the regression coefficients, we use this relationship to calculate the projected changes in the annual HCF by 2050 as a function of changes in runoff, such that:

$$\Delta G/G_0 = a \Delta R/R_0 \qquad \text{Eq. (2)}$$

where a is calculated from (Kao et al., 2015), based on the average of estimates with $R^2 \geq 85\%$ (a=0.8314). These changes were then recalculated by season and linearly interpolated between present and 2050 to enter TIMES_PT model.

Projected runoff variations and resulting HCF for 2050 for each climate change scenario are summarized in Table 7.6. For the No_CC scenario we assume an average hydrological year (with seasonal variations), with a national HCF similar to the year 2006 (an “average” hydrological year; (REN, 2015)). The national HCF is applied in TIMES_PT in a simplified form, by reducing or increasing the seasonal availability factors of (existing and new) hydropower plant technologies.

Table 7.6. National hydropower capacity factor (HCF) by 2050 per climate change scenario

	Projected HCF for 2050				
Scenario	No_CC	RV_A2c	RV_B2a	RV_RCP 4.5	RV_RCP 8.5
Winter	0.627	0.778	1.013	0.874	0.638
Spring	0.700	0.685	0.835	0.782	0.570
Summer	0.650	0.493	0.621	0.616	0.450
Fall	1.936	0.636	0.742	0.810	0.591

Source: Runoff projected variations for RV_A2c and RV_B2a scenarios were taken from (Cleto et al., 2008); Runoff projected variations for RV_RCP4.5 scenario were adapted from (Santos, 2014); Runoff projected variations for RV_RCP8.5 scenario were adapted from (van Vliet et al., 2015); Historical annual HCF used in the calculation of HCF2050 were provided by (REN, 2015).

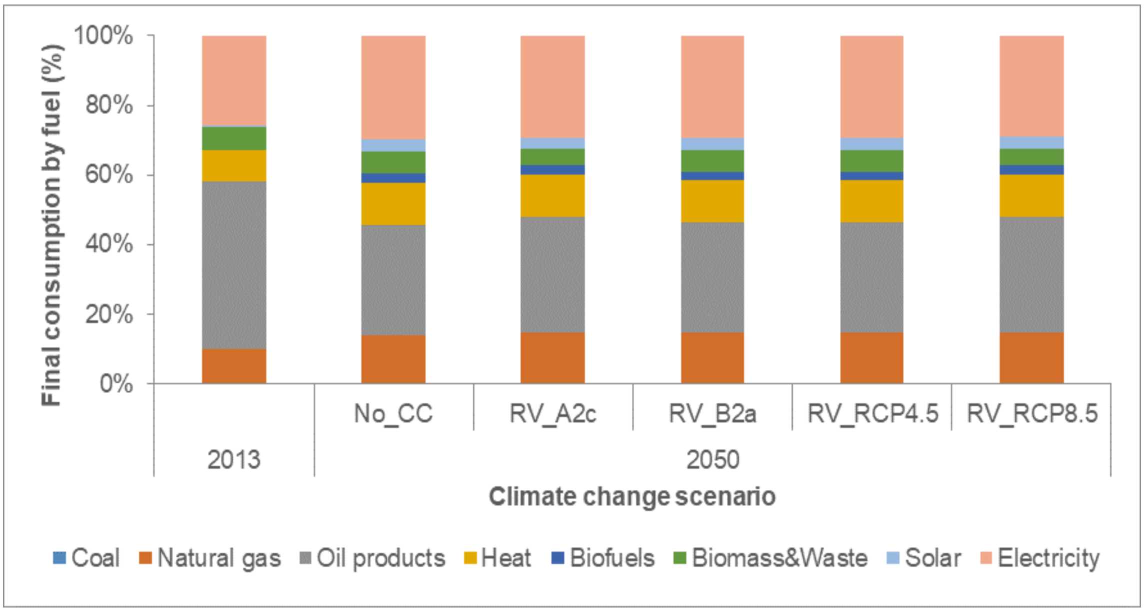
7.4. Results

This section presents the main results for the base (No_CC scenario) and the four climate change (RV) scenarios. Results are presented for the Portuguese final energy consumption, GHG emissions and electrical mix by 2050, considering installed capacity, electrical generation and electricity generation costs.

7.4.1. No_CC scenario

Final energy consumption in Portugal will remain almost unchanged by 2050 as compared to that in 2013 (-2%), although the fuel mix projected is quite different (see Figure 7.2). Main changes are due to the substitution of oil products (-35%) by gas (+36%) and due to the increase in electricity consumption (+14%).

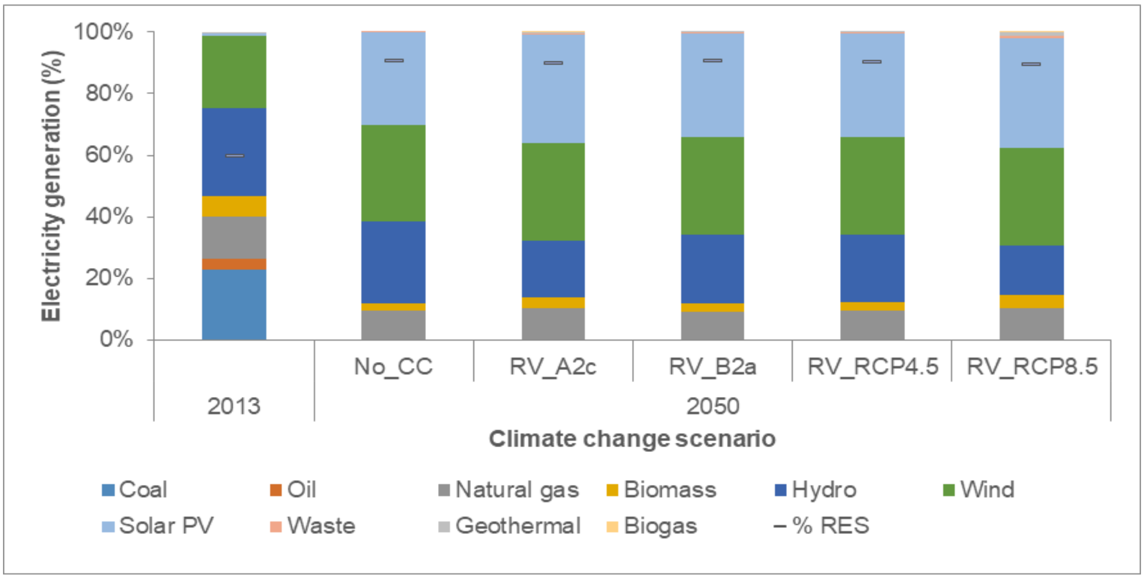
Figure 7.2. Final energy consumption by fuel type in 2013 and 2050 per climate change scenario



In order to satisfy demand for energy services by the different end-use sectors, electricity generation increases by 10% between 2013 and 2050 in the absence of climate change impacts (from 51,672 to 56,685 GWh). This increase is totally owed to the RES technologies, at the detriment of fossil-fuel based generation (coal, oil and natural gas). This is due to i) the decrease in RES investment costs over time, which increases the cost-effectiveness of these technologies, ii) the impact on prices of the EU ETS that turns fossil-fuels less attractive from an economic perspective, and iii) the decommission of existent coal power plants. Accordingly, total renewable energy production increases from

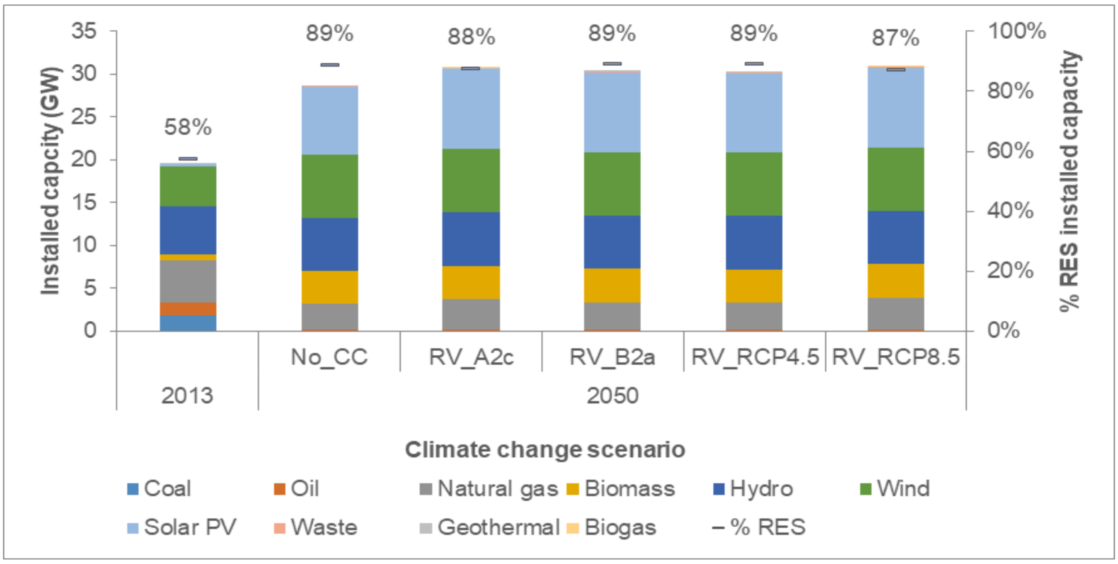
60% in 2013 to 91% by 2050 (from 30,895 to 51,518 GWh), encompassing considerable changes in the electrical generation mix. Whereas at present the RES portfolio is composed of hydropower (29% of total generation), wind power (23%) and biomass (6%), by 2050 electricity generation will be led by wind power (31%), solar PV (30%), hydropower (27%) and biomass (2%). As a consequence, fossil-fuel based electrical generation reduces from 40% in 2013 to 9% by 2050 (from 20,777 GWh to 5,267 GWh) and will rely on natural gas (see Figure 7.3).

Figure 7.3. Electricity generation by type in 2013 and 2050 per climate change scenario



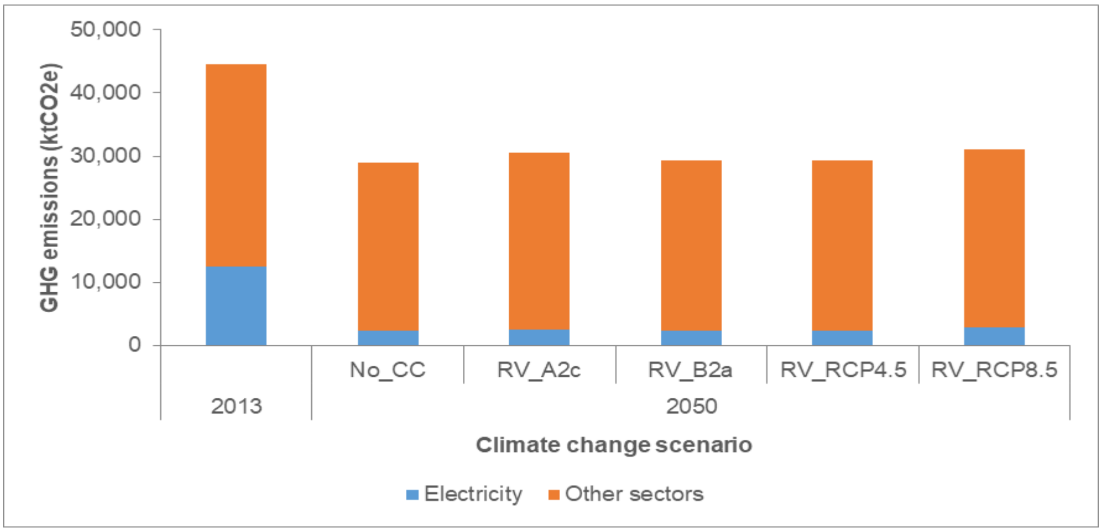
Accordingly, a 47% growth in installed capacity is projected until 2050 (from 19.7 to 28.7 GW), whereas the fossil-fuels installed capacity decreases in all cases (see Figure 7.4). In line with these outcomes, the ratio between production and installed capacity ('production-capacity' ratio - a proxy for the annual usage rate of each technology) decreases from 30% at present to 23% by 2050. The more the electrical system relies on renewable energy sources, the more likely this ratio is to decrease given their variable output.

Figure 7.4. Installed capacity in the electrical sector by type in 2013 and 2050 per climate change scenario



The described changes in final energy consumption and in the electrical generation mix, with the quasi abolishment of fossil-fuelled generation, result in a 35% decrease in total GHG emissions (from 44,474 to 28,998 kt CO2e) and in a 81% decrease in GHG emissions from the power sector (from 12,560 to 2,345 kt CO2e) for the No_CC scenario (see Figure 7.5). Consequently, GHG emissions from the power sector reduce from 19% (2013) to 8% (2050) of total GHG emissions.

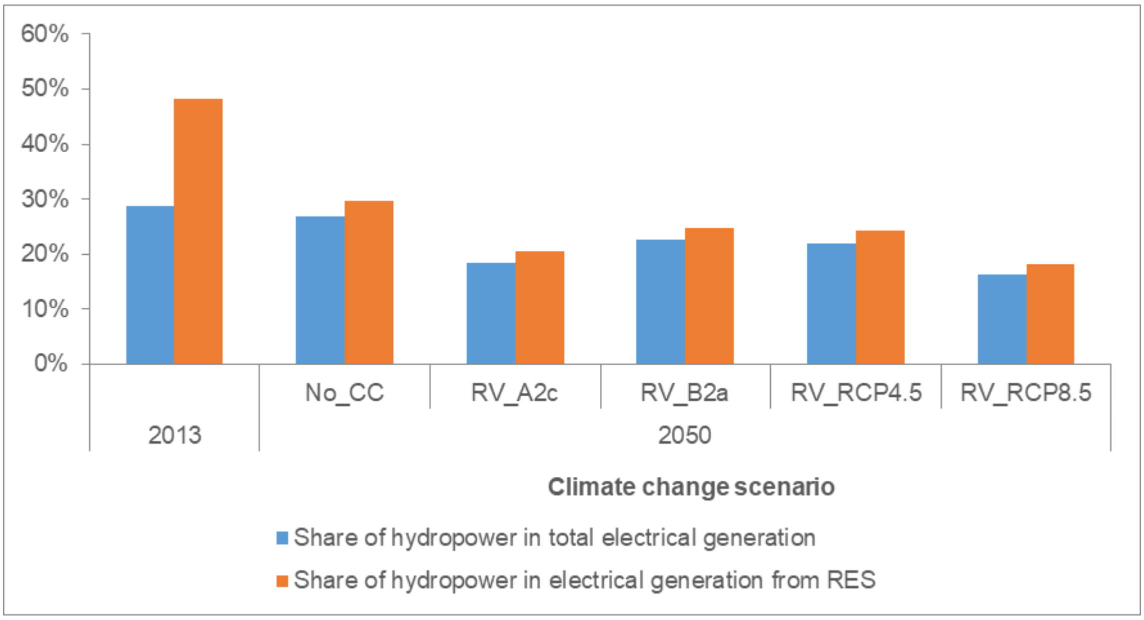
Figure 7.5. GHG emissions by sector in 2013 and 2050 per climate change scenario



7.4.2. Climate change scenarios

Compared to the No_CC scenario, simulations show that electrical generation decreases slightly (up to -2%) in the presence of climate change impacts: around -1% in the RV_B2a, RV_RCP4.5 and RV_A2c scenarios, and -2% in the RV_RCP8.5 scenario (see Figure 7.3). Though small, such reductions result from considerable changes in hydropower generation. The decrease in hydropower generation ranges from -2,500 GWh in the RV_B2a (-17%) and -2,800 GWh in the RV_RCP4.5 scenarios (-19%) to -5,000 GWh in the RV_A2c scenario (-33%) and -6,200 GWh in the RV_RCP8.5 scenario (-41%). For that reason, the share of hydropower in electrical generation reduces in all climate change scenarios (compared to the No_CC scenario), both in total and in RES electrical generation (see Figure 7.6). In the No_CC scenario, hydropower represents 27% of total electrical generation and 30% within RES, but these shares decrease to 16% and 18%, respectively, in the most severe climate change scenario (RV_RCP8.5 scenario). These reductions are mainly offset by the significant increase in solar PV (up to 2,700 GWh in the RV_RCP8.5 scenario; +16%), followed by other RES (biomass, geothermal) and, ultimately, by natural gas.

Figure 7.6. Hydropower generation share in total electrical generation and in renewable energy sources (RES) electrical generation in 2013 and 2050 per climate change scenario



Thus, considering climate change impacts, major changes in the electricity mix correspond to the strengthening of solar PV (which reaches around 35% of total generation in all climate scenarios) and the impairment of hydropower. The remainder of the technologies maintain their role in the electrical mix, compared to the No_CC scenario: wind power assures around 32% of generation; biomass corresponds to around 3% of generation; and natural gas represents between 9% and 10% in the mix (Figure 7.3). This new mix in electricity generation implies that the installed capacity in solar PV increases by around 1.3 GW (+16%). The reduction in hydropower generation in the most severe scenarios (RV_A2c and RV_RCP8.5), in combination with the insufficiency of the solar PV potential to satisfy demand, implies that the installed capacity in natural gas is reinforced by 0.633 GW and 0.752 GW, respectively (+21% and +26% as compared to No_CC scenario). Thus, the overall installed capacity has to increase by between 5% and 8% compared to the No_CC scenario (from 28.7 GW to, respectively, 30.2 and 30.9 GW in the RV_RCP4.5 and RCP8.5 scenarios; see Figure 7.4) despite the slight reduction of electrical generation in the presence of climate change impacts (up to -2%). The predominance of renewable energy in the electrical mix leads to a slight reduction (up to 2 percent points) in the ‘production-capacity’ ratio in climate change scenarios, compared to the No_CC scenario.

Climate change will also have an impact on electricity generation costs. These will rise by between 7% in the RV_B2a scenario and 39% in the RV_RCP8.5 scenario, compared to the No_CC scenario. As a consequence, the electricity price to final users (including transmission and distribution costs) will also be higher in the presence of climate change – with increases ranging between 3% and 17% in the RV_B2a and RV_RCP8.5 scenarios, respectively. The higher electricity prices will not critically affect electricity final demand, which is projected to decrease by only 1% in all climate change scenarios, compared to the No_CC scenario. Indeed, final energy consumption patterns under the considered climate change scenarios are quite similar to the No_CC scenario (see Figure 7.2). Still, natural gas demand increases by 6% in all scenarios, while oil products demand increases also in the RV_A2c and RV_RCP8.5 scenarios (+6%) to offset the reduction in biomass (-25%).

Finally, total GHG emissions increase in all climate change scenarios compared to the No_CC scenario (between 0.9% and 7.2%), the RV_A2c and RV_RCP8.5 scenarios showing the largest increases (5.3% and 7.2%, respectively) due to the greater utilization of fossil-fuels (see Figure 7.5). Within the power sector, the increase in these two scenarios towards the No_CC scenario is even higher (+9% in the RV_A2c and +23% in the RV_RCP8.5 scenario). In contrast, in the RV_RCP4.5 and RV_B2a scenarios, GHG emissions only slightly increase (+0.8%) or even decrease (-1.1%) as compared to the No_CC scenario. This is due to the large share of hydropower in the electricity mix, resulting from less stringent impacts of climate change on water resources and, thus, reduced need for fossil-fuels.

7.5. Conclusions and policy implications

Renewable energy plays a determinant role within global and EU energy policies for a low-carbon economy. Nonetheless, renewable energy is itself vulnerable to climate change as it is dependent on natural resources and climate conditions. Concerning hydropower, its strong dependence on water resources poses major challenges for electricity generation in the presence of climate change impacts – due to increased temporal and spatial variability of water resources as well as increased competition between water-dependent economic sectors and between countries sharing common river basins.

Even though climate change impacts on hydropower are widely recognized in literature, their quantification is scant. Few studies focus on the impacts of climate change on the energy sector supply (Ciscar & Dowling, 2014) and particularly for a Mediterranean country. This paper contributes simultaneously to filling these two gaps, by quantifying the climate change impacts on energy supply in Portugal, with specific focus on the hydropower potential and its role in the national electrical mix.

Our results confirm hydropower vulnerability to climate change, given that any decrease in water availability induces an immediate decrease in electrical hydropower generation (between 17% and 41%). These results are in accordance with previous studies arguing that climate change will negatively affect hydropower potential in Portugal (see e.g. (Lehner et al., 2005)). Our simulations show, however, stronger effects than similar analyses carried out for Portugal with TIMES_PT model (Alves, 2013; Cleto, 2008). (Cleto, 2008) combined runoff projections provided by (Santos et al., 2002; Santos & Miranda, 2006) with the A2c and B2a SRES scenarios to simulate strong and weak impacts of climate change, respectively. The main outcome is that hydropower generation will be 7% lower in the strong climate change scenario than in the alternative one, while power generation values or shares per technology are not provided. (Alves, 2013) used (Lehner et al., 2005) projections for the total Portuguese hydropower potential by 2070 to conclude that hydropower generation in 2050 will be 7% lower than in the reference scenario (2010), while the regional and seasonal dimensions were not considered in the analysis. The different magnitude of impacts provided by our results is explained by three main factors: i) improved calculations on the relationship between runoff and the hydropower capacity factor; ii) most recent climate change scenarios; and iii) updated projections concerning technology costs, energy services demand and primary energy prices. Results are also coherent with previous research focusing on regions with similar climate conditions. (van Vliet, van Beek, et al., 2016) estimate that the hydropower potential in Southern Europe will decrease by more than 20% under RCP8.5, by 2050. (Tarroja et al., 2016) conclude that climate change may increase inflow volumes in Californian reservoirs by 2050 under RCP4.5 and RCP8.5, but this will not lead to an increase in hydropower generation due to dam structure characteristics.

In addition, and similar to our analysis, (Tarroja et al., 2016) conclude that GHG emissions may increase due to the use of natural gas to offset the reduction in hydropower generation, especially following extreme precipitation and drought events. Our results show that the stronger the climate change impacts, the higher the GHG emissions – thus undermining the compliance with EU climate goals for 2050 (EUCO, 2011) and the Portuguese Roadmap towards a low-carbon economy in 2050 (APA, 2012). As the solar PV potential is insufficient to offset the reduction in hydropower generation caused by climate change, natural gas increases its share in the electrical mix and, thus, results in an increase in the power sector's GHG emissions. Note that our simulations consider an ETS price but do not impose any GHG emissions target, leaving the model free to find the most cost-effective solution for the energy system (i.e. the cost-minimizing rationale of the TIMES_PT model implies that the energy system is set such that the most cost-effective technologies are deployed). Our results thus stress that stronger direct GHG policy is required in the future to assure the compliance with EU climate goals for 2050.

Notwithstanding hydropower vulnerability to climate change is undeniable, it is also true that its role will be strengthened with the increasing penetration of intermittent renewable energy sources, mostly wind and sun, which will bring increased fluctuations to generation (Eurelectric, 2011; Gaudard & Romerio, 2014). Given its flexibility and storage capacity (plants can either start and stop instantly and store electricity for periods that range from days to years), hydropower provides the necessary backup to balance demand and supply - thus optimising the use of variable renewable energy sources in the electrical system, assuring security of supply and establishing itself as the solution for the challenges of a power system in transition (Eurelectric, 2015). In practice, the complementarity between hydro and wind/solar power means that during periods of excess supply of wind and/or solar power, that energy may be used to pump water back into the storage reservoir such that this water can be converted into hydropower when electricity demand increases. Although this integration is already in practice (Eurelectric, 2011; Goodbody, Walsh, McDonnell, & Owende, 2013), it is highly likely that it will increase with the certain expanding share of wind and solar power in the electrical mix expected in the near future (Eurelectric, 2015). Despite this complementarity between hydro and wind/solar is not modelled explicitly in TIMES_PT, the model comprises in the total hydro capacity the hydropower pumped storage plans. It takes into account the historic capacity factor of the technology and assumes the projected hydropower expansion plans set by the national policy (APA, 2015). This expansion will result in an increase of the current pumped storage plan capacity in total hydropower from 26% (REN, 2016) up to a maximum of 38%.

From an economic perspective, our simulations show that climate change scenarios will imply additional investments on generation capacity, mainly in solar PV and natural gas. This will crowd-out some other investments in the Portuguese economy. Accordingly, there will be a loss of economic efficiency in the energy system as long as more capacity (investments and fixed costs) is needed to satisfy electricity demand. Also, an increase in the price of electricity supplied to the Portuguese economy (up to 17%) is projected. Thus, as a result of climate change impacts on electricity generation, the Portuguese economy may undergo a GDP loss both directly (e.g. crowd-out effects on investments, larger natural gas imports reducing the generation of added value by the electricity sector, and loss of economic efficiency in the energy system) and indirectly (e.g. the impact of rising electricity prices on the Portuguese economy). Unfortunately, the partial equilibrium approach of TIMES_PT does not allow to estimate such macro-economic impacts (e.g. GDP and employment losses), which should be addressed in future research. Considering the central role electricity is expected to play in the 2050 low-carbon economy (EC, 2011b), the projected increase in electricity generation costs and, therefore, consumer prices, also arises as an important issue for policy-making.

Although energy models, such as TIMES_PT are currently one of the most popular methods of energy modelling and forecasting, some shortcomings may be recognized: i) user behaviour is sometimes not properly modelled (Hall & Buckley, 2016; Nguene et al., 2011; Pfenninger, Hawkes, & Keirstead, 2014; Swan & Ugursal, 2009), ii) inherent reliance on scenario analysis and lack of uncertainty assessment (Pfenninger et al., 2014), and iii) limited transparency and reproducibility of model and data (Glynn et al., 2015; Hall & Buckley, 2016; Howells et al., 2011; Pfenninger et al., 2014). Regarding this particular study, the following caveats need to be pointed out. First, the presented results hold under the premises that climate change does significantly impact water resources availability though does not significantly impact wind, biofuels, solar irradiance and geothermal resources, as indicated by (IPCC, 2011; Santos et al., 2002). Second, TIMES_PT does not possess a spatial component, which is crucial to accurately capture climate change impacts on water availability. To overcome this limitation, national data was derived from weighted regional values. Third, the natural resources' availability factor and energy demand corresponds to a weighted seasonal (four seasons) and day, night and peak time slices average, which represents a simplified approach to represent the electricity load curve. Finally, TIMES_PT is a bottom-up partial equilibrium model, that neither considers agent preferences nor the interactions between the energy sector and the remainder of the economy. Considering that the energy sector is a key input of almost all economic sectors and that every shock in the energy sector is rapidly transferred to the economy as a whole, a top-down approach would provide a comprehensive (economy-wide) understanding of the impacts and feedbacks between climate change, the energy sector and the economy (e.g. following (Böhringer & Rutherford, 2008)). Future research will study the economic impact of results from this analysis on the Portuguese economy by using a general equilibrium top-down approach.

Appendix 7.1. Techno-economic inputs of selected power sector technologies

This table presents a summary of the techno-economic characterization of selected power generation technologies included in TIMES_PT database. It should be noted that the technology data reflect the characteristics and specificities of the country, e.g., hydropower investment costs which takes into account the construction costs in Portugal and offshore wind turbines for deep water through floating platforms.

Fuel	Technology name	Life time (years)	Investment Costs (EUR_{2015}/kW)				Fixed Costs (EUR_{2015}/kW)				Variable costs (EUR_{2015}/GJ)				Efficiency (%)				Availability factor[a] (%)	CO2 capture rate (%)
			2010	2020	2030	2050	2010	2020	2030	2050	2010	2020	2030	2050	2010	2020	2030	2050		
Natural Gas	Combined cycle power plant - conventional	25	916	916	916	916	28	24	22	22	0,6	0,6	0,6	0,6	58%	59%	62%	64%	85%	
	Combined cycle power plant with post-combustion CO2 capture	25		1,286	1,239	1,172		46	45	42		0,9	0,8	0,8		53%	53%	53%	70%	88%
Coal	Supercritical steam turbine	35	1,770	1,770	1,770	1,770	36	36	36	36	0,4	0,4	0,4	0,4	46%	49%	52%	52%	85%	
	Supercritical steam turbine with post-combustion CO2 capture	40		2,495	2,369	2,164		45	43	36		0,6	0,6	0,6		33%	37%	39%	75%	88%
Biomass	Steam turbine - conventional	30	3,949	3,754	3,716	3,640	137	137	137	137					22%	23%	23%	23%	78%	
Biogas	Anaerobic digestion biogas with gas engine	30	4,269	4,269	4,269	4,269	85	85	85	85	0,7	0,7	0,7	0,7	32%	32%	32%	32%	58%	
Hydro	Run of River hydroelectricity	70	1,844	1,729	1,622	1,474	18	18	18	18					100%	100%	100%	100%	Variable according with the hydrologic scenario	
	Lake - Medium scale hydroelectricity	80	1,059	1,036	1,015	909	10	10	10	10					100%	100%	100%	100%		
Geothermal	Geothermal hydrothermal with flash power plants	30	5,855	5,085	4,424	4,424	293	182	155	137					85%	85%	85%	85%	85%	
Wind	Wind offshore	25		3,735	3,202	2,135		82	82	82					100%	100%	100%	100%	32%	
	Wind Onshore	25	1,355	1,251	1,094	990	33	26	24	21					100%	100%	100%	100%	27%	
Ocean	Wave	20		4,253	3,686	2,949	85	80	69	49					100%	100%	100%	100%	30%	
Solar	Solar PV utility scale	30	3,964	1,121	1,008	814	59	16	15	13					100%	100%	100%	100%	24%	
	Solar PV high concentration	30	7,845	3,042	2,432	1,661	117	45	36	25					100%	100%	100%	100%	27%	
	Solar CSP (with storage 6-9hours)	30	5,955	4,168	2,977	2,382	149	104	74	60					100%	100%	100%	100%	35%	

[a] Availability factor represents the percentage of the year in which the technology is functional.

CHAPTER 8

WATER COMPETITION THROUGH THE 'WATER-ENERGY' NEXUS: ASSESSING THE ECONOMIC IMPACTS OF CLIMATE CHANGE IN A MEDITERRANEAN CONTEXT*

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Abstract

The impacts of climate change on water resources availability are expected to be adverse, especially in drier climate regions such as the Mediterranean. Increased water scarcity will exacerbate competition for water resources, not only between sectors but also between countries sharing transboundary river basins. Due to the mutual dependence of the energy sector on water resources and of the water services provision sector on energy inputs, the 'water-energy' nexus is acknowledged as a major challenge for the near future – with hydropower representing one of the most direct links in this nexus. The aim of this paper is to assess the economy-wide impacts of the concurrent effects of climate change-driven impacts on water availability and the sectoral and regional competition for scarcer water resources. In order to accomplish that goal, an integrated modelling approach is developed, where a computable general equilibrium model including raw water as a production factor is linked to TIMES_PT, a bottom-up model of the energy sector. A case study is provided for the Mediterranean country of Portugal. The results for 2050 show that macroeconomic impacts are significant, and encompass important inter-sectoral differences that, in turn, depend on the degree of competition between sectors. Impacts are stronger when water consumption by Spanish sectors is considered, as this intensifies water scarcity in Portugal. Thus the paper allows us to gain insight in the broader 'water-energy-economy' nexus and the additional costs that the dependence on water resources availability in transboundary river basins represents to an economy – both aspects being of utmost importance for climate adaptation and energy policy making.

8.1. Introduction

Climate change affects several domains of life on Earth, with the impacts on water resources amongst one of the most important. Climate change modifies the hydrological cycle, thereby affecting the availability of water resources and the timing and variability of supply and demand of water resources and services (Cunha et al., 2007; WWAP, 2014). In particular, higher temperatures and evaporation will negatively affect water supply and, simultaneously, increase water demand by the agricultural and energy sectors (WWAP, 2014).

Projections from the Intergovernmental Panel on Climate Change (IPCC, 2013b) show that climate change is increasing the vulnerability associated with present use of water resources and augmenting the uncertainties concerning water quantity and quality over the coming decades. Expected changes in temperature and precipitation will lead to changes in runoff and water availability, and regions already prone to droughts are anticipated to become more so. The Mediterranean region, including the Iberian Peninsula, is identified as one of the regions in the world most vulnerable to changes in water resources availability and distribution (EEA, 2017a; Guerreiro, Birkinshaw, et al., 2017; IPCC, 2013b). For Portugal, projected higher temperatures, higher potential evapotranspiration, lower precipitation and more frequent extreme rainfall events will lead to an increase in drought and flood risk. Spatial and seasonal variability of precipitation will, in turn, reduce runoff while increasing its seasonal asymmetry (Cunha et al., 2007; Guerreiro, Kilsby, & Fowler, 2017; Koutroulis et al., 2018; Vautard et al., 2014). Altogether, these factors are expected to negatively affect water availability and quality in Portugal (APA, 2013; Cunha et al., 2007)[22].

The reduced availability of water resources is expected to exacerbate the existing competition among different sectors, notably agriculture, energy and urban uses (WWAP, 2014), as well as among countries sharing common river basins (IEA, 2016; WWAP, 2014). The energy sector is particularly relevant in this respect as water resources are essential in the entire chain of energy production, notably in the extraction and mining of fossil fuels, irrigation of biofuel crops, cooling of thermal plants and hydropower generation. As to the power sector in particular, around 90% of the global power generation sector is water intensive and the cooling of thermal power plants represents

[22] A comprehensive review of the climate change impacts projected for Portugal can be found in (Teotónio et al., 2017).

43% of total freshwater withdrawals in Europe (WWAP, 2014). Hydropower is the largest water-using sector, but most of the water used to drive turbines is returned to the river system. Thus, effective consumption of water by hydropower (i.e., water that does not return to the river system) is mainly due to evaporation in reservoirs and seepage. Water needs for power production naturally depend on the power generation portfolio but, on the other hand, the allocation of (scarce) water resources among multiple uses also determines how much water will be available for the power sector (WWAP, 2014).

Water resources and the energy sector are thus closely interlinked and every management/political decision concerning the allocation of water will have broader, economy-wide, impacts. Such interlinkages and resulting externalities are the cornerstone of the so-called 'water-energy' nexus (WWAP, 2014). While the strength of the nexus may depend on regional distribution of water resources and infrastructures (for water and energy), there are some additional factors reshaping the 'water-energy' nexus, such as the increasing living standards of a world population in continuous growth (that will rise water and energy demand) and climate change impacts (that will affect natural resources availability and energy demand) – thus tightening the relationship between water and energy (Khan et al., 2017). Accordingly, the 'water-energy' nexus is acknowledged by international organisations, such as the World Bank and the United Nations, as a global challenge for the near future (IEA, 2016; Khan et al., 2017).

This interdependency is particularly acute for hydropower generation, for which conflicts about distinct and concurrent uses for scarce water resources are evident. In Europe, the uncertainties associated with the impacts of climate change on the hydrological cycle, water availability and energy production are acknowledged as a critical issue (Khan et al., 2017; WWAP, 2014). Moreover, following worldwide trends in favour of a low carbon economy, European national energy mixes are rapidly shifting from fossil to renewable energies (notably wind power and solar photovoltaic) that need to be backed-up, mostly by hydropower. In other words, given its low operational costs, rapid/efficient start-up and storage capacity, hydropower is considered the most feasible and cost-effective option for the management of intermittent renewable energy sources in the grid (IRENA, 2012; REN21, 2011; Schaefli, 2015; WWAP, 2014). Hence, both climate change impacts on the hydrological cycle and energy policy strategies will likely exacerbate competition between sectors for limited water resources in the near future.

The increasing concern about the impacts of climate change on water resources availability and the resulting consequences for human and economic activities is at the origin of a vast literature. In particular, relationships between water resources and the economy are commonly examined through integrated hydro-economic models, notably using computable general equilibrium (CGE) models (Brouwer, Hofkes, & Linderhof, 2008). Notwithstanding the large number of analyses of the economic impacts of changes in water availability, these studies are mainly devoted to economy-wide impacts of changes in water endowments (e.g., (Koopman et al., 2017; Roson & Damania, 2017) or focussed on the agricultural sector (e.g., (Calzadilla, Rehdanz, et al., 2013; Calzadilla et al., 2014). The economic impacts of the interlinkages between water resources and the energy sector are, however, scarcely studied, which is explained by the fact that the great majority of studies addressing the 'water-energy' nexus are primarily focussed on its technological dimension (Hamiche et al., 2016). In this paper we fill this gap in literature, by adopting an innovative methodology that addresses the economic dimension of the 'water-energy' nexus and explicitly considers: i) climate change impacts on the hydrological cycle through changes in runoff, ii) competition for water resources between the power sector and the remaining economic sectors, and iii) dependence on water resources availability in transboundary river basins. Hence, the ultimate objective of this paper is the comprehensive assessment of the economic impacts of the competition for scarcer water resources under climate change scenarios by 2050, with particular emphasis on the 'water-energy' nexus. For the case of the Mediterranean country of Portugal, the computable general equilibrium model described in (Labandeira, Labeaga, et al., 2009) is extended with the inclusion of raw water as a production factor in all production sectors and with a technological disaggregation of the power sector – this latter building on the detailed energy system characteristics and structure provided by the TIMES_PT bottom-up model presented in (Teotónio et al., 2017).

The remainder of this paper is organized as follows. Section 8.2 is devoted to a literature review on water-oriented CGE models. Section 8.3 describes the CGE model, the business-as-usual scenario for the year 2050 and the methodology used to incorporate raw water in the model. Section 8.4 presents and describes the considered scenarios regarding competition for water resources between sectors and countries. Section 8.5 presents and analyses the main results. Finally, Section 8.6 discusses the simulated impacts, assesses their policy implications and concludes.

8.2. Literature review

The complex interconnections between water resources and the economy is mostly examined through integrated hydro-economic models (Brouwer et al., 2008a). These models adopt a single framework to link: i) hydrological and biogeochemical processes, ii) engineering and environmental characteristics of water resources, and iii) the economy via the demand for and supply of scarce water services (Brouwer et al., 2008; Harou et al., 2009). CGE models are one of the hydro-economic modelling approaches in the empirical literature that, in particular, represent the circular flow of the economy while taking into account the economic behaviour of different economic agents. Their features allow for a detailed representation of the climate change impacts affecting markets, sectors and regions (OECD, 2015; Wing & Lanzi, 2014). (Berck, Robinson, & Goldman, 1991) were the first to apply a CGE model to water problems. Since then, CGE models have been widely used to approach water-related issues – focusing on the river basin, country, region or, even, adopting a global perspective.

Categories of water-oriented CGE analyses

According to (Calzadilla et al., 2016), water-oriented CGE analyses can be grouped into two broad categories. One refers to the economy-wide impacts of changes in water endowments triggered by climate change or infrastructure investment. The other refers to the economic impacts, such as on consumption, costs, water demand and the economic system, driven by economic instruments and policies.

Concerning the first category of CGE analyses, the economy-wide effects of climate change (i.e. changes in precipitation, temperature and river flows) on water endowments have been studied for different geographic areas: single countries, such as Italy (Galeotti & Roson, 2012), Switzerland (Faust et al., 2015) and China (Zhan et al., 2015); countries sharing common river basins, such as the Rhine and Meuse (Koopman et al., 2015; Koopman et al., 2017); broader regions, such as the Mediterranean (Roson & Sartori, 2014, 2015); and the world (Calzadilla, Rehdanz, et al., 2013; Calzadilla et al., 2010; Dellink et al., 2017; Roson & Damania, 2017; Roson & van der Mensbrugghe, 2012). Most of these studies considered the climate change scenarios from the IPCC 'SRES scenarios' (IPCC, 2000). Impacts arising from the most recent Representative Concentration Pathways (RCPs; (van Vuuren, Edmonds, et al., 2011)) or Shared

Socioeconomic Pathways (SSPs; (Kriegler et al., 2012)) climate change scenarios have not yet been extensively analysed ((Roson & Damania, 2017) constitutes an exception).

Concerning the second category of CGE analyses, the economic impacts of policy instruments aiming to improve efficiency in the usage of water resources have been assessed for, e.g.: water pricing systems (Cardenete & Hewings, 2011; Luckmann, Flaig, Grethe, & Siddig, 2016; Rivers & Groves, 2013; Zhao et al., 2016); water-related taxes and subsidies (Berrittella et al., 2008; Cazcarro, Duarte, Choliz, & Sarasa, 2011; Qin, Jia, Su, Bressers, & Wang, 2012; Zhong, Shen, Liu, Zhang, & Shen, 2017); water use efficiency improvements (Calzadilla, Rehdanz, & Tol, 2011; Liu, Hu, Zhang, & Zheng, 2017); public investments in the water sector (Llop & Ponce-Alifonso, 2012; Luckmann, Grethe, McDonald, Orlov, & Siddig, 2014); introduction of water markets (Berrittella, Hoekstra, Rehdanz, Roson, & Tol, 2007; Hassan & Thurlow, 2011; Solís & Zhu, 2015; Tirado, Lozano, & Gómez, 2010); and sectoral reallocation of water resources (Juana, Strzepek, & Kirsten, 2011; Seung, Harris, Englin, & Netusil, 2000).

Besides these two major categories, CGE models have also been applied to assess other water-related issues, such as water quality (e.g. (Brouwer et al., 2008b; Dellink, Brouwer, Linderhof, & Stone, 2011), water infrastructure disruption (Rose, Liao, & Bonneau, 2011), income and population growth pressures on freshwater resources (Jiang, Wu, Liu, & Deng, 2014; Nechifor & Winning, 2017; Watson & Davies, 2011), and economic growth strategies (Cazcarro, Duarte, Sánchez-Chóliz, Sarasa, & Serrano, 2015). A particular additional form of approaching water in CGE models is through the ‘virtual water’ concept[23], i.e., considering the implicit water content of internationally traded goods (e.g. (Berrittella et al., 2007; Cazcarro et al., 2015)).

Structure of water-oriented CGE analyses

In water-oriented CGE models, a distinction may be made between raw water resources extracted from the environment, usually considered a factor of production for some sectors, and distributed water, which is provided by the drinking water distribution and supply sector as an intermediate input for economic activities and as a final consumption good for households. Water enters as a factor of production in the agricultural sector (Hassan & Thurlow, 2011), in the agricultural and water supply sectors (Berrittella et al.,

[23] ‘Virtual water’ consumption is the direct and indirect usage of water associated with the production or consumption of any good or service (Allan, 1992).

2007; Watson & Davies, 2011) or, alternatively, in all economic sectors (Faust et al., 2015; Koopman et al., 2017; Luckmann et al., 2016; Roson & Damania, 2017). Few water-oriented CGE analyses only consider water as an intermediate input provided by the distribution and supply sectors (Llop & Ponce-Alifonso, 2012; Zhao et al., 2016). Inter-sectoral competition for water thus exists through the interaction between demand and supply, but the implications for the 'water-energy' nexus are not considered in these analyses.

Whenever water is a production factor, it is common practice to combine water resources with land. This may be explained by the argument that the value of land is, not only, determined by the soil characteristics but, also, by the water that can be extracted from it and, hence, an implicit water rent can be derived from the total land rent (Calzadilla et al., 2016). This is the modelling structure applied by different authors, such as (Calzadilla, Rehdanz, et al., 2013; Calzadilla et al., 2010, 2014; Calzadilla, Zhu, Rehdanz, Tol, & Ringler, 2013; Koopman et al., 2017; Liu et al., 2017; Luckmann et al., 2016). The land-water aggregation is mostly associated with the agricultural sector, as this is one of the largest water consumers in the economy (examples of analyses focused on agriculture include (Calzadilla et al., 2014; Calzadilla, Zhu, et al., 2013; Roson & Sartori, 2015)). Studies that do not combine water with land resources, adopt alternative nesting structures – either considering substitution possibilities between a composite of primary factors (water, labour, capital, land) and intermediate inputs (e.g. (Luckmann et al., 2016; Solís & Zhu, 2015; Zhan et al., 2015)), or isolating water to represent its substitution possibilities with the remaining primary factors and intermediate inputs (e.g. (Faust et al., 2015)).

Integrated approaches in water-oriented CGE analyses, combining top-down CGE models with bottom-up models, are adopted to integrate bio-physical and/or socio-economic heterogeneity in the analysis (Ponce et al., 2012). To this end, farm models (Baum, Palatnik, Kan, & Rapaport-Rom, 2016; Cakmak et al., 2008; Roe, Dinar, Tsur, & Diao, 2005), hydrological models (Smajgl, 2006), agent-based models (Smajgl, Morris, & Heckbert, 2009) and revealed preference models (Pérez-Blanco, Standardi, Mysiak, Parrado, & Gutiérrez-Martín, 2016) have been used. CGE models have also been combined with integrated assessment models to capture the long term market and non-market impacts of climate change (e.g.(OECD, 2015)).

Although the majority of these water-oriented CGE analyses seek to address the impacts of restricted water supply (either directly, considering the impacts of climate change on water resources availability, or indirectly, considering policy instruments to cope with reduced water supply), changes in water availability are frequently modelled via exogenous shocks in productivity (i.e., water is a hidden factor of production), rather than through an explicit change in water endowments (Ponce et al., 2012). This, in particular, through changes in land productivity (e.g. (Calzadilla, Rehdanz, et al., 2013; Calzadilla et al., 2011)) or multifactor productivity (e.g. (Galeotti & Roson, 2012; Roson & Sartori, 2015). Exceptions of studies that directly consider changes in water endowments include the assessment of the potential for water markets in the context of reduced water availability in the Netherlands (Koopman et al., 2017) and the assessments of the economic impacts of climate change in Italy (Galeotti & Roson, 2012), Switzerland (Faust et al., 2015) and the world (Roson & Damania, 2017).

Even though this review on water-oriented CGE studies is not exhaustive, the revised literature clearly shows the lack of studies that explicitly consider and quantify the 'water-energy' nexus. In the next sections we describe the CGE model and the methodology adopted to address this issue. The simulation of such interdependency constitutes the major added-value of this study.

8.3. Methodology

8.3.1. The model and the business-as-usual scenario for 2050

To assess the economic impacts of the sectoral and international competition for water resources, a static CGE model for a small open economy, calibrated for 2008, is used. It relies on the model comprehensively described in (Labandeira, Labeaga, et al., 2009), which was extended to include a technological disaggregation of the power sector based on the inputs provided by the TIMES_PT bottom-up model (Teotónio et al., 2017), and raw water as the third primary factor of production, along with labour and capital (see Appendix 8.1 for further details of the model). The model comprises 31 production sectors and three institutional sectors: the private sector (households, firms and non-profit institutions), the public sector and the foreign sector. Note that whereas raw water is a factor of production, distributed water is an intermediate input / final consumption good provided by the "water distribution and supply" production sector.

Producer behaviour is based on the profit maximization principle, such that in each sector a representative firm maximizes profits subject to a constant returns to scale technology. Produced goods and services are split between the domestic and export markets. International trade is modelled under the Armington assumption that domestic and imported goods are imperfect substitutes for domestic consumption (Armington, 1969). Likewise, domestically produced goods can be supplied to the domestic or export market, under a constant elasticity of transformation supply function. Household behaviour follows the welfare maximization principle, such that a representative consumer maximizes welfare subject to a budget constraint. Similarly, Government aims to maximize public consumption subject to a budget constraint. Primary production factors are perfectly mobile between sectors at the national scale, but immobile internationally. The labour market is taken to be imperfect, as involuntary unemployment exists. The macroeconomic equilibrium is determined by the national net lending/borrowing capacity. The elasticities of substitution were taken from (EC, 2013b)[24].

Existing projections for the Portuguese economy were used to develop the 2050 business-as-usual (BaU) scenario, which is the basis for scenario simulation and comparison. The 2050 BaU scenario relies on the projections for energy demand, electrical supply mix (taken from (Teotónio et al., 2017), thus including energy efficiency technological change)), gross domestic product (GDP; (APA, 2015)), population (APA, 2015) and international fossil fuel prices (OECD/IEA, 2015b). Raw water intensities computed for 2008 (see Section 8.3.2) are assumed to be kept constant for 2050 which represents a very conservative assumption. Resulting sectoral gross value added (GVA) breakdown is in accordance with existing projections for the year 2050 in Portugal (APA, 2012).

The reduction in water availability on the Portuguese energy system (see Section 8.4) is simulated using the bottom-up model of the energy system 'TIMES_PT' (see (Fortes et al., 2015)), following the methodology described in (Teotónio et al., 2017). TIMES_PT simulations considers seasonal and/or daily variability of renewable energy resources, including water availability for hydropower. The model provides, for each scenario, the corresponding electrical mix and electrical generation costs that, in turn, enter as inputs in the top-down CGE model[25] to simulate the economy-wide impacts of changes in water

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[24] The only exception refers to the mining and quarrying production sector, whose elasticities were taken from (Aguiar et al., 2016), given these were not available from (EC, 2013b).

[25] Hence, within our integrated assessment framework, technological advances in the energy sector are embodied in the inputs provided by the bottom-up TIMES-PT model.

resources availability in the light of the 'water-energy' nexus. In particular, the technological disaggregation of the electrical generation sector was introduced using a bottom-up approach as follows. The aggregate "Electricity" production sector of the Social Accounting Matrix (SAM; the core dataset of the CGE model) was split into six representative power generation technologies given by the TIMES_PT model[26] for each simulated scenario (see Section 8.4). The Electricity sector's total output was then broken-down according to the cost structure (capital, fuel, and labour costs) projected for 2050 ((Teotónio et al., 2017)) and the output shares of each representative generation technology per climate scenario in order to convert electrical generation from physical units (GWh), as given by the TIMES_PT model, into monetary units (that are compatible with the SAM). We thus obtained the necessary technological breakdown of the "Electricity" production sector in the SAM that is consistent with the TIMES_PT model simulations. These data were introduced in the CGE model to provide the bottom-up representation of the electrical generation sector in each scenario. Both methodologies (top-down and bottom-up) are thus integrated into a single framework, as illustrated in (Böhringer & Rutherford, 2008).

8.3.2. The inclusion of raw water resources

Raw water is included in the model as a factor of production that enters the production function of all sectors. It is combined with value-added and energy inputs, in the second nest, through a Leontief production function so that the degree of substitution between water and the other factors of production is null. Following (Faust et al., 2015), raw water extraction results from a combination of the natural resource with energy and capital, being the energy and capital costs per cubic meter of water equivalent to those exhibited by the water distribution sector. It is assumed that there is no competition for raw water between sectors in the absence of climate change impacts and, therefore, it is freely available. In the presence of climate change, raw water availability is reduced and becomes a scarce resource with a positive price (it is no longer freely available) – this representing the opportunity cost associated to its scarcity. Water is mobile between sectors – i.e., following changes in relative prices, water is reallocated between sectors such that its price is equal across sectors. Raw water is assumed to be an imperfect public good as long as the property rights are not perfectly defined (it is subject to the

[26] The CGE model included the following power technologies: hydropower, wind power, solar photovoltaic, biomass, geothermal and natural gas.

"problem of the commons"; (Hardin, 1968)). As such, the Government is endowed with water resources, meaning that when its price becomes positive Government will receive the associated scarcity rents.

Raw water resources are included in the model via sectoral raw water intensity coefficients (i.e. the ratio between consumed raw water and GVA, measured in m^3/€), following e.g. (Berrittella et al., 2007; Roson & Damania, 2017). Departing from sectoral water intensities and taking into account the breakdown of water consumption between distributed and self-supplied to obtain raw water consumption per sector, raw water is included in the production function as a production factor, whereas distributed water is an intermediate input provided by the "water distribution and supply" sector.

Sectoral raw water intensities for Portugal are calculated as follows. First, despite the Social Accounting Matrix for 2008 (see Section 8.3.1), water consumption data refers to 2009 (Eurostat, 2016) as this is the year with most complete information while still being coherent with the 2008 economy. Second, Spain is used as a reference whenever data for Portugal is missing. In particular, water intensity per manufacturing sector in Portugal is unavailable and, hence, this indicator is computed considering the sectoral Spanish water intensities as to obtain the (available) total water consumed by Portuguese manufacturing activities. Water needs by the power sector are obtained using available data for a representative set of thermal power plants in Portugal[27] (see (Brenhas, Machado, & Dinis, 2008)) and their respective cooling systems, as to calculate a weighted average of water needs per GWh of electricity produced per type of fuel (gas, coal, petrol and biomass).

Finally, note that almost all the production sectors consume both distributed and raw water. The exceptions are the services sectors and households, which are considered consumers of distributed water only (i.e., of water provided by the "water distribution and supply" sector) and meaning that raw water intensity is zero in these cases. Computed sectoral raw water intensities for Portugal are presented in Appendix 8.2.

[27] With the exception of concentrated solar power, which does not enter the Portuguese projected power mix for 2050, water consumption by renewable power technologies in the operating phase is low (Macknick, Newmark, Heath, & Hallett, 2012). Hence, only water consumption by biomass was considered in the analysis.

8.4. Scenarios

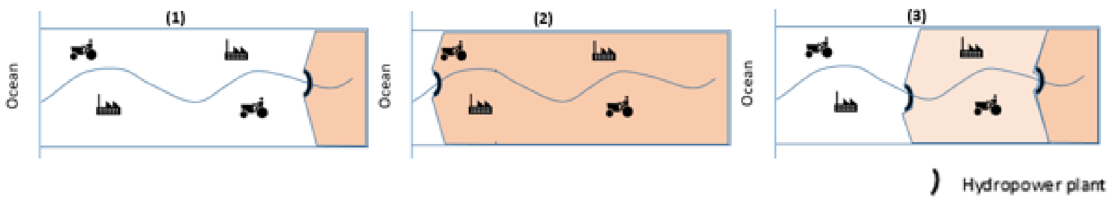
The purpose of this paper is to simulate the economic effects of climate change-driven impacts on water resources in Portugal considering the 'water-energy' nexus. To do so, a total of 6 scenarios is developed considering three main assumptions: competition for water resources between users, competition for water resources between countries and climate change scenarios (RCP4.5 and RCP 8.5). This section describes the scenarios building process and their main assumptions.

As to the competition between users, two alternative scenarios for water resources competition between the power sector and the remaining economic sectors are simulated:

- Scenario 'No competition' (No_Comp): Competition for water resources does not exist, meaning that hydropower generation and the remaining production sectors bear the impacts of climate change on water resources availability.
- Scenario 'Total competition' (Comp_): Competition for water resources exists, meaning that production sectors increase their water consumption so as to keep activity levels unchanged. Hydropower generation, thus, bears the cumulative effects of i) reduced water availability caused by climate change and ii) adaptation of the remaining economic sectors.

It is likely that the real situation is in between these two extreme scenarios, so, they may be understood as the interval for the real impact. The next paragraphs describe the building process for 'Total competition' scenario. As a departing point, it is assumed that water used for hydropower generation cannot be used again upstream by any production sector without full loss of the energy initially produced by it. Subsequently, it is considered that three different situations of competition for water resources may occur, according to three alternative locations for hydropower plants (see Figure 8.1).

Figure 8.1. Competition for water resources according to hydropower plants' location



Source: authors' elaboration

Situation 1 – Upstream hydropower plants: There is no competition for water between the middle- and downstream production sectors and upstream hydropower generation, i.e., all water used for upstream hydropower generation is available for middle- and downstream sectors.

Situation 2 – Downstream hydropower plants: There is competition for water between the middle- and downstream production sectors and downstream hydropower generation (throughout the catchment), i.e., all water used by middle- and downstream sectors is not available for downstream hydropower generation.

Situation 3 – Middle-stream hydropower plants: This is a hybrid situation between the previous two, which implies: i) no competition for water between the middle- and downstream production sectors and upstream hydropower generation; ii) competition for water between the middle stream production sectors and middle stream hydropower generation (middle catchment), and iii) no competition for water between the downstream production sectors and middle stream hydropower generation.

According to the geographical distribution of hydropower plants in Portugal (see Figure 8.2), Situation 3 is the most representative in the country. Hence, the quantification of the impacts of competition on water resources availability, as described for Situation 3, is obtained as follows:

Figure 8.2. Large dams in Portugal

Source: (APA, 2017)

Step 1. Water resources availability in the eight main river basins in Portugal[28] is calculated using the average annual flow and considering the water origin (Spain or Portugal). Water originating in Portugal is further disaggregated according to geographical location in the country – either upstream (interior) or downstream (coastal) of the hydropower plant nearest to the river mouth (see Table 8.1). The relevant water resources for the hydropower sector in Portugal correspond to the sum of water resources coming from Spain and those from the interior river basins upstream of the hydropower plants. Note that water coming from Spain represents around two thirds of the relevant water resources for hydropower generation in Portugal, highlighting the interdependence of Portugal and Spain in water resources management.

Table 8.1. Water resources per river basin, in Portugal (total flow; hm^3/year)

Water origin	Spain	Portugal			Total flow	Water resources available for hydropower generation in Portugal
Location in the river basin	Total (1)	Upstream (interior) (2)	Downstream (coastal) (3)	Total (4)=(2)+(3)	(5)=(1)+(4)	(6)=(1)+(2)
Minho	8,217	0	1,059	1,059	9,276	-*
Lima	1,442	405	156	562	2,004	1,848
Cávado	0	2,030	193	2,224	2,224	2,030
Douro	8,340	5,851	14,286	20,137	28,477	14,191
Vouga	0	219	799	1,019	1,019	219
Mondego	0	2,093	439	2,532	2,532	2,093
Tagus	8,163	472	1,305	1,777	9,940	8,636
Guadiana	1,214	191	1,461	1,653	2,867	1,405
Total	19,159	11,261	18,639	29,904	49,063	30,422

Source: Calculations based on data from (APA, 2016b; MARETEC, 2016)

* Note: No hydropower plants have been considered in the Portuguese part of the Minho river.

Step 2. Sustained by the Regional Accounts (INE, 2016c), the regional GVA of sectors in the interior and coastal regions is calculated to obtain the share of national sectoral production that will be affected by competition for water resources in the interior region. Table 8.2 shows that production sectors in the interior region represent 13% of total GVA, while production sectors in the coastal region represent 87% of total GVA.

Step 3. Water resource use by production sectors (in physical units) is calculated considering sectoral water intensities (described in Section 8.3.2) and territorial

[28] Minho, Lima, Cávado, Douro, Vouga, Mondego, Tagus and Guadiana river basins

disaggregation of economic activities (we assume the coastal vs. interior territorial disaggregation for 2008 as there is no available data for 2050). Table 8.2 shows that production sectors in the interior region consume 29% of total sectoral water while the production sectors in the coastal region consume 71%. In addition, production sectors in the interior region consume 9% of the upstream flow, while production sectors in the coast consume 14% of the downstream flow. This results in contrasting regional water intensities: 0.055m^3/€ in the interior region against 0.020m^3/€ in the coastal region. This difference is explained by the largest share of the agricultural sector in the interior region (6% of regional GVA against 2% in the coast), which is, by far, the largest water consumer.

Table 8.2. Total water consumption per sector and region in Portugal in 2008

Region	Unit	Interior region (upstream)			Coastal region (downstream)			Total
Production sector		Agriculture	Industry	Services	Agriculture	Industry	Services	
Sectoral GVA	M€	1,122	4,459	13,493	2,039	30,929	96,726	148,769
Regional GVA		19,074			129,695			
Sectoral consumption of water	hm^3	916	61	67	1,665	424	479	3,612
Regional consumption of water		1,044			2,568			
Sectoral water intensity (average)	m^3/€	0.817	0.014	0.005	0.817	0.014	0.005	0.024
Regional water intensity (average)		0.055			0.02			

Source: Calculations based on data from (APA, 2016b; Eurostat, 2016; INE, 2016c). Total water consumption corresponds to the sum of raw water and distributed water consumption.

Notes: The water consumption in the industry sector considers the power mix projected by 2050 for a no-climate change scenario, simulated by TIMES_PT model and available in (Teotónio et al., 2017).

The most recent expansion of the irrigated area around the Alqueva dam (Alentejo) was not considered in our analysis, as this was not reflected in the agricultural sector data of the utilized regional accounts and SAM 2008.

Step 4. Given the water consumed by economic sectors, the additional reduction in water availability for hydropower generation when production sectors do adapt to climate change (i.e., they increase water consumption due to larger evaporation and evapotranspiration; see (Valverde et al., 2015)) was calculated (scenarios Comp_ in Table 8.3).

The Total competition (Comp_) scenario was, furthermore, broken down into two alternative scenarios as to equate water resources coming from Spain: the first assumes that there is no competition between countries so that reduced water availability in Portugal results only from climate change impacts in Portugal and Spain as well as increased sectoral water consumption in Portugal (Comp_PT scenario); the second assumes that there is competition between Portugal and Spain so that water availability in Portugal is the result of climate change impacts and increased sectoral water consumption in both countries (Comp_PT-SP scenario). Note that, likewise for Portugal, it is assumed that the Spanish non-hydropower production sectors adapt to climate change by increasing their water consumption so as to offset the effects of larger evaporation and evapotranspiration. Sectoral water consumption in Spain is obtained considering sectoral water intensities computed from Eurostat data (Eurostat, 2016, 2017) as well as the energy mix projected for 2050 (Bailera & Lisbona, 2018).

Finally, the effects of climate change on water availability, obtained as described above, are calculated for two distinct climate scenarios – RCP4.5 and RCP8.5, encompassing moderate and severe impacts of climate change, respectively (see (van Vuuren, Edmonds, et al., 2011)). Table 8.3 summarizes the scenarios modelled and the corresponding impacts of climate change and competition on water resources availability for each scenario, as compared to water availability in the no climate change scenario.

Summing up, the impacts of reduced water availability and competition (between users and countries) resulting from climate change are simulated in the CGE model as follows. In the scenario 'No_comp', such impacts consist, for each climate scenario, in reduced water availability for all economic activities plus the electricity prices simulated by the TIMES_PT model. In the scenarios 'Comp_PT' and 'Comp_PT_SP', the impacts are simulated only via the electricity prices simulated by the TIMES_PT model for each climate scenario, as the non-hydropower sectors do not face any water restrictions. Note that the electricity prices in the 'Comp_' scenarios surpass those of the 'No_comp' scenario, because water restrictions for hydropower generation are stronger and, therefore, the share of more expensive power technologies in the mix is larger.

Table 8.3. Impacts on water availability resulting from competition between hydropower and the other production sectors, per climate scenario, compared to the 'no climate change scenario'.

Water competition scenario			Climate scenario	% change in water availability compared to the 'no climate change scenario'	
				Hydropower	Other production sectors
No competition (No_Comp)	Production sectors and hydropower generation bear identical impacts of climate change on water resources availability		RCP 4.5	-5.3%	-5.3%
			RCP 8.5	-32.8%	-32.8%
Total competition (Comp_)	Hydropower generation bears all the impacts of climate change on water resources availability while production sectors increase water consumption levels	Competition in Portugal (Comp_PT)	RCP 4.5	-5.5%	0.0%*
			RCP 8.5	-34.6%	0.0%*
		Competition in Portugal and Competition between Portugal and Spain (Comp_PT-SP)	RCP 4.5	-8.5%	0.0%*
			RCP 8.5	-52.8%	0.0%*

Note: *Recall that, in the Comp_ scenarios, hydropower generation bears the cumulative effects of reduced water availability caused by climate change and adaptation of the remaining production sectors, whereas these latter do not face any water restrictions (i.e. the change in water resources availability for these sectors is null).

8.5. Results

This section describes the impacts of climate change on the Portuguese economy arising from reduced availability of water resources and subsequent impacts on electricity prices. While the former is a direct consequence of climate change (increasing the opportunity cost of raw water and the price of distributed water), the latter is explained by changes in the power sector profile following the reduced water availability for hydropower that result in larger shares of other, generally more expensive, power generation technologies.

8.5.1. Impacts on the electricity generation sector

The impacts of climate change on water resources availability have a direct effect on the hydropower generation potential, thereby changing the power mix. Table 8.4 presents, for each scenario, the cost-effective power mix and inherent generation costs, as given by the bottom-up TIMES_PT model. Given that onshore wind power potential is projected to be nearly fully exploited even in the absence of climate change (BaU2050), the reduced hydropower share is primarily offset by solar photovoltaic, biomass and natural gas. As hydropower is one of the cheapest power generation technologies (see, e.g., (IRENA, 2018)), its replacement by more expensive ones leads to a corresponding increase in overall power generation costs. Accordingly, in the RCP4.5 scenario power generation costs increase by up to 4% (as hydropower keeps a significant role in the power mix) whereas in the RCP8.5 scenario power generation costs increase by up to 27% (as hydropower generation is significantly impaired).

The impairment of hydropower and the associated increases in generation costs are stronger if competition between hydropower and the remaining economic sectors is taken into account (Comp_ scenarios), as this further reduces water availability for hydropower generation[29]. The impacts are even more stringent if competition between Portugal and Spain is included (Comp_PT-SP scenario), as this entails an additional reduction of water resources on the Portuguese side of the shared river basins. In particular, the share of hydropower reduces by up to 5.6p.p. in a moderate climate scenario (RCP4.5) and by up to 15.4p.p. in a severe climate scenario (RCP8.5).

Table 8.4. Impacts of climate change and competition scenarios on the power generation mix and power generation costs, compared to the business-as-usual scenario (BaU2050)

Scenario		BaU2050	RCP 4.5			RCP 8.5		
			No_comp	Comp_PT	Comp_PT-SP	No_comp	Comp_PT	Comp_PT-SP
Power generation mix by technology	Hydropower	26.9%	22.0%	22.0%	21.3%	16.3%	15.8%	11.5%
	Wind power	31.3%	31.6%	31.5%	31.6%	31.9%	32.0%	32.2%
	Solar PV	29.9%	33.9%	34.0%	34.8%	35.4%	35.5%	37.4%
	Biomass	2.7%	3.0%	3.0%	2.9%	5.0%	5.1%	5.2%
	Geothermal	0.0%	0.0%	0.0%	0.0%	1.1%	1.2%	1.9%
	Natural gas	9.3%	9.5%	9.5%	9.4%	10.3%	10.4%	11.8%
Unitary power generation costs	€2011/GJ	€ 43.48	€ 44.95	€ 44.95	€ 45.22	€ 50.76	€ 52.67	€ 55.04
	% change compared to BaU2050	-	3.4%	3.4%	4.0%	16.7%	21.1%	26.6%

[29] As a consequence, the Comp_ scenarios encompass higher electricity prices than the No_Comp scenario, due to the lower share of hydropower in the power mix.

These power mixes and corresponding changes in generation costs constitute inputs to the CGE model so as to simulate the economic impacts from the simultaneous effects of climate change-driven impacts on the availability of and competition for scarcer water resources, in view of the 'water-energy' nexus. Subsections 8.5.2 and 8.5.3 describe the economy-wide effects at the macroeconomic and sectoral level, respectively.

8.5.2. Macroeconomic impacts

At the macroeconomic level (see Table 8.5), the impacts of climate change and water availability on real GDP are negative and relatively minor for the RCP4.5 scenario (around -0.1% compared to BaU2050) while significant for the RCP8.5 scenario (up to -3.2%). For the RCP8.5 scenario, the economic impacts are more stringent if non-electricity production sectors do not compete for water with hydropower and all bear the reduced water availability imposed by climate change (scenario No_Comp). If sectors do compete for water in such a way that only the electrical sector bears the effects of climate change on water resources (scenarios Comp_), reductions in GDP will be smaller as the marginal costs of water reductions in the energy sector are smaller than those of the upstream sectors[30]. Finally, the negative impacts of climate change on the Portuguese economy are stronger if the dependency of Portugal on Spanish decisions about common river basins are included in the analysis (scenario Comp_PT-SP).

Water restrictions and consequent rising electricity prices, in particular under the No_Comp scenario, lead to an increase in production costs and, therefore, in consumer price index[31]. As production costs increase, producers reduce activity levels – leading to a reduction in the demand for production inputs, an increase in unemployment rates and a decrease in real wages. Private consumption remains unchanged because consumer prices of goods and services that represent the greater share in the consumer basket barely vary and also due to the heterogeneous impacts among different goods and services. Public consumption is negatively affected, especially in the No_Comp scenario, due to the significant impacts on the public services sectors. Finally, the trade balance deficit only worsens in the RCP8.5 No_Comp scenario, due to the larger contraction of

[30] Note that, for the RCP4.5, the most negative impacts broadly occur in the Comp_ scenarios. As the reduction of water availability in the RCP4.5_No_Comp scenario is small, it turns out that an increase in electricity prices (which is larger in the Comp_ than in the No_Comp scenarios, as previously explained) lead to stronger macroeconomic impacts.

[31] This is not the case for the Comp_ scenarios, where more raw water is allocated to economic activities that counterbalance the increase in electricity costs and, thus, result in a moderate effect on production costs.

production sectors producing internationally tradable goods, which leads to an increase in imports that surpasses that of exports.

Table 8.5. Macroeconomic impacts of climate change and competition scenarios, compared to the business-as-usual scenario (BaU2050)

	% change compared to the BaU2050					
	RCP 4.5			RCP 8.5		
	No_comp	Comp_PT	Comp_PT-SP	No_comp	Comp_PT	Comp_PT-SP
Real GDP	-0.1%	-0.1%	-0.1%	-3.2%	-0.7%	-0.9%
Consumer Price Index	0.0%	-0.1%	-0.1%	1.4%	-0.2%	-0.2%
Private consumption	0.0%	0.1%	0.1%	1.4%	0.2%	0.2%
Public consumption	0.9%	-0.2%	-0.3%	-18.3%	-0.9%	-1.2%
Trade balance	-0.8%	-0.8%	-1.0%	17.5%	-3.2%	-4.3%
Unemployment	-1.4%	0.0%	0.0%	28.2%	0.0%	0.0%
Real wages	-0.4%	-0.1%	-0.1%	-2.4%	-0.8%	-0.9%
Welfare (HEV)	0.1%	0.0%	0.1%	0.5%	0.1%	0.0%

8.5.3. Sectoral impacts

Results encompass important inter-sectoral differences that mostly arise from two distinguishing features between production sectors: i) the raw water intensity, and ii) the shares of distributed water and electricity costs in total production costs.

The impacts of the RCP4.5 climate scenario on water resources availability are limited and, thus, so are the effects on electricity generation costs (see Table 8.4). As a consequence, small economic impacts are found at the macroeconomic (see Table 8.5) as well as sectoral levels (see Figure 8.3 and Appendix 8.3). Hence, this section will focus on the impacts arising from the RCP8.5 and, in particular, comparing the No_Comp and the Comp_PT-SP scenarios – noting that the results for Comp_PT and Comp_PT-SP have identical signs with the latter showing larger changes.

The projected impacts for the 31 production sectors disaggregated in the model are grouped into four major types of economic activities: i) agriculture & forestry and fishing, ii) water distribution and supply, iii) industry and construction, and iv) services. Table 8.6 summarizes the impacts on these four broad sectors, showing negative overall impacts in all cases. Agriculture & forestry and fishing and water distribution and supply activities are the most affected in the No_Comp scenario, whilst industry is the major loser in the Comp_PT-SP scenario. It is also noteworthy that, under RCP8.5, the industry sector as a whole manages to increase production levels under increased water scarcity conditions (No_Comp scenario).

Table 8.6. Impacts of climate change (RCP 8.5) and competition (No_Comp; Comp_PT-SP) scenarios on domestic production levels, per broad economic sectors, compared to the business-as-usual scenario (BaU2050)

Economic sector	BaU2050 (% of total production)	% change compared to the BaU2050			
		RCP4.5		RCP8.5	
		No_Comp	Comp_PT-SP	No_Comp	Comp_PT-SP
Agriculture & forestry and fishing	2.8%	-5.5%	0.2%	-36.0%	1.1%
Water distribution and supply	0.3%	-2.1%	-0.1%	-15.9%	-0.5%
Industry and construction	41.8%	-0.6%	-0.2%	2.0%	-1.4%
Services	55.1%	0.4%	0.1%	-2.8%	0.4%
Total	100.0%	-0.2%	-0.1%	-1.8%	-0.4%

Figure 8.3 presents the sectoral results regarding domestic production levels. As to water consumption, all sectors are sharply affected if there is no adaptation (i.e., if they bear the climate change impacts on water availability; No_Comp scenario), whilst in the absence of water restrictions (Comp_PT-SP scenario) only the industrial sector reduces water consumption due to the lower production levels which result from higher electricity costs. Table 8.7 summarizes the inherent impacts on water consumption (both raw and distributed water).

Figure 8.3. Sectoral impacts of climate change (RCP 8.5) and competition (No_Comp; Comp_PT-SP) scenarios on production levels (% change compared to the business-as-usual scenario)

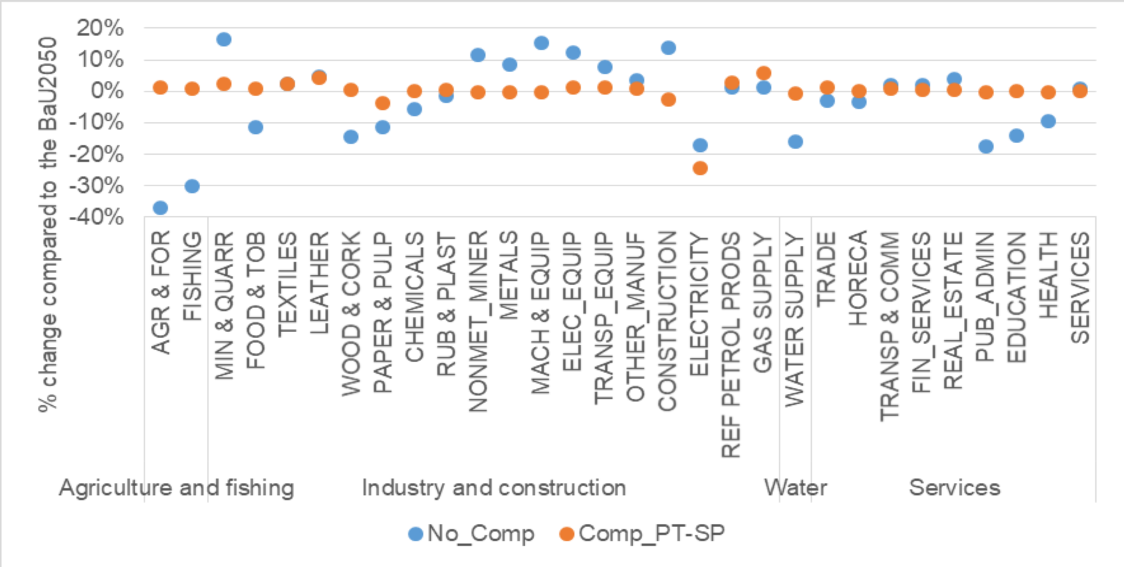


Table 8.7. Sectoral impacts of climate change (RCP 8.5) and competition (No_Comp; Comp_PT_SP) scenarios on water consumption (% change compared to the business-as-usual scenario)

Economic sector	BaU2050 (% of total consumption)		% change compared to the BaU2050			
			No_Comp		Comp_PT-SP	
	Raw water	Distributed water	Raw water	Distributed water	Raw water	Distributed water
Agriculture & forestry and fishing	71.8%	0.3%	-39.6%	-40.3%	1.1%	1.1%
Water distribution and supply	12.2%	7.3%	-20.4%	-15.9%	-0.5%	-0.5%
Industry and construction	16.0%	17.3%	-8.8%	-12.9%	-6.9%	-6.9%
Services	0.0%	27.7%	-	-18.2%	-	0.1%
Households	0.0%	47.4%	-	-14.6%	-	0.1%
Total	100.0%	100.0%	-32.8%	-15.8%	-0.2%	-0.5%

Agriculture & forestry and fishing

Agriculture & forestry and fishing activities record one of the largest impacts, depending on whether these sectors internalize the negative effects of climate change on water resources (scenario No_Comp) or whether they increase water consumption in order to maintain activity levels (scenario Comp_PT-SP). If the agriculture & forestry and fishing sectors face water restrictions (scenario No_Comp), their domestic production levels decrease by 37.0% and 30.0%, respectively. Intensified water scarcity increases the opportunity cost of raw water, leading to an increase in production costs of the agriculture & forestry (+33.1%) and fishing (+27.3%) sectors. If the agriculture & forestry and fishing sectors do not face water restrictions (scenario Comp_PT-SP), the impacts are considerably different. In this case, sectoral production slightly increases (up to +1.1% and +0.7%, respectively) because of the relative reduction in production costs as compared to other sectors (by -0.7% and -0.8%, respectively). These results are explained by the fact that, in the Comp_ scenarios, the direct impacts of climate change consist only in higher electricity costs that represent a minor part of these sectors' production costs.

Water distribution and supply

The impacts on the water distribution sector are negative, irrespective of whether competition with hydropower exists or not. If there is no competition for water (scenario No_Comp), the water distribution sector suffers the direct consequences of reduced availability of raw water and its production decreases accordingly (-15.8%). As raw water becomes scarcer, its opportunity cost increases and production costs of the water distribution services sector reflect such scarcity (+86.2%). Note that distributed water is a relevant input for many sectors and, thus, constitutes an important channel for increasing production costs in some sectors (notably services; see next subsections).

Considering that distributed water is not an internationally tradable good, the effects of climate change on water availability are internalized in a way that domestic consumption decreases by approximately the same proportion of domestic production. Given that potable water is an essential good, consumers are not very sensitive to price fluctuations[32]. Hence, in the face of restricted water supply (scenario No_Comp), the reduction in the intermediate consumption of water by production sectors is larger than the reduction in final consumption of water by households (up to -16.8% and -14.6%, respectively). If there is competition for water (scenario Comp_PT-SP), the water distribution sector accounts for modest impacts on production levels and costs (-0.5% and -0.8%, respectively).

[32] Following (Reynaud, 2015) estimations for Portugal, the CGE model was calibrated so as to replicate a price elasticity of households' water consumption of -0.27.

Industry and construction

The impacts of water restrictions resulting from climate change on the industry sector are heterogeneous and closely linked to the relevance of water and electricity in the sectors' production costs. Besides, the shrinkage of those sectors bearing the most negative impacts will induce a rebalance of the economic structure by enlarging the shares of some other sectors. The following paragraphs are devoted to explain that phenomenon.

Sectors with the highest rates of water consumption per output, such as paper, chemical and plastic manufacturing, are negatively affected by climate change if they bear reduced water resources availability (No_Comp scenario). Sectoral production reduces by 11.3% in paper manufacturing, 5.5% in chemicals manufacturing and 1.6% in plastic manufacturing. Negative impacts on domestic production are associated with higher production costs (+3.3%, +0.5% and +1.2%, respectively), which follow the increases in the opportunity cost of raw water and in the prices paid for distributed water and electricity. If these sectors do not face water restrictions (Comp_PT-SP scenario), only paper manufacturing reduces production levels and increases production costs (-3.7% and +1.1%, respectively), whereas chemicals and plastic manufacturing production slightly increase (+0.2% and +0.4%, respectively) and production costs slightly decrease (-0.2%), due to the relatively lower share of electricity costs in their production functions. The manufacturing of food products and beverages (which combines a significant water intensity with the largest consumption of distributed water within the manufacturing sector) records one of the worst impacts on production levels and costs (-11.5% and +4.9%, respectively) in the No_Comp scenario. Conversely, if there are no water constraints apart from for hydropower (Comp_PT-SP scenario), this sector slightly increases its activity level (+1.0%) and decreases production costs (-0.6%) due to the limited electricity costs.

Sectors with moderate water intensities and electricity costs, such as the manufacturing of leather products and textiles, maintain their production costs almost unchanged (-0.7% and -0.3%, respectively, in the No_Comp scenario; and -0.8% and -0.6%, respectively, in the Comp_PT-SP scenario), and, therefore, increase their production levels in both scenarios (exceeding 4% in the manufacturing of leather products and 2% in the manufacturing of textiles).

Those production sectors with lower shares of inputs impacted by climate change (water consumption levels and electricity costs), such as mining and quarrying, construction and the manufacturing of electrical equipment, transport equipment, non-metallic minerals and machinery & equipment, are not significantly affected in their production costs –

irrespective of the degree of competition for water resources with power generation (they decrease by between -0.5% and -1.7% in the No_Comp scenario, and between -0.5% and -0.9% in the Comp PT-SP scenario). Thus, these manufacturing activities exhibit significant expansion of production levels in the No_Comp scenario, ranging between 7.7% (transport equipment) and 16.6% (mining and quarrying), but smaller variations in the Comp_PT-SP scenario (ranging between -2.5% in construction and +2.5% in the mining and quarrying sectors).

Finally, within the energy sectors, only electricity generation records negative impacts. Following the reported changes in power generation costs (see Section 8.5.1), domestic production decreases by 17.2% in the No_Comp scenario and by 24.5% in the Comp_PT-SP scenario. As a consequence, petroleum products refinery and natural gas supply increase their production levels in both scenarios (by up to 2.6% and 5.9%, respectively), as their production costs are hardly affected and, thus, energy demand is increasingly satisfied by natural gas and oil products.

Services

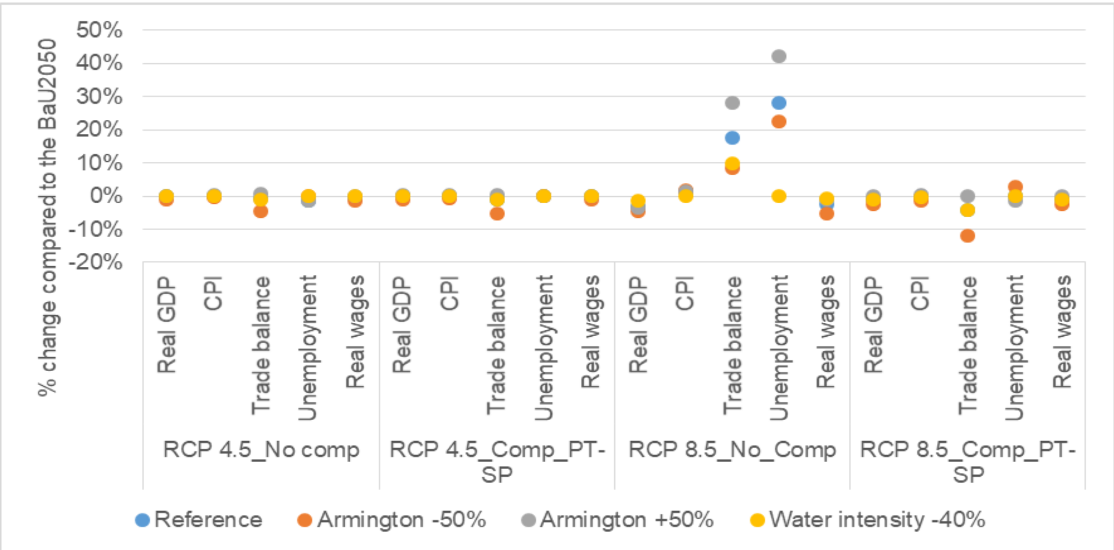
Many activities belonging to the services sector are amongst the most important consumers of distributed water and electricity and, therefore, their activity levels are impacted by climate change. Non-tradable services, notably the health, education and public administration sectors, are the most affected and the negative impacts are particularly strong if water resources availability is diminished (scenario No_Comp), due to the hike in prices for distributed water. As a result, their production levels decrease by 9.5%, 13.9% and 17.3%, respectively. If there are no water constraints (scenario Comp_PT-SP), effects are negligible (production decreases by up to 0.4% and costs decrease by around 1% in all cases).

The commercial and restaurant & accommodation sectors are negatively impacted by the increases in distributed water prices characterizing the No_Comp scenario – production contracts by approximately 3% in both sectors. In the absence of water scarcity (Comp_PT-SP scenario) these sectors record small increases in production (+1.1% for commercial sector and +0.2% for restaurant & accommodation activities). Finally, other services, namely the financial activities, real estate, transport and communication and personal & business sectors, manage to increase or maintain their activity levels in both water competition scenarios (between 1.0% and 3.9% in the No_Comp scenario, and between 0.1% and 1.0% in the Comp_PT-SP scenario) due to the relative low share of water and electricity in their production costs.

8.5.4. Sensitivity analysis

To check the robustness of the presented results, a sensitivity analysis was performed considering variations in the Armington trade elasticities (-50% and +50% as compared to the reference case) as well as in water intensities (-40%; based on an extrapolation of the 13% decrease in water intensity observed for Southern Europe between 2005 and 2013; (EEA, 2017b)). Figure 8.4 presents the impacts on key macroeconomic variables. Changed parameters have no noticeable impacts, with the exception of the RCP8.5_No_Comp scenario. For the latter, given the lower/higher degree of openness to international trade (represented by a 50% reduction/increase in trade elasticities, respectively), the trade balance deficit deteriorates less/more, respectively, than with reference elasticities. Furthermore, a higher degree of openness will increase the unemployment rate, as compared to the reference situation (the opposite occurring for a lower degree of openness). On the other hand, the 40% reduction in water intensity implies smaller economic impacts than the reference intensities, as lower water consumption counterbalances the diminished water availability resulting from climate change.

Figure 8.4. Sensitivity analysis – Macroeconomic impacts of alternative Armington trade elasticities and sectoral water intensities



8.6. Discussion and conclusions

Climate change impacts on water resources will pose important challenges to social and economic development. From an economic perspective, two of the most important refer to the increased competition between regions and countries sharing transboundary river basins as well as between users (production sectors and households). Regarding competition for water resources between countries, climate change is expected to increase the existing complexity of transboundary water management, as any change in the upstream country affects the availability of water resources in the downstream country. Thus, if the upstream country increases its water withdrawals, the downstream country will face reduced water availability that will negatively affect water dependent-economic activities such as agriculture and energy (Flörke, Wimmer, et al., 2011). Concerning competition for water resources between users, increased water scarcity will likely intensify competition between production sectors, being the bi-directional link between water resources and the energy sector, in particular, of major importance. Water resources are essential in all phases of energy production processes and, in turn, energy is indispensable to guarantee that water is supplied to users – from extraction and pumping to distribution and treatment (Brouwer et al., 2017; IEA, 2016; Khan et al., 2017).

In this paper we assessed the economic consequences of climate change-driven impacts on water resources availability in Portugal, taking into consideration the ‘water-energy’ nexus for two distinct climate scenarios (RCP4.5 and RCP8.5), two sectoral water competition scenarios (between hydropower generation and the remaining production sectors) and two transboundary water competition scenarios (between Portugal and Spain). Hence, the increased competition for water resources in the context of climate change is simulated considering: i) competition between users, and ii) competition between users and countries.

Results show that the economic consequences of climate change impacts on water resources availability depend on the severity of water restrictions. The moderate climate change scenario (RCP4.5) has no significant impacts from a macroeconomic perspective, whereas the strongest climate change scenario (RCP8.5) produces a negative impact on real GDP (-3.2%) in the absence of competition between users (i.e. all sectors bear water shortage, including hydropower, with subsequent increases in electricity costs). In fact, the magnitude of changes is considerably larger if competition between hydropower and the other economic activities is not considered. When priority for water consumption is given to other sectors than power generation (that is, when competition exists), impacts are stronger if water consumption by Spanish users is considered – amplifying the reduction in water availability in the Portuguese part of the transboundary river basins (-0.9% of real GDP vis-à-vis -0.7% of real GDP without the transboundary competition effect). While the macroeconomic impacts are significant, impacts at the sectoral level are very heterogeneous where some sectors bear strong downturns on activity levels. In a context of no competition for water between the energy sector and the remaining production sectors, the most water-intensive sectors (agriculture & forestry, fishing, water distribution and supply, and the manufacturing of food & beverages and paper) become less profitable and therefore reduce their production levels, whereas least water-intensive sectors (manufacturing of non-mineral products, electrical equipment, and machinery & equipment) become more profitable and increase their production levels. Conversely, if production sectors compete for water with hydropower generation, the effects of water scarcity on non-energy sectors will only be exerted via higher electricity prices – impairing production sectors with relevant electricity costs (notably manufacturing of paper).

The results provided by this paper are in line with recent research about the economic consequences of climate change-driven impacts on water resources availability. These consensually foresee losses in real GDP, which are stronger in regions facing more severe impacts of climate change (e.g., around 8% in Tunisia (Roson & Sartori, 2015), -2.5% in Israel (Baum et al., 2016) and -1.1% in Spain (Galeotti & Roson, 2012), against -0.04% in Switzerland (Faust et al., 2015) and -0.02% in the Netherlands (Koopman et al., 2017)). For the world economy, projected GDP losses of 0.3% (Calzadilla, Rehdanz, et al., 2013) or 0.5% (Roson, 2017) reinforce the idea that some regions will be negatively affected by climate change impacts whereas others will be positively impacted. The relatively small magnitude of the macroeconomic impacts of water restrictions is explained by the small share of water costs in the production structure of the majority of sectors (Faust et al., 2015).

Some policy implications may be inferred from the obtained results. Climate change impacts on water resources availability will have small (RCP4.5) to significant (RCP8.5) impacts on the economy. Comparison of two scenarios for sectoral competition for water (hydropower versus the remaining sectors) shows that economic and social costs are minimized when priority is given to the water use by non-electricity production sectors. Furthermore, projected technological development of the power sector will likely accommodate reduced availability of water input, thanks to the increasing penetration of non- or minor water consuming renewable-sourced technologies, such as wind power and solar photovoltaic. Still, such increased water scarcity for the power sector is reflected in higher electricity generation costs (up to just over 25%) and in a shift in energy consumption towards fossil fuels that hampers mitigation efforts. Despite the expected increase in power generation costs and, hence, in electricity prices, public policies stimulating that water allocation scheme (i.e., prioritizing water allocation to non-electricity production sectors) are worth being promoted, as they are capable of: i) limiting the water market distortions arising from scarcity that raises water prices to unaffordable levels, and ii) minimizing the economic costs of climate-change driven impacts on water resources availability. Public policies should also stimulate competition for water such that the market allocation of the increasingly scarce resource takes sectoral opportunity costs into account. That will allow allocating more water resources (in relative terms) to those sectors with a more inelastic demand for water, i.e. facing higher costs to reduce consumption. Results corroborate also that increased water scarcity will pose additional challenges to the water management in transboundary river basins[33], as the economic impacts of reduced water availability are amplified when competition between countries is considered. Finally, our results are of utmost relevance as Portugal aims to achieve carbon neutrality by 2050 (APA, 2016a), which may imply an increasing electrification of the economy and the decarbonisation of the power sector, with hydropower playing a significant role.

This analysis presents some shortcomings. First, the paper does not consider the impacts of climate change on energy demand nor the effects of mitigation policies which would imply a higher consumption of electricity (notably by the transport sector and private passenger transport, in the case of mitigation scenarios). Their inclusion would amplify the impacts of water scarcity on the economy through the ‘water-energy’ nexus. Moreover, the TIMES_PT model ignores the climate change impacts on power plants efficiency (as this is out of scope of this analysis), and only considers reduced water availability for hydropower (ignoring restrictions for thermal power plants). To overcome this latter caveat, cooling water consumption in the active power technologies by 2050 (biomass and natural gas) was considered in the CGE model. Second, sectoral water intensities were computed for the base year of the CGE model (2008) and kept constant for 2050[34] (disregarding the effects of increased efficiency). The performed sensitivity analysis,

[33] Notably concerning the fulfilment of the transnational treaties. In this case, the Albufeira Convention, that regulates the water use and exploitation of transboundary river basins between Portugal and Spain.
[34] With the exception of the Electricity production sector, whose water intensity was calculated based on the mix projected for 2050, in a no-climate change scenario.

considering a strong reduction in water intensities, shows that this may be a way to circumvent/minimize the economic consequences of climate change impacts on water resources availability. In addition, two simplifications may be highlighted. Firstly, the degree of substitution between raw water and the other production factors is null, like in e.g. (Berrittella et al., 2007) and (Gómez, Tirado, & Rey-Maquieira, 2004). This means that the simulated impacts of water restrictions on the economy correspond to the most severe case. Secondly, the ‘water-energy’ nexus is quantified via two extreme scenarios that determine the lower and upper limits of economic consequences of climate change: while the ‘no competition for water’ scenario corresponds to the strongest impacts, the ‘competition’ scenarios illustrate the weakest impact we may expect.

Despite these limitations, this paper is one of the first attempts to quantify the interdependency between water resources, the energy system and the economy – expanding the ‘water-energy’ nexus analysis to a larger dimension, i.e. the ‘water-energy-economy’ nexus that is of utmost importance for policy makers. It is also the first quantification of the economic impacts of water scarcity due to climate change in Portugal and the first to quantify the additional costs that the dependence on transboundary river basins with Spain represents to the Portuguese economy.

The approach and methodology presented in this paper may be replicated to other regions, and its insights demonstrate the importance of ‘water-energy-economy’ nexus assessment under climate change impacts analyses. It advances on the understanding of the impacts and feedbacks between climate change, the energy sector, economic performance and social welfare.

Appendix 8.1. Model description

This Appendix summarises the main components of the model: production, foreign trade, household demand, government, labour supply, macroeconomic equilibrium and closure rule.
There are 31 production sectors, denoted by i, which are described in detail in Appendix 8.2. Greek letters stand for scale parameters {α, λ, γ, φ} and elasticity of substitution {σ}. Latin letters stand for share parameters in the production and consumption functions {a, b, c, d, s}. Subscripts A and H stand for production activity and households, respectively.

Production

Figure 8.A. 1. Production structure of all sectors except "Electricity"

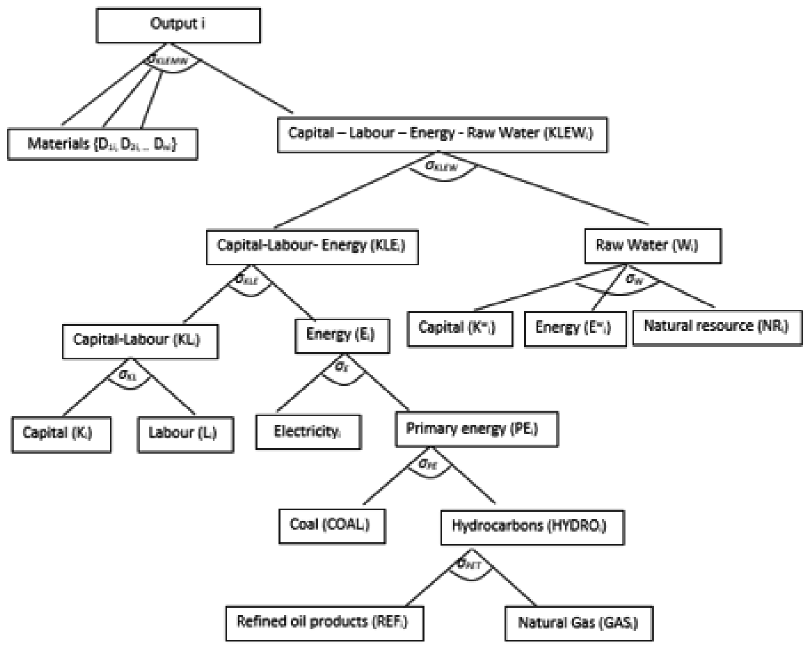
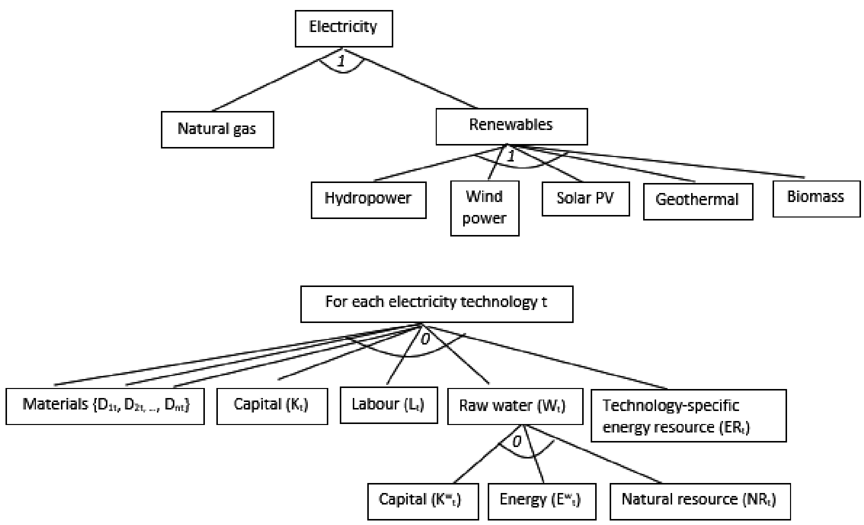


Figure 8.A. 2. Production structure of the "Electricity" production sector



Where "t" represents each electricity generation technology.

Producer behaviour is based on the profit maximization principle, such that in each sector a representative firm maximizes profits subject to a constant returns to scale technology. We assume perfect competition and therefore zero profits. As a result, the optimization problem for the representative firm is to minimize production costs subject to the technological constraints represented by the functions below - each one attached to one nest in the production structure represented by Figure 7.A.1. These represent constant elasticity of substitution (CES) functions except for equations 2, 3, 11 and 12, which correspond to Leontief functions, and equations 9 and 10, which are Cobb-Douglas functions.

$$Output_i = \alpha_i \left(a_i KLEW_i^{\frac{\sigma_i^{KLEWM}-1}{\sigma_i^{KLEWM}}} + \sum_{j=1}^{n} b_{ji} \left(D_{ij}\right)^{\frac{\sigma_i^{KLEWM}-1}{\sigma_i^{KLEWM}}} \right)^{\frac{\sigma_i^{KLEWM}}{\sigma_i^{KLEWM}-1}}, \sum_{j=1}^{n} b_{ji} = \left(1-a_i\right)$$

Eq. 1 - Output from sector i {KLEW + intermediate inputs}

$$KLEW_i = \min\left(\frac{KLE_i}{c_{0i}}, \frac{W_i}{c_{1i}} \right)$$

Eq. 2 - $KLEW_i$ {composite input KLE + W}

$$W_i = \min\left(\frac{NR_i}{c_{0i}}, \frac{K_i^w}{c_{1i}}, \frac{E_i^w}{c_{2i}} \right)$$

Eq. 3 - RW_i {composite input Raw water resource (NR) + Raw water extraction capital (K^w) + Raw water extraction Energy (E^w)}

$$KLE_i = \alpha_i \left(a_i KL_i^{\frac{\sigma_i^{KLE}-1}{\sigma_i^{KLE}}} + (1-a_i) E_i^{\frac{\sigma_i^{KLE}-1}{\sigma_i^{KLE}}} \right)^{\frac{\sigma_i^{KLE}}{\sigma_i^{KLE}-1}}$$

Eq. 4 - KLE_i {composite input KL + E}

$$KL_i = \alpha_{iKL} (a_{iKL} L_i^{\frac{\sigma_i^{KL}-1}{\sigma_i^{KL}}} + (1-a_{iKL}) K_i^{\frac{\sigma_i^{KL}-1}{\sigma_i^{KL}}})^{\frac{\sigma_i^{KL}}{\sigma_i^{KL}-1}}$$

Eq. 5 - KL_i {composite input capital (K) + labour (L)}

$$E_i = \alpha_{iE} \left(a_{iE} ELECTRICITY_i^{\frac{\sigma_i^{E}-1}{\sigma_i^{E}}} + (1-a_{iE}) PE_i^{\frac{\sigma_i^{E}-1}{\sigma_i^{E}}} \right)^{\frac{\sigma_i^{E}}{\sigma_i^{E}-1}}$$

Eq. 6 - Ei {composite input Electricity (Electricity) + Primary energy (PE)}

$$PE_i = \alpha_{iPE} \left(a_{iPE} COAL_{iA}^{\frac{\sigma_i^{PE}-1}{\sigma_i^{PE}}} + (1-a_{iPE}) HYDRO_i^{\frac{\sigma_i^{PE}-1}{\sigma_i^{PE}}} \right)^{\frac{\sigma_i^{PE}}{\sigma_i^{PE}-1}}$$

Eq. 7 - PE_i {composite input COAL + Hydrocarbons (HYDRO)}

$$HYDRO_i = \alpha_{iPET} \left(a_{iPET} REF_{iA}^{\frac{\sigma_i^{PET}-1}{\sigma_i^{PET}}} + (1-a_{iPET}) GAS_{iA}^{\frac{\sigma_i^{PET}-1}{\sigma_i^{PET}}} \right)^{\frac{\sigma_i^{PET}}{\sigma_i^{PET}-1}}$$

Eq. 8 - $HYDRO_i$ {composite input Refined oil products (REF) + Natural Gas (GAS)}

$$ELECTRICITY = NATURALGAS^{\alpha} \cdot RENEWABLES^{\beta}$$

Eq. 9 - Composite of ELECTRICITY

$$RENEWABLES = \prod_{t=1}^{n} RENEWABLE_t^{SRt}$$

Eq. 10 - Production of electricity from Renewables

$$\text{For each generation technology t} = \min\left(\frac{K_t}{c_{0t}}, \frac{D_{1t}}{c_{1t}}, \ldots, \frac{D_{nt}}{c_{nt}}, \frac{L_t}{c_{n+1,t}}, \frac{W_t}{c_{n+2,t}}, \frac{ER_t}{c_{n+3,t}}\right)$$

Eq. 11 - Electricity from technology t

$$W_t = \min\left(\frac{NR_t}{c_{0t}}, \frac{K_t^w}{c_{1t}}, \frac{E_t^w}{c_{2t}}\right)$$

Eq. 12 – W_t {composite input Raw water resource (NR) + Raw water extraction capital (K^w) + Raw water extraction Energy (E^w) for technology t}

Foreign trade

The total supply of goods and services is a combination of domestic production plus imports. Following the Armington specification, both are imperfect substitutes and therefore we minimize the cost of this composite good subject to the CES technology represented by equation 13. Similarly, the destination of the total supply of goods and services is the domestic market (e.g. firms, households, government) and exports. As usual in literature, we assume that the representative firm in each sector consider both destinations as imperfect substitutes. Thus, the problem is to maximize the revenues subject to the CET technology represented by equation 14. We assume Portugal is a small open economy where the majority of its trade partners belong to the EU. As a result, we consider that prices for imports/exports are exogenous and fixed.

$$A_i = \lambda_i \left(b_i Output_i^{\frac{\sigma_i^A - 1}{\sigma_i^A}} + (1 - b_i) IMP_i^{\frac{\sigma_i^A - 1}{\sigma_i^A}} \right)^{\frac{\sigma_i^A}{\sigma_i^A - 1}}$$

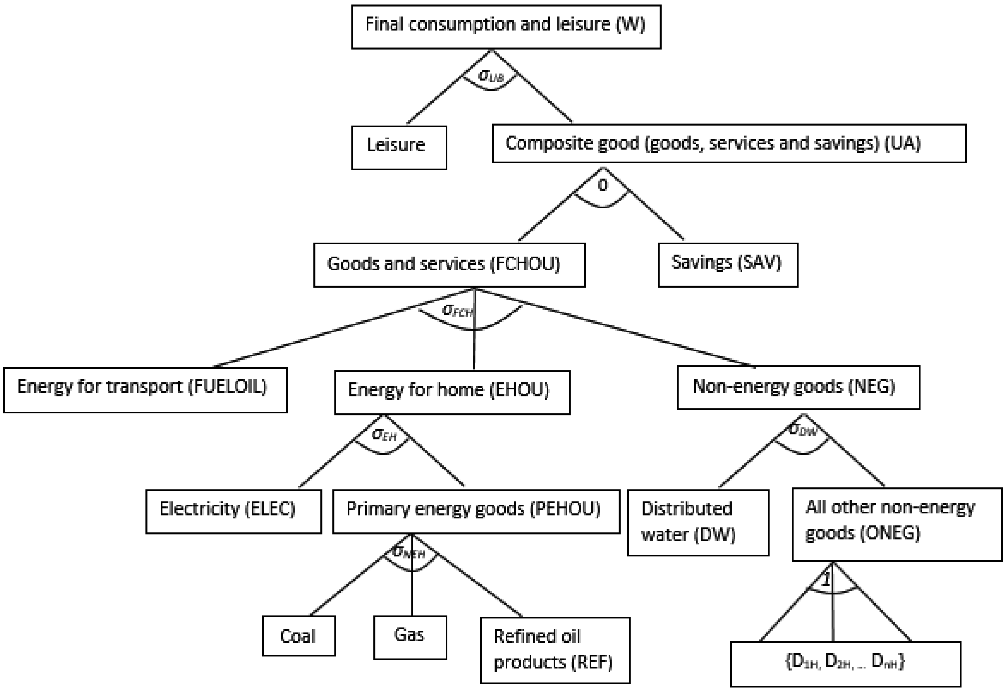
Eq. 13 - Armington nest for total supply {Output + Imports}

$$A_i = \gamma_i \left(d_i D_i^{\frac{\sigma_i^\varepsilon + 1}{\sigma_i^\varepsilon}} + (1 - d_i) EXP_i^{\frac{\sigma_i^\varepsilon + 1}{\sigma_i^\varepsilon}} \right)^{\frac{\sigma_i^\varepsilon}{\sigma_i^\varepsilon + 1}}$$

Eq. 14 - Armington nest for total demand {Domestic demand + Exports}

Consumption

Figure 8.A. 3. Consumption structure



The representative consumer has a fixed endowment of capital and time. The endowment of time is allocated to leisure and labour supply, being the last one the main source of income to finance the consumption of goods and services. Thus, the problem for the representative household is to maximize the welfare level subject to the budget constraint. Household's income derives from the supply of labour, the fixed endowment of capital, and the net transfers from government. We consider the wage (net of social contributions from the worker) represents the opportunity cost of leisure (the price for leisure). Besides, we assume a constant marginal propensity to save (i.e. a constant share of final consumption of goods and services). We use CES consumption functions for all nests except for equation 16 (Leontief) and equation 21 (Cobb-Douglas).

$$W = \left(s_{UB} LEISURE^{\frac{\sigma^{UB}-1}{\sigma^{UB}}} + (1 - s_{UB}) UA^{\frac{\sigma^{UB}-1}{\sigma^{UB}}} \right)^{\frac{\sigma^{UB}}{\sigma^{UB}-1}}$$

Eq. 15 – Welfare function {Leisure + Consumption (UA)}

$$UA = \min\left(\frac{SAV_{CONS}}{s_{UA}}, \frac{FCHOU}{(1 - s_{UA})} \right)$$

Eq. 16 – UA composite good {savings (SAV) + Final consumption (FCHOU)}

$$FCHOU = \varphi_{FCH} \left(s_{EH} EHOU^{\frac{\sigma^{FCH}-1}{\sigma^{FCH}}} + s_{FH} FUELOIL^{\frac{\sigma^{FCH}-1}{\sigma^{FCH}}} + (1 - s_{EH} - s_{FH}) NEG^{\frac{\sigma^{FCH}-1}{\sigma^{FCH}}} \right)^{\frac{\sigma^{FCH}}{\sigma^{FCH}-1}}$$

Eq. 17 – FCHOU {composite good of Energy for home (EHOU) + Energy for transport (FUELOIL) + Non-energy goods (NEG)}

$$EHOU_h = \varphi_{EH}\left(s_{EH}ELEC_H^{\frac{\sigma^{EH}-1}{\sigma^{EH}}} + (1-s_{EH})PEHOU^{\frac{\sigma^{EH}-1}{\sigma^{EH}}} \right)^{\frac{\sigma^{EH}}{\sigma^{EH}-1}}$$

Eq. 18 – EHOU {composite good of Electricity (ELEC) + Primary energy (PEHOU)}

$$PEHOU = \varphi_{NEH}\left(s_C COAL_H^{\frac{\sigma^{NEH}-1}{\sigma^{NEH}}} + s_G GAS_H^{\frac{\sigma^{NEH}-1}{\sigma^{NEH}}} + (1-s_C-s_G)REF_H^{\frac{\sigma^{NEH}-1}{\sigma^{NEH}}} \right)^{\frac{\sigma^{NEH}}{\sigma^{NEH}-1}}$$

Eq. 19 – PEHOU {composite good of Coal + Gas + Refined petroleum products}

$$NEG_h = \varphi_{WH}\left(s_{WH}DW_H^{\frac{\sigma^{DW}-1}{\sigma^{DW}}} + (1-s_{WH})ONEG^{\frac{\sigma^{DW}-1}{\sigma^{DW}}} \right)^{\frac{\sigma^{DW}}{\sigma^{DW}-1}}$$

Eq. 20 – NEG {composite consumption of non-energy goods}

$ONEG = \prod_{i=1}^{n} D_{iH}^{SO_i}$, where i ≠ {distributed water and energy products}

Eq. 21 – ONEG {composite consumption of non-energy goods, except distributed water

Government

Government maximizes public consumption subject to a budget constraint. Public consumption is an aggregate good comprising different goods and services (e.g. social security, healthcare, education) represented by a Cobb-Douglas function. Public expenditure is financed by tax revenues (taxes on production “$Output_i$”, consumption “D_i”, households’ income, and social security contributions paid by employers and employees), income from a fixed endowment of capital, net transfers and savings (or deficits).

Factors market

The labour market is taken to be imperfect, where involuntary unemployment exists. This is introduced in the model by a wage curve $w_{real} = \beta \log u_r$, where w_{real} is the real wage, u_r is the unemployment rate and β is elasticity of wage to unemployment (-0.1 according to Blanchflower and Oswald, 1995). Equilibrium is determined by the intersection of the labour demand curve and the wage curve, setting a real wage that is above the market clearing level. Involuntary unemployment results from the difference between labour supply (given by the wage curve) and labour demand, which becomes endogenous to the model. The demand for labour by each production sector is determined by the solution of the producers’ cost minimization problem. Capital supply is inelastic and capital demand is determined by the abovementioned cost minimization problem of sectors.

Macroeconomic equilibrium

The model assumes all markets of goods and services are in equilibrium, i.e., for each market, total supply equals total demand (households, firms' intermediate inputs, government, foreign trade, investments). Investments (gross capital formation) is a bundle of final goods represented by a Leontief function. Total investment is equal to the sum of savings made by households and the government (fixed deficit) plus net lending from abroad. Thus, the macroeconomic equilibrium of Portuguese economy towards the rest of the world is determined by the balance of payments, where the net lending/borrowing capacity (deficit) has to be equal to the sum of imports and exports and a fixed volume of net transfers. The national economy's net lending/borrowing capacity, which corresponds to the difference between national saving (private and public) and investment, is exogenous. As a result, this implies that investments is ultimately driven by household savings.

The model has been programmed within General Algebraic Modelling System (GAMS (Rosenthal, 2012)), using the Mathematical Programming System for General Equilibrium (MPSGE) subsystem (Rutherford, 1999) and solved using the PATH solver (Ferris & Munson, 2008).

Appendix 8.2. Elasticities of substitution

	Production substitution elasticities								International trade elasticities	
Production sector	Capital, labour, energy, water and materials	Capital, labour, energy and water	Raw Water	Capital, labour and energy	Capital vs. Labour	Electricity vs. Fossil fuels	Coal vs. Oil and gas	Oil vs. Gas	Armington substitution between domestic and imports	Armington transformation between domestic and exports
	σ_{KLEMW}	σ_{KLEW}	σ_W	σ_{KLE}	σ_{KL}	σ_E	σ_{PE}	σ_{PET}	σ_A	σ_I^E
AGR&FOR	0.2	0	0	0.25	0.23	0.5	0.9	0.9	2.91	5.81
FISHING	0.2	0	0	0.25	0.23	0.5	0.9	0.9	2.91	5.81
MIN&EXTRACT_FUELS	0.2	0	0	0.25	0.2	0.5	0.9	0.9	5.2	10.4
MIN&QUARR	0.2	0	0	0.25	0.2	0.5	0.9	0.9	0.9	1.8
FOOD&TOB	0.2	0	0	0.25	1.17	0.5	0.9	0.9	3.21	6.43
TEXTILES	0.2	0	0	0.25	1.17	0.5	0.9	0.9	3.21	6.43
LEATHER	0.2	0	0	0.25	1.17	0.5	0.9	0.9	3.21	6.43
WOOD&CORK	0.2	0	0	0.25	1.17	0.5	0.9	0.9	3.21	6.43
PAPER&PULP	0.2	0	0	0.25	1.26	0.5	0.9	0.9	2.95	5.9
REFPET	0.2	0	0	0.25	1.26	0.5	0.9	0.9	2.1	4.2
CHEMICALS	0.2	0	0	0.25	1.26	0.5	0.9	0.9	3.3	6.6
RUB&PLAST	0.2	0	0	0.25	1.26	0.5	0.9	0.9	3.3	6.6
NONMET_MINER	0.2	0	0	0.25	0.73	0.5	0.9	0.9	1.9	3.8
METALS	0.2	0	0	0.25	1.26	0.5	0.9	0.9	2.95	5.9
MACH&EQUIP	0.2	0	0	0.25	1.26	0.5	0.9	0.9	3.9	7.8
ELEC_EQUIP	0.2	0	0	0.25	1.26	0.5	0.9	0.9	4.4	8.8
TRANSP_EQUIP	0.2	0	0	0.25	1.26	0.5	0.9	0.9	3.55	7.1
OTHER_MANUF	0.2	0	0	0.25	1.17	0.5	0.9	0.9	3.21	6.43
ELECT	0.2	0	0	0.25	1.26	0.5	0.9	0.9	2.8	5.6
GAS	0.2	0	0	0.25	0.73	0.5	0.9	0.9	10	20
WATER	0.2	0	0	0.25	1.26	0.5	0.9	0.9	1.9	3.8
CONSTRUCTION	0.2	0	0	0.25	1.4	0.5	0.9	0.9	1.9	3.8
TRADE	0.2	0	0	0.25	1.32	0.5	0.9	0.9	2.03	4.06
HORECA	0.2	0	0	0.25	1.32	0.5	0.9	0.9	2.03	4.06
TRANSP&COMM	0.2	0	0	0.25	1.68	0.5	0.9	0.9	1.9	3.8
FIN_SERVICES	0.2	0	0	0.25	1.32	0.5	0.9	0.9	2.03	4.06
REAL_ESTATE	0.2	0	0	0.25	1.32	0.5	0.9	0.9	2.03	4.06
PUB_ADMIN	0.2	0	0	0.25	1.26	0.5	0.9	0.9	1.9	3.8
EDUCATION	0.2	0	0	0.25	1.26	0.5	0.9	0.9	1.9	3.8
HEALTH	0.2	0	0	0.25	1.26	0.5	0.9	0.9	1.9	3.8
SERVICES	0.2	0	0	0.25	1.32	0.5	0.9	0.9	2.03	4.06

Source: (Aguiar et al., 2016; EC, 2013b)

Final demand substitution elasticities

Consumption vs. Leisure*	σ_{UB}	1.45
Consumption of energy for transport, energy for home and non-energy goods	σ_{FCH}	0.1
Consumption of distributed water vs. other non-energy goods**	σ_{DW}	0.26
Consumption of electricity vs. fossil energy products	σ_{EH}	1.5
Consumption of fossil energy products	σ_{NEH}	1

Source: these elasticities were taken from a previous version of this CGE, published in (Labandeira, Labeaga, et al., 2009)

Note:

*σ_{LC} was calibrated so that the model reproduced the uncompensated labour supply elasticity of 0.4 available in literature (see (Labandeira, Labeaga, et al., 2009))

** σ_{DW} was calibrated so that the model reproduced the price elasticity of households' water consumption of -0.27 available in literature (see (Reynaud, 2015))

Appendix 8.3. Raw water intensity per sector

Economic activity	Production sector	Description	Raw water intensity m^3/€
Agriculture and fishing	AGR & FOR	Agriculture and forestry	0.8163
	FISHING	Fishing and aquaculture	0.8163
Industry and construction	MIN & EXTRACT_FUELS	Mining of coal; extraction of crude petroleum and natural gas	0.0025
	MIN & QUARR	Other mining and quarrying	0
	FOOD & TOB	Manufacture of food, beverages and tobacco products	0.015
	TEXTILES	Manufacture of textiles products	0.0065
	LEATHER	Manufacture of leather products	0.0065
	WOOD & CORK	Manufacture of wood and cork products	0.0025
	PAPER & PULP	Manufacture of paper and paper products; printing	0.0469
	REFPET	Manufacture of coke and refined petroleum products	0.041
	CHEMICALS	Manufacture of pharmaceutical and chemical products	0.041
	RUB & PLAST	Manufacture of rubber and plastic products	0.041
	NONMET_MINER	Manufacture of non-metallic mineral products	0.0025
	METALS	Manufacture of basic metals and metal products	0.0218
	MACH & EQUIP	Manufacture and repair of machinery and equipment	0.0025
	ELEC_EQUIP	Manufacture of electric and electronic products	0.0025
	TRANSP_EQUIP	Manufacture of transport equipment	0.0025
	OTHER_MANUF	Other manufacturing	0.0025
	ELECT	Electricity, steam and air conditioning supply	0.056
	GAS	Natural gas supply	0.0025
	CONSTRUCTION	Construction	0.0002
Water	WATER SUPPLY	Water collection, treatment and supply	1.125
Services	TRADE	Trade and repair	0
	HORECA	Accommodation and food service activities	0
	TRANSP & COMM	Transport and communications	0
	FIN_SERVICES	Financial and insurance activities	0
	REAL_ESTATE	Real estate and rental activities	0
	PUB_ADMIN	Public administration	0
	EDUCATION	Education	0
	HEALTH	Human health activities	0
	SERVICES	Other professional and personal services	0

Source: own elaboration based on (DPP, 2011; Eurostat, 2016)

Appendix 8.4. Simulation results under RCP4.5 scenario

Economic activity	Production sector	Domestic production	
		No_Comp	Comp_PT-SP
Agriculture and fishing	AGR & FOR	-5.60%	0.20%
	FISHING	-4.60%	0.10%
Industry and construction	MIN & QUARR	1.20%	0.50%
	FOOD & TOB	-1.20%	0.20%
	TEXTILES	1.20%	0.50%
	LEATHER	1.60%	0.70%
	WOOD & CORK	-3.10%	0.20%
	PAPER & PULP	-1.30%	-0.50%
	CHEMICALS	0.30%	0.00%
	RUB & PLAST	-0.10%	0.10%
	NONMET_MINER	-0.10%	0.00%
	METALS	-0.10%	0.00%
	MACH & EQUIP	-0.10%	0.10%
	ELEC_EQUIP	0.70%	0.20%
	TRANSP_EQUIP	0.60%	0.20%
	OTHER_MANUF	0.30%	0.20%
	CONSTRUCTION	-1.20%	-0.40%
	ELECTRICITY	-3.80%	-4.40%
	REF PETROL PRODS	0.40%	0.50%
	GAS SUPPLY	0.40%	0.70%
Water	WATER SUPPLY	-2.10%	-0.10%
Services	TRADE	-0.30%	0.20%
	HORECA	0.10%	0.10%
	TRANSP & COMM	1.10%	0.20%
	FIN_SERVICES	0.30%	0.10%
	REAL_ESTATE	0.30%	0.10%
	PUB_ADMIN	1.10%	-0.10%
	EDUCATION	1.00%	0.00%
	HEALTH	0.70%	-0.10%
	SERVICES	0.20%	0.00%

CHAPTER 9

CONCLUSIONS AND DISCUSSION

The overall objective of this thesis is to analyse the impacts and feedbacks between water resources, the energy sector and the economy in the face of climate change and energy and climate goals. A double perspective is adopted, focussing, first, on climate and energy policies and targets in the near term and, second, on the physical impacts of climate change and the resulting effects on water resources, energy supply and the economy, in the medium to long term. A case study is provided for the Mediterranean country of Portugal.

This study contributes to the existing body of knowledge in three ways. First, it advances in the quantification of the impacts, on the real economy, of binding energy targets set by energy public policies, such as the energy efficiency targets set within the EU Climate and Energy Package 2020. This study, not only, provides a detailed sectoral assessment of the economic and environmental impacts of those targets, but also, presents some unexpected outcomes (such as the undesirable impacts resulting from a tax on energy quantities that penalises lower carbon-content fossil fuels and the more distorting impacts resulting from a tax on all energy products, as compared to a tax on fossil fuels only) that need to be taken into consideration in future climate and energy policies and targets. Second, it enriches the literature on the quantitative impacts that the reduction in water availability (resulting from climate change) will have on hydropower generation and the electrical system, focusing on a Mediterranean country and using the most recent IPCC scenarios. This study confirms the heterogeneity of climate change impacts on the energy supply sector according to the climate region and, thus, highlights the importance of the regional approach in these analyses. Third, it advances in the comprehensive assessment of the impacts and feedbacks between climate change, water resources, the energy sector, economic performance and social welfare, by developing a hybrid E3 model that specifically considers raw water as a factor of production and that includes detailed data on water use in the economy. This extension provides insights in the 'water-energy-economy' nexus that are of utmost importance for policy makers. Moreover, it quantifies the additional costs that the dependence on transboundary river basins represents to an economy through the comparison of scenarios that disregard or include competition for water between countries sharing river basins. To this end, an innovative methodology comprising four key steps is adopted. These consist in: i) the quantification of the climate change-induced impacts on water availability for the case study considering the most recent IPCC climate change scenarios (RCP); ii) the quantification of changes in water availability for economic activities arising, simultaneously, from climate change and the resulting increased competition for water resources (i.e. between sectors and countries);

iii) the development of a hybrid CGE model with the integration of the bottom-up detail of the power sector and the incorporation of outcomes from technological model runs (i.e. energy consumption and prices); and iv) the inclusion of raw water in the CGE model as to best capture the 'water-energy-economy' nexus.

Notwithstanding the case study for Portugal, the approach and methodologies presented may be replicated to other regions, considering that the economic impacts of climate policies and the economic impacts of climate change on water resources are of general interest to the scientific community and policy-makers committed to climate change mitigation and adaptation as well as sustainability goals. This thesis highlights the trade-offs in the 'water-energy-economy' nexus, which provide fundamental insights for more comprehensive, coherent and effective climate and energy policy making.

The remainder of this chapter provides an overview of the main results and subsequent policy implications (Section 9.1), a critical assessment of the applied approach and methods (Section 9.2) and, finally, a set of recommendations for future research (Section 9.3).

9.1. Main results and policy implications

The first part of this thesis (Chapters 2 to 5) provides a theoretical and practical background. This entails a literature review of climate change impacts and projections, the presentation of the Portuguese energy sector, and a broad description of the methodological approach. The second part of this thesis (Chapters 6 to 8) consists in the empirical assessment of the impacts of climate policies and climate change on the Portuguese economy: first, from the perspective of climate and energy policies and targets; second, from the perspective of climate change and the 'water-energy-economy' nexus by 2050. The next paragraphs provide an overview of each chapter.

Chapter 2 provides a conceptual framing of climate change impacts on water resources and the resulting consequences for hydropower generation and the economy. Climate change alters seasonal, regional and intensity precipitation patterns and, as a consequence, the amount and temporal distribution of runoff and the magnitude of river discharge. River regime disturbances, in turn, affect the overall quantity and temporal distribution of water resources – ultimately interfering with the hydropower generation potential. Climate change impacts on hydropower generation can, in turn, be grouped into two categories. The first concerns the above described climate change impacts on hydro-meteorological variables that directly affect the availability of water for hydropower generation. The second refers to indirect impacts, such as increased competition for water resources, which covers competition between water-dependent economic sectors (e.g. agriculture, energy, recreation) as well as between countries sharing common river basins. The interdependency between water resources and the energy sector is of major importance. Such interlinkages and resulting externalities are the cornerstone of the 'water-energy' nexus, in which hydropower generation plays a crucial role. While hydropower appears the most feasible and cost-effective option to back-up intermittent renewable energy sources that are increasingly dominating the power mixes, uncertainties associated with the impacts of climate change on the hydrological cycle, water availability and hydropower production escalate the conflicts about distinct and concomitant uses for scarce water resources.

Chapter 3 reviews existing projections of climate change impacts on hydrological variables and hydropower generation potential for the Southern European region and Portugal by the mid to end 21st century. Concerning Southern Europe, climate projections encompass higher temperatures (up to a 2.3°C increase by 2050) and lower annual precipitation (up to a 20% decrease by 2071-2100), with increased seasonal asymmetries that involve a consensual decrease for summer precipitation (up to -35%) but not for winter precipitation (with projections ranging between -15% and +4%). As a consequence, projections also point towards decreased runoff rates (up to -50% by 2050) and river flows. These climate conditions are expected to reduce hydropower potential in Southern Europe. By the end of the 21st century, the electricity effectively supplied by hydropower is projected to decrease by up to 40%. Regarding projections for Portugal, these are consistent with those for the Southern European region, but provide further detail on the projected impacts at the national and basin-scale. Accordingly, projected impacts for 2050 entail higher temperatures (between +2.0°C and +3.0°C) and lower precipitation, this latter with increased asymmetries at the regional and seasonal levels – i.e. precipitation may increase for some regions and seasons (e.g. +10% winter precipitation in the North) and decrease for other regions and seasons (e.g. -30% summer precipitation in the South). Runoff is highly variable across regions and seasons, and projections for 2050 indicate a decrease in annual runoff by up to 10% in the North and by up to 50% in the South. Projected changes for precipitation regimes in Portugal, as well as the resulting increases in seasonal and spatial asymmetries in river flows and reductions in runoff, are expected to decrease hydropower generation and widen inter-annual disparities. The majority of projections point towards a reduction of the Portuguese hydropower potential (up to -21% by 2050 and by up to -44% in 2070).

Chapter 4 is devoted to a detailed presentation of the Portuguese energy sector over the period 1990-2015, considering primary production, final consumption, prices, economic indicators and greenhouse gas (GHG) emissions. Portuguese primary production of energy relies almost entirely on renewable sources, with hydropower being one of the most important sources (ranging between 10% and 33% of primary energy production), despite fluctuations caused by hydrological variability. Being a net energy importer, oscillations in the annual energy dependency rate in Portugal (ranging between 71% and 89%) are directly associated with the hydrological conditions, thus highlighting the role of hydropower in the Portuguese energy mix. GHG emissions released by energy-related activities represent around 70% of total GHG emissions, where the energy sectors are responsible for the largest share in this total.

Chapter 5 describes the methodological approach underlying the developed hybrid E3 model, which combines a top-down CGE model for the Portuguese economy with a bottom-up partial equilibrium model of the Portuguese energy sector (TIMES_PT). This approach has been widely used to address climate and energy issues and assist policy-making, as its integrated framework allows for the representation of the interactions and feedbacks between the energy sector, the environment and the economy – which top-down or bottom-up approaches, separately, do not. A thorough assessment of climate change impacts requires, however, that pressures on natural resources are expressly modelled and measured in physical units. In the particular case of this study, accounting for raw water endowments is a key input for the assessment of the economy-wide effects of climate change-driven impacts on water resources availability under the premise of the 'water-energy' nexus. Nevertheless, in conventional hybrid E3 models the representation of raw water usually remains out of scope. The economic consequences of restricted water supply resulting from climate change are, frequently, analysed with water-oriented top-down CGE models, which devote particular attention to the 'water-food' nexus. In these cases, the bidirectional relationship between water resources and the energy sector, i.e., the 'water-energy' nexus, as well as the environmental and economic consequences that these entail are not dealt with.

Chapter 6 assesses the economic and environmental impacts of achieving energy efficiency targets set by climate policies – in particular, a 25% of primary energy saving by 2020. A hybrid static CGE model for a small open economy calibrated for Portugal, comprising 31 production sectors and the technological disaggregation of the electricity production sector into the eight most representative power technologies in the country, is used. Departing from the Portuguese under-performance in energy efficiency improvements set to be attained by 2020, alternative scenarios simulate the economic impacts of energy fiscal policies that encourage energy savings and, thus, ensure the national compliance with the energy efficiency targets – in particular, the taxation of either primary or final energy consumption and, concerning the latter, the taxation of all energy products or fossil-fuels only. The economic impacts of the simulated policies are negative and encompass a reduction in real GDP (up to -6.2%), lower wages and higher unemployment rates, although the energy trade balance improves and final energy intensity decreases. At the sectoral level, the energy sectors and most energy-intensive manufacturing sectors record the largest contractions in production. It is shown that achieving the energy saving target through a reduction in primary energy consumption of fossil fuels is the most cost-effective policy, as it generates the smallest reduction in real GDP and still contributes to attaining the energy and climate goals. It is also shown that, concerning final energy consumption, the most cost-effective policy is the taxation of all energy products because the tax burden is spread across a larger tax basis, and, thus, the resulting economic distortions are smaller. Finally, results show that fiscal policies burdening consumed energy quantities (ktoe) may penalise relatively more those energy products with lower carbon content (in this case natural gas versus refined petroleum products). Hence, the relationship between improvements in energy savings and reductions in GHG emissions is not straightforward – suggesting that energy efficiency policies may be coupled with mitigation policies (e.g. carbon taxation).

Chapter 7 assesses the effects of reductions in water resources availability projected for Portugal as a consequence of climate change (see Chapter 3) on hydropower generation and the Portuguese electrical system by 2050. To this end, the bottom-up partial equilibrium energy system model TIMES_PT is used, considering the SRES A2c, SRES B2a, RCP 4.5 and RCP 8.5 climate change scenarios. Results show that power generation decreases slightly in the presence of climate change impacts, though comprises considerable changes in hydropower generation that vary according to the severity of climate change scenario and result in decreasing shares of hydropower in the national power mix. The reduction in hydropower generation in the most severe scenarios, combined with wind and solar PV operating at the maximum potential, leads to an increase in the installed capacity of natural gas. Hence, the stronger the climate change impacts, the higher the GHG emissions – thus undermining the compliance with European and Portuguese climate goals for 2050 described in Chapter 1 (Introduction). Climate change will also affect electricity generation costs and, consequently, the electricity prices charged to final users, which may impact the Portuguese economy. Being a partial equilibrium model, however, TIMES_PT does not consider the interactions between the energy sector and the remainder of the economy and, hence, does not provide an economy-wide assessment of the simulated climate change impacts on the energy system.

Chapter 8 provides such economy-wide perspective. Considering that the energy sector is a key input for almost all economic sectors and that any shock in the energy sector is rapidly transferred to the national economy, this chapter departs from the 'water-energy' nexus to: i) quantify the climate change-driven impacts on the availability of water endowments in Portugal by 2050, and ii) assess the economic consequences of the sectoral and transboundary competition for scarcer water resources. To this end, the CGE model (developed in Chapter 6) is extended with the inclusion of raw water as a production factor and with an integrated modelling approach through a soft link between the CGE and the TIMES_PT bottom-up model (presented in Chapter 7). Alternative scenarios simulate competition for water resources between sectors (hydropower versus other economic sectors) and between countries (Portugal versus Spain), under two distinct climate change scenarios (RCP 4.5 and RCP 8.5). Regarding the competition between sectors, two extreme situations are considered: the first considers there is no inter-sectoral competition for raw water resources (i.e. all sectors bear the effects of reduced raw water availability); and the second considers there is inter-sectoral competition for raw water resources between the energy sector and other sectors (i.e. only hydropower bears the effects of reduced raw water availability). Results show that the macroeconomic and sectoral impacts are stronger if competition for water between hydropower and the other economic sectors is not considered and if transboundary competition for water is taken into account. In case inter-sectoral competition for water does not exist, the most water-intensive sectors record the strongest impacts (reductions) in their production levels, due to the higher opportunity cost of raw water and price of distributed water. Conversely, in case inter-sectoral competition does exist, those sectors bearing higher electricity costs in their production functions are the most affected, due to the higher electricity prices resulting from lower shares of (cheap) hydropower generation in the energy mix. Projected power mixes point towards the increasing penetration of non- or low water consuming renewable-sourced technologies (notably wind power and solar photovoltaic), meaning that the reduced availability of raw water input will not significantly hinder power generation. However, associated higher electricity generation costs may induce a shift in energy consumption towards fossil fuels, which hamper climate change mitigation efforts. Overall, the impacts of climate change related reductions in raw water resources availability result in decreases in GDP of between -0.1% and -3.2%. Hence, from a policy-making perspective, results show that economic and social costs are minimized when priority is given to the water use by non-electricity production sectors. Such water allocation schemes reduce water market distortions (arising from raw water scarcity that increase water prices) and minimize the economic costs of climate-change driven impacts on water resources availability. At the national level, these results are of utmost relevance, as Portugal aims to achieve carbon neutrality by 2050. This may imply an increasing electrification of the economy and the decarbonisation of the power sector. In this regard, the abovementioned effects on the power mix and resulting electricity prices may strengthen the role of hydropower.

9.2. Limitations of the study

Two main sets of limitations of the current study can be identified. The first refers to the uncertainty associated with the quantitative assessment of climate change impacts, which is widely recognized in literature. This uncertainty results from, not only, the long term climate projections and greenhouse gas (GHG) emissions pathways from which climate change impacts are simulated, but also, from the modelling tools that simulate the energy and economic impacts as these depend on the quality of data and realism of the model. For these reasons, these studies should be carried out as projective scenario analyses rather than predictions (as argued by (Ebinger & Vergara, 2011)).

The second refers to the CGE model. First, the model is static and, thus, only allows for a comparative-static analysis while not considering the economy's adjustment path over time. Dynamic models are, due to their higher complexity, usually more aggregate, and, therefore, their flexibility to adapt to shocks (policy shocks or climate change impacts, in our case) is lower. As a consequence, a dynamic model could overestimate economic and environmental costs of simulated climate changes. Second, the model assumes perfect competition (except for labour market) and constant returns to scale technologies, thereby not considering the possibility of free market entry or exit nor the ability to exploit scale economies. Such modifications of the model would, nonetheless, entail additional assumptions on market strategic behaviour and data for CGE calibration, such as the profit margins, the number of firms or the types of strategic interaction (Roson, 2006). Hence, these model refinements would involve a significant increase in model complexity and input requirements that are beyond the scope of this thesis. Third, the model uses, as usual in CGE models, exogenous elasticities of substitution and transformation taken from the empirical literature that are estimated from historical data and may not remain valid indefinitely. Hence, sensitivity analyses of key parameters were performed to confirm the robustness of results and, thus, reducing uncertainty associated with the presented results.

9.3. Future research developments

Future research developments, springing from this study, encompass CGE model refinements such that it can reproduce reality with increased precision as well as extending the analysis to other dimensions of critical relevance within climate change impacts assessments.

Concerning the CGE model refinements, the main improvements consist in: i) including a spatial component so that the regional asymmetries of climate change impacts on raw water resources can be captured; ii) including water efficiency improvements so as to better capture the extent to which such efficiency gains may attenuate the effects of increased scarcity resulting from climate change; and iii) refining water inputs of the model, namely with the inclusion of ground water as well as the distinction between blue and green water. The analysis may, also, be extended with a more complex representation of the 'water-energy' nexus that considers, in particular, the possibility of pumping water so that water resources used for hydropower generation may be pumped upstream and reused by, either, the hydropower sector, or, other economic sectors. Further improvements would also encompass the introduction of a dynamic structure in the model and of imperfect competition in some industries, such as the energy and the water distribution and supply sectors.

Concerning the possibility of extending the present analysis, future developments consist in the assessment of climate change impacts on other sectors with preponderance in the national economy, notably tourism and agriculture. Finally, the present modelling framework can be further applied to assess the impacts of the recently defined policy goal of achieving carbon neutrality by 2050 as well as to support the development of national Climate Change Adaptation Plans.

REFERENCES

Aguiar, A., Narayanan, B., & McDougall, R. (2016). An Overview of the GTAP 9 Data Base. Journal of Global Economic Analysis, 1(1), 181–208. https://doi.org/10.21642/JGEA.010103AF

Allan; J.A. (1992). Fortunately there are substitutes for water: otherwise our hydropolitical futures would be impossible. In Proceedings of the Conference on Priorities for Water Resources Allocation and Management: Natural Resources and Engineering Advisers Conference (pp. 13–26). Southampton, July 1992.

Almeida, M. C., Coelho, P. S., Rodrigues, A. C., Diogo, P. A., Maurício, R., Cardoso, R. M., & Soares, P. M. (2015). Thermal stratification of Portuguese reservoirs: potential impact of extreme climate scenarios. Journal of Water and Climate Change, 6(3), 544 LP-560. https://doi.org/10.2166/wcc.2015.071

Alves, M. (2013). Impacto de Cenários de Alterações Climáticas nos Recursos Energéticos Renováveis : Sistema Elétrico Português até 2070. MsC. Thesis. Faculdade de Ciências e Tecnologia da Universidade Nova de Lisboa. Lisboa.

APA. (2012). Roteiro Nacional de Baixo Carbono 2050 - Opções de transição para uma economia de baixo carbono competitiva em 2050 [Low Carbon RoadMap: Portugal 2050]. Amadora: Portuguese Environment Agency.

APA. (2013). Estratégia setorial de adaptação aos impactos das alterações climáticas relacionados com os recursos hídricos [Sectorial strategy for adaptation to the impacts of climate change related to water resources]. Amadora: Portuguese Environment Agency.

APA. (2015). Programa Nacional para as Alterações Climáticas 2020/2030 [National Climate Change Programme 2020/2030]. Amadora: Portuguese Environment Agency.

APA. (2016a). Multilateral Assessment Portugal. Portuguese Environment Agency. Amadora. Retrieved from https://unfccc.int/sites/default/files/prt_presentationma_sbi46.pdf

APA. (2016b). SNIRH - Sistema Nacional de Informação de Recursos Hídricos. [National Water Resources Information System]. Portuguese Environment Agency. Retrieved from snirh.apambiente.pt/. Accessed february 2016

APA. (2017). Large dams in Portugal. Portuguese Environment Agency. Retrieved from snirh.apambiente.pt/. Accessed may 2017

Armington, P. (1969). A Theory of Demand for Products Distinguished by Place of Production. International Monetary Fund Staff Papers, 16(1), 159–178. https://doi.org/10.2307/3866403

Arnell, N. W. (1999). The effect of climate change on hydrological regimes in Europe: A continental perspective. Global Environmental Change, 9(1), 5–23. https://doi.org/10.1016/S0959-3780(98)00015-6

Arnell, N. W. (2004). Climate change and global water resources: SRES emissions and socio-economic scenarios. Global Environmental Change, 14(1), 31–52. https://doi.org/10.1016/j.gloenvcha.2003.10.006

Arnell, N. W., & Gosling, S. N. (2013). The impacts of climate change on river flow regimes at the global scale. Journal of Hydrology, 486, 351–364. https://doi.org/10.1016/j.jhydrol.2013.02.010

Babatunde, K., Begum, R., & Said, F. (2017). Application of computable general equilibrium (CGE) to climate change mitigation policy: A systematic review. Renewable and Sustainable Energy Reviews, 78, 61–71. https://doi.org/https://doi.org/10.1016/j.rser.2017.04.064

Bailera, M., & Lisbona, P. (2018). Energy storage in Spain: Forecasting electricity excess and assessment of power-to-gas potential up to 2050. Energy, 143, 900–910. https://doi.org/10.1016/j.energy.2017.11.069

Bakken, T. H., Engeland, K., Killingtveit, A., Alfredsen, K., & Harby, A. (2013). Water consumption from hydropower plants - Review of published estimates and an assessment of the concept. Hydrology and Earth System Sciences, 17(10), 3983–4000. https://doi.org/10.5194/hess-17-3983-2013

Ban, N., Schmidli, J., & Schär, C. (2015). Heavy precipitation in a changing climate: Does short-term summer precipitation increase faster? Geophysical Research Letters, 42(4), 1165–1172. https://doi.org/10.1002/2014GL062588

Bataille, C., Jaccard, M., Nyboer, J., & Rivers, N. (2006). Towards general equilibrium in a technology-rich model with empirically estimated behavioral parameters. The Energy Journal, 27, 93–112.

Bataille, C., & Melton, N. (2017). Energy efficiency and economic growth: A retrospective CGE analysis for Canada from 2002 to 2012. Energy Economics, 64, 118–130. https://doi.org/https://doi.org/10.1016/j.eneco.2017.03.008

Baum, Z., Palatnik, R. R., Kan, I., & Rapaport-Rom, M. (2016). Economic Impacts of Water Scarcity Under Diverse Water Salinities. Water Economics and Policy, 02(01), 1550013. https://doi.org/10.1142/S2382624X15500137

Belo-Pereira, M., Dutra, E., & Viterbo, P. (2011). Evaluation of global precipitation data sets over the Iberian Peninsula. Journal of Geophysical Research Atmospheres, 116(20), 1–16. https://doi.org/10.1029/2010JD015481

Berck, P., Robinson, S., & Goldman, G. (1991). The Use of Computable General Equilibrium Models to Assess Water Policies. In A. Dinar & D. Zilberman (Eds.), The Economics and Management of Water and Drainage in Agriculture (pp. 489–509). Boston, MA: Springer US. https://doi.org/10.1007/978-1-4615-4028-1_25

Berga, L. (2016). The Role of Hydropower in Climate Change Mitigation and Adaptation: A Review. Engineering, 2(3), 313–318. https://doi.org/10.1016/J.ENG.2016.03.004

Berrittella, M., Hoekstra, A. Y., Rehdanz, K., Roson, R., & Tol, R. S. J. (2007). The economic impact of restricted water supply: a computable general equilibrium analysis. Water Research, 41(8), 1799–1813. https://doi.org/10.1016/j.watres.2007.01.010

Berrittella, M., Rehdanz, K., Roson, R., & Tol, R. S. J. (2008). The economic impact of water taxes: a computable general equilibrium analysis with an international data set. Water Policy, 10(3), 259 LP-271. https://doi.org/10.2139/ssrn.1457625

Bhattacharyya, S. C., & Timilsina, G. R. (2010). A review of energy system models. International Journal of Energy Sector Management, 4(4), 494–518. https://doi.org/10.1108/17506221011092742

Blanchflower, D., & Oswald, A. (1995). An Introduction to the Wage Curve. The Journal of Economic Perspectives, 9(3), 153–167.

Böhringer, C. (1998). The synthesis of bottom-up and top-down in energy policy modeling. Energy Economics, 20(3), 233–248.

Böhringer, C., Ferris, M., & Rutherford, T. (1998). Alternative CO2 Abatement Strategies for the European Union. In S. Proost & J. B. Braden (Eds.), Climate Change, Transport and Environmental Policy (pp. 16–47). Cheltenham: Edward Elgar.

Bohringer, C., & Loschel, A. (2006). Promoting Renewable Energy in Europe: A Hybrid Computable General Equilibrium Approach. The Energy Journal, SI2006(01), 135–151. https://doi.org/10.5547/ISSN0195-6574-EJ-VolSI2006-NoSI2-7

Böhringer, C., & Rutherford, T. (2013). Transition towards a low carbon economy: A computable general equilibrium analysis for Poland. Energy Policy, 55, 16–26. https://doi.org/10.1016/j.enpol.2012.11.056

Böhringer, C., & Rutherford, T. F. (2008). Combining bottom-up and top-down. Energy Economics, 30(2), 574–596. https://doi.org/10.1016/j.eneco.2007.03.004

Böhringer, C., & Rutherford, T. F. (2009). Integrated assessment of energy policies: Decomposing top-down and bottom-up. Journal of Economic Dynamics and Control, 33(9), 1648–1661. https://doi.org/10.1016/j.jedc.2008.12.007

Böhringer, C., & Rutherford, T. F. (2010). The Costs of Compliance: A CGE Assessment of Canada's Policy Options under the Kyoto Protocol. World Economy, 33(2), 177–211. https://doi.org/10.1111/j.1467-9701.2009.01229.x

Bosetti, V., Carraro, C., Galeotti, M., Massetti, E., & Tavoni, M. (2006). WITCH A World Induced Technical Change Hybrid Model. The Energy Journal, 27, 13–37.

Brenhas, M. J., Machado, R., & Dinis, M. A. P. (2008). Vantagens do Ciclo Combinado a Gás Natural Face a Outras Tecnologias de Produção de Energia. Estudo de Caso: A Central da Tapada do Outeiro, Portugal. Revista Da Faculdade de Ciência e Tecnologia, 5, 22–39.

Broberg, T., Berg, C., & Samakovlis, E. (2015). The economy-wide rebound effect from improved energy efficiency in Swedish industries–A general equilibrium analysis. Energy Policy, 83, 26–37. https://doi.org/10.1016/j.enpol.2015.03.026

Brouwer, F., Avgerinopoulos, G., Fazekas, D., Laspidou, C., Mercure, J.-F., Pollitt, H., … Howells, M. (2017). Energy modelling and the Nexus concept. Energy Strategy Reviews, 1–6. https://doi.org/10.1016/j.esr.2017.10.005

Brouwer, R., & Hofkes, M. (2008a). Integrated hydro-economic modelling: Approaches, key issues and future research directions. Ecological Economics, 66(1), 16–22. https://doi.org/10.1016/j.ecolecon.2008.02.009

Brouwer, R., Hofkes, M., & Linderhof, V. (2008b). General equilibrium modelling of the direct and indirect economic impacts of water quality improvements in the Netherlands at national and river basin scale. Ecological Economics, 66(1), 127–140. https://doi.org/10.1016/j.ecolecon.2007.11.015

Brundtland, G. H. (1987). Our Common Future: Report of the World Commission On Environment and Development. Oxford University.

Cabalu, H., Koshy, P., Corong, E., Rodriguez, U., & Endriga, B. (2015). Modelling the impact of energy policies on the Philippine economy: Carbon tax, energy efficiency, and changes in the energy mix. Economic Analysis and Policy, 48, 222–237. https://doi.org/10.1016/j.eap.2015.11.014

Cai, Y., & Arora, V. (2015). Disaggregating electricity generation technologies in CGE models: A revised technology bundle approach with an application to the U.S. Clean Power Plan. Applied Energy, 154, 543–555. https://doi.org/10.1016/j.apenergy.2015.05.041

Cakmak, E. H., Dudu, H., Saraçoğlu, Ş. D., Diao, X., Roe, T., & Tsur, Y. (2008). Macro-Micro Feedback Links Of Irrigation Water Management In Turkey. World Bank Policy Research Working Paper Series, 4781(November).

Calzadilla, A., Rehdanz, K., Betts, R., Falloon, P., Wiltshire, A., & Tol, R. S. J. (2013). Climate change impacts on global agriculture. Climatic Change, 120(1–2), 357–374. https://doi.org/10.1007/s10584-013-0822-4

Calzadilla, A., Rehdanz, K., Roson, R., Sartori, M., & Tol, R. S. J. (2016). Review of CGE Models of Water Issues. In A. Calzadilla, K. Rehdanz, R. Roson, M. Sartori, & R. S. J. Tol (Eds.), The WSPC Reference on Natural Resources and Environmental Policy in the Era of Global Change (pp. 101–123). World Scientific Publishing. https://doi.org/10.1142/9789813208179_0004

Calzadilla, A., Rehdanz, K., & Tol, R. S. J. (2010). The economic impact of more sustainable water use in agriculture: A computable general equilibrium analysis. Journal of Hydrology, 384(3–4), 292–305. https://doi.org/10.1016/j.jhydrol.2009.12.012

Calzadilla, A., Rehdanz, K., & Tol, R. S. J. (2011). Water scarcity and the impact of improved irrigation management: A computable general equilibrium analysis. In Agricultural Economics (Vol. 42, pp. 305–323). https://doi.org/10.1111/j.1574-0862.2010.00516.x

Calzadilla, A., Zhu, T., Rehdanz, K., Tol, R. S. J., & Ringler, C. (2013). Economy-wide impacts of climate change on agriculture in Sub-Saharan Africa. Ecological Economics, 93, 150–165. https://doi.org/https://doi.org/10.1016/j.ecolecon.2013.05.006

Calzadilla, A., Zhu, T., Rehdanz, K., Tol, R. S. J., & Ringler, C. (2014). Climate change and agriculture: Impacts and adaptation options in South Africa. Water Resources and Economics, 5, 24–48. https://doi.org/10.1016/j.wre.2014.03.001

Cardenete, M. A., & Hewings, G. J. D. (2011). Water Price and Water Sectoral Reallocation in Andalusia: A Computable General Equilibrium Approach. Environmental Economics, 2(1), 17–27.

Cazcarro, I., Duarte, R., Choliz, J. S., & Sarasa, C. (2011). Water rates and the responsibilities of direct, indirect and end-users in Spain. Economic Systems Research, 23(4), 409–430. https://doi.org/10.1080/09535314.2011.611794

Cazcarro, I., Duarte, R., Sánchez-Chóliz, J., Sarasa, C., & Serrano, A. (2015). Environmental Footprints and Scenario Analysis for Assessing the Impacts of the Agri-Food Industry on a Regional Economy: A Case Study in Spain. Journal of Industrial Ecology, 19(4), 618–627. https://doi.org/10.1111/jiec.12209

CCSP. (2007). Effects of Climate Change on Energy Production and Use in the United States. (T. J. Wilbanks, V. Bhatt, D. E. Bilello, S. R. Bull, J. Ekmann, W. C. Horak, … M. J. Scott, Eds.), A Report by the U.S. Climate Change Science Program and the subcommittee on Global Change Research. Department of Energy, Office of Biological & Environmental Research, Washington, DC.

Chandramowli, S. N., & Felder, F. A. (2014). Impact of climate change on electricity systems and markets – A review of models and forecasts. Sustainable Energy Technologies and Assessments, 5, 62–74. https://doi.org/10.1016/j.seta.2013.11.003

Christensen, J. H. (2005). Prediction of Regional scenarios and Uncertainties for Defining European Climate change risks and Effects - PRUDENCE. Final Project Report. EU 5th Framework Programme. Retrieved from http://prudence.dmi.dk/

Christensen, J. H. (coord). (2005). Prediction of Regional scenarios and Uncertainties for Defining European Climate change risks and Effects - PRUDENCE Final Project Report (Vol. 2004). EU 5th Framework Programme - Project EVK2-CT2001-00132. Retrieved from http://prudence.dmi.dk/

Christensen, J. H., Carter, T. R., Rummukainen, M., & Amanatidis, G. (2007). Evaluating the performance and utility of regional climate models: the PRUDENCE project. Climatic Change, 81(1), 1–6. https://doi.org/10.1007/s10584-006-9211-6

Ciscar, J., & Dowling, P. (2014). Integrated assessment of climate impacts and adaptation in the energy sector. Energy Economics, 46, 531–538. https://doi.org/10.1016/j.eneco.2014.07.003

Ciscar, J., Feyen, L., Soria, A., Lavalle, C., Raes, F., Perry, M., … Ibarreta, D. (2014). Climate Impacts in Europe. The JRC PESETA II Project. JRC Scientific and Policy Reports, EUR 26586EN. https://doi.org/10.2791/7409

Cleto, J. (2008). Climate Change Impacts on Portuguese Energy System in 2050 An assessment with TIMES model. MsC. Thesis. Faculdade de Ciências e Tecnologia da Universidade Nova de Lisboa. Lisboa.

Cleto, J., Simões, S., Fortes, P., & Seixas, J. (2008). Renewable energy sources availability under climate change scenarios - Impacts on the Portuguese energy system. In 5th International Conference on the European Electricity Market Proceedings. Lisboa, Portugal. https://doi.org/10.1109/EEM.2008.4579074

Costa, A. C., Santos, J. a., & Pinto, J. G. (2012). Climate change scenarios for precipitation extremes in Portugal. Theoretical and Applied Climatology, 108(1–2), 217–234. https://doi.org/10.1007/s00704-011-0528-3

Criqui, P., Mima, S., Menanteau, P., & Kitous, A. (2015). Mitigation strategies and energy technology learning: An assessment with the POLES model. Technological Forecasting and Social Change, 90(PA), 119–136. https://doi.org/10.1016/j.techfore.2014.05.005

Cunha, L. V., Oliveira, R. P., Nascimento, J., & Ribeiro, L. (2007). Impacts of climate change on water resources : a case-study for Portugal. In Proceedings of the Fourth InterCeltic Colloquium on Hydrology and Management of Water Resources. Guimarães, Portugal, July 2005.

Dai, H., Masui, T., Matsuoka, Y., & Fujimori, S. (2011). Assessment of China's climate commitment and non-fossil energy plan towards 2020 using hybrid AIM/CGE model. Energy Policy, 39(5), 2875–2887. https://doi.org/10.1016/j.enpol.2011.02.062

Dai, J., Wu, S., Han, G., Weinberg, J., Xie, X., Wu, X., … Yang, Q. (2018). Water-energy nexus: A review of methods and tools for macro-assessment. Applied Energy, 210(November 2016), 393–408. https://doi.org/10.1016/j.apenergy.2017.08.243

de Melo-Gonçalves, P., Rocha, A., & Santos, J. A. (2016). Robust inferences on climate change patterns of precipitation extremes in the Iberian Peninsula. Physics and Chemistry of the Earth, 94, 114–126. https://doi.org/10.1016/j.pce.2016.05.003

Dellink, R., Brouwer, R., Linderhof, V., & Stone, K. (2011). Bio-economic modeling of water quality improvements using a dynamic applied general equilibrium approach. Ecological Economics, 71(1), 63–79. https://doi.org/10.1016/j.ecolecon.2011.06.001

Dellink, R., Lanzi, E., & Chateau, J. (2017). The Sectoral and Regional Economic Consequences of Climate Change to 2060. Environmental and Resource Economics. https://doi.org/10.1007/s10640-017-0197-5

DGEG. (2016a). Balanço Energético 2008 [Energy Balance 2008]. General Directorate for Energy and Geology. [In Portuguese]. Retrieved from http://www.dgeg.gov.pt/. Accessed March 2017

DGEG. (2016b). Estatísticas e Preços - Balanços e Indicadores Energéticos. [Statistics and Prices - Energy balances and indicators]. General Directorate for Energy and Geology [In Portuguese]. Retrieved from http://www.dgeg.gov.pt/. Accessed January 2016

DGEG. (2016c). Estatísticas e Preços - Estatística da Energia - Eletricidade [Statistics and Prices - Energy statistics - Electricity]. General Directorate for Energy and Geology [In Portuguese]. Retrieved from http://www.dgeg.gov.pt/. Accessed March 2017

DGEG. (2016d). Energia em Portugal 2014 [Energy in Portugal 2014]. Lisboa: General Directorate for Energy and Geology. [In Portuguese];

Dowling, P. (2013). The impact of climate change on the European energy system. Energy Policy, 60, 406–417. https://doi.org/10.1016/j.enpol.2013.05.093

DPP. (2011). Sistemas Integrados de Matrizes Input-Output para Portugal, 2008. [Integrated System of input-output Tables for Portugal, 2008]. Department of Prospective and Planning and International Relations of the Portuguese. Lisboa: Ministry of Agriculture, Sea, Environment and Spatial Planning. [In Portuguese].

Dubrovský, M., Hayes, M., Duce, P., Trnka, M., Svoboda, M., & Zara, P. (2014). Multi-GCM projections of future drought and climate variability indicators for the Mediterranean region. Regional Environmental Change, 14(5), 1907–1919. https://doi.org/10.1007/s10113-013-0562-z

E2p energias endógenas de Portugal. (2017). Database of electrical power plants based on renewable energy sources. Retrieved from http://e2p.inegi.up.pt/. Accessed January 2017

Ebinger, J., & Vergara, W. (2011). Climate Impacts on Energy Systems. Key Issues for Energy Sector Adaptation. Washington, D.C.: The World Bank. https://doi.org/10.1596/978-0-8213-8697-2

EC. (2008). European Energy and Transport - Trends to 2030 - Update 2007. Directorate-General for Energy and Transport. Luxembourg: Office for Official Publications of the European Communities.

EC. (2009). Impact Assessment, Commission Staff Working Document accompanying the White Paper on Adapting to Climate Change: Towards a European Framework for Action (COM(2009, 147 final), SEC(2009) 387/2). Brussels: European Commission.

EC. (2011a). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. A roadmap for moving to a competitive low carbon economy in 2050 (COM(2011) 112 final). Brussels: European Commission. https://doi.org/10.1002/jsc.572

EC. (2011b). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Energy Roadmap 2050. (COM(2011) 885 final). Brussels: European Commission. https://doi.org/10.2833/10759

EC. (2013a). EU Energy, Transport and GHG Emissions: Trends to 2050 - Reference Scenario 2013. Luxembourg: European Commission: Directorate-General for Energy, Directorate-General for Climate Action and Directorate-General for Mobility and Transport. https://doi.org/10.2833/17897:

EC. (2013b). GEM-E3 Model Documentation. Joint Research Centre - Institute for Prospective Technological Studies. JRC Technical Reports. Luxembourg: Publications Office of the European Union. https://doi.org/10.2788/47872

EC. (2014a). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions - A policy framework for climate and energy in the period from 2020 to 2030 (COM(2014) 15 final). Brussels: European Commission.

EC. (2014b). Impact Assessment, Comission Staff Working Document accompanying the *document “Energy Efficiency and its contribution t*o energy security and the 2030 Framework *for climate and energy policy” (COM (2014) 520 final , SWD (2014) 256 final)*. Brussels: European Commission. https://doi.org/10.1017/CBO9781107415324.004

EC. (2015). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions - Energy Roadmap 2050 (COM(2011) 885 final). Brussels: European Commission.

EC. (2016). Proposal for a Directive of the European Parliament and of the Council amending Directive 2012/27/EU on energy efficiency. (COM(2016) 761 final) Brussels: European Commission.

EEA. (2017a). Climate change, impacts and vulnerability in Europe 2016 An indicator-based report. European Environment Agency. Luxembourg: Publications Office of the European Union. https://doi.org/10.2800/534806

EEA. (2017b). Indicator Assessment - Water intensity of crop production. Retrieved from https://www.eea.europa.eu/data-and-maps/indicators/economic-water-productivity-of-irrigated-1/assessment. Accessed December 2017

Erol, A., & Randhir, T. O. (2012). Climatic change impacts on the ecohydrology of Mediterranean watersheds. Climatic Change, 114(2), 319–341. https://doi.org/10.1007/s10584-012-0406-8

Eskeland, G. S., & Mideksa, T. K. (2009). Climate Change and Residential Electricity Demand in Europe. SSRN Electronic Journal. https://doi.org/10.2139/ssrn.1338835

Eskeland, G. S., Rive, N. A., & Mideksa, T. K. (2012). Europe's climate goals and the electricity sector. Energy Policy, 41, 200–211. https://doi.org/10.1016/j.enpol.2011.10.038

EUCO. (2011). Conclusions of the European Council (4 February 2011) (Vol. 1). Brussels: European Council. https://doi.org/10.1017/CBO9781107415324.004

Eurelectric. (2011). Hydro in Europe: Powering renewables. Brussels: Union of the Electricity Industry - Eurelectric aisbl.

Eurelectric. (2015). Hydropower supporting a power system in transition. Brussels: Union of the Electricity Industry - Eurelectric aisbl. https://doi.org/10.1007/s13398-014-0173-7.2

European Union. (2009). Decision No 406/2009/EC of the European Parliament and of the Council of 23 April 2009 on the effort of Member States to reduce their greenhouse gas emissions to meet the Community's greenhouse gas emission reduction commitments up to 2020. Official Journal of the European Union, L140, 136–148.

Eurostat. (2016). Water use by supply category and economical sector. Retrieved from http://ec.europa.eu/eurostat/data/database. Accessed February 2016

Eurostat. (2017). Gross value added at basic prices by NUTS 3 regions. Retrieved from http://ec.europa.eu/eurostat/data/database. Accessed December 2017

Eurostat. (2018a). Online Statistics Database. Retrieved from https://ec.europa.eu/eurostat/data/database. Accessed May 2018

Eurostat. (2018b). Glossary. Retrieved from https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Category:Energy_glossary. Accessed November 2018

Falloon, P., & Betts, R. (2006). The impact of climate change on global river flow in HadGEM1 simulations. Atmospheric Science Letters, 7, 62–68. https://doi.org/10.1002/asl

Falloon, P., & Betts, R. (2010). Climate impacts on European agriculture and water management in the context of adaptation and mitigation - the importance of an integrated approach. The Science of the Total Environment, 408(23), 5667–5687. https://doi.org/10.1016/j.scitotenv.2009.05.002

Faust, A. K., Gonseth, C., & Vielle, M. (2015). The economic impact of climate-driven changes in water availability in Switzerland. Water Policy, 17(5), 848–864. https://doi.org/10.2166/wp.2015.064

Fayad, A., Gascoin, S., Faour, G., López-Moreno, J. I., Drapeau, L., Page, M. Le, & Escadafal, R. (2017). Snow hydrology in Mediterranean mountain regions: A review. Journal of Hydrology, 551, 374–396. https://doi.org/10.1016/j.jhydrol.2017.05.063

Fernandes, L., & Ferreira, P. (2014). Renewable energy scenarios in the Portuguese electricity system. Energy, 69, 51–57. https://doi.org/10.1016/j.energy.2014.02.098

Ferris, M., & Munson, T. (2008). Complementarity Problems in GAMS and the PATH Solver. University of Wisconsin.

Flörke, M., Laaser, C., Vidaurre, R., Tröltzsch, J., Dworak, T., Marinova, N., … Mysiak, J. (2011). Climate Adaptation – modelling water scenarios and sectoral impacts - Project Final Report. CESR – Center for Environmental Systems Research.

Flörke, M., Wimmer, F., Laaser, C., Vidaurre, R., Tröltzsch, J., Dworak, T., … Mysiak, J. (2011). Final Report for the project Climate Adaptation – modelling water scenarios and sectoral impacts. CESR – Center for Environmental Systems Research.

Fortes, P., Alvarenga, A., Seixas, J., & Rodrigues, S. (2015). Long-term energy scenarios: Bridging the gap between socio-economic storylines and energy modeling. Technological Forecasting and Social Change, 91, 161–178. https://doi.org/10.1016/j.techfore.2014.02.006

Fortes, P., Pereira, R., Pereira, A., & Seixas, J. (2014). Integrated technological-economic modeling platform for energy and climate policy analysis. Energy, 73, 716–730. https://doi.org/10.1016/j.energy.2014.06.075

Forzieri, G., Feyen, L., Rojas, R., Flörke, M., Wimmer, F., & Bianchi, A. (2014). Ensemble projections of future streamflow droughts in Europe. Hydrology and Earth System Sciences, 18(1), 85–108. https://doi.org/10.5194/hess-18-85-2014

Frei, C. W., Haldi, P. A., & Sarlos, G. (2003). Dynamic formulation of a top-down and bottom-up merging energy policy model. Energy Policy, 31(10), 1017–1031. https://doi.org/10.1016/S0301-4215(02)00170-2

Galeotti, M., & Roson, R. (2012). Economic Impacts of Climate Change in Italy and the Mediterranean: Updating the Evidence. Journal of Sustainable Development, 5(5), 27–42. https://doi.org/10.5539/jsd.v5n5p27

García-Ruiz, J. M., López-Moreno, J. I., Vicente-Serrano, S. M., Lasanta–Martínez, T., & Beguería, S. (2011). Mediterranean water resources in a global change scenario. Earth-Science Reviews (Vol. 105). Elsevier B.V. https://doi.org/10.1016/j.earscirev.2011.01.006

Gaudard, L., & Romerio, F. (2014). The future of hydropower in Europe: Interconnecting climate, markets and policies. Environmental Science and Policy, 43, 5–14. https://doi.org/10.1016/j.envsci.2014.05.005

Giannakopoulos, C., Le Sager, P., Bindi, M., Moriondo, M., Kostopoulou, E., & Goodess, C. M. (2009). Climatic changes and associated impacts in the Mediterranean resulting from a 2 °C global warming. Global and Planetary Change, 68(3), 209–224. https://doi.org/10.1016/j.gloplacha.2009.06.001

Giorgi, F. (2006). Climate change hot-spots. Geophysical Research Letters, 33(8), 1–4. https://doi.org/10.1029/2006GL025734

Glynn, J., Fortes, P., Krook-Riekkola, A., Labriet, M., Vielle, M., Kypreos, S., … Ó Gallachóir, B. (2015). Economic Impacts of Future Changes in the Energy System -Global Perspectives. In G. Giannakidis, M. Labriet, B. Ó Gallachóir, & G. Tosato (Eds.), Informing Energy and Climate Policies Using Energy Systems Models: Insights from Scenario Analysis Increasing the Evidence Base (pp. 333–358). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-16540-0_19

Golombek, R., Kittelsen, S. a. C., & Haddeland, I. (2012). Climate change: impacts on electricity markets in Western Europe. Climatic Change, 113(2), 357–370. https://doi.org/10.1007/s10584-011-0348-6

Gómez, C. M., Tirado, D., & Rey-Maquieira, J. (2004). Water exchanges versus water works: Insights from a computable general equilibrium model for the Balearic Islands. Water Resources Research, 40(10). https://doi.org/10.1029/2004WR003235

Goodbody, C., Walsh, E., McDonnell, K. P., & Owende, P. (2013). Regional integration of renewable energy systems in Ireland - The role of hybrid energy systems for small communities. International Journal of Electrical Power and Energy Systems, 44(1), 713–720. https://doi.org/10.1016/j.ijepes.2012.08.012

Gosling, S. N., & Arnell, N. W. (2016). A global assessment of the impact of climate change on water scarcity. Climatic Change, 134(3), 371–385. https://doi.org/10.1007/s10584-013-0853-x

Grubb, M., Edmonds, J., ten Brink, P., & Morrison, M. (1993). The Costs of Limiting Fossil-Fuel CO2 Emissions: A Survey and Analysis. Annual Review of Energy and the Environment, 18(1), 397–478. https://doi.org/10.1146/annurev.eg.18.110193.002145

Grubb, M., Köhler, J., & Anderson, D. (2002). Induced Technical Change in Energy and Environmental Modeling: Analytic Approaches and Policy Implications. Annual Review of Energy and the Environment, 27(1), 271–308. https://doi.org/10.1146/annurev.energy.27.122001.083408

Gudmundsson, L., & Seneviratne, S. I. (2016). Anthropogenic climate change affects meteorological drought risk in Europe. Environmental Research Letters, 11(4), 044005. https://doi.org/10.1088/1748-9326/11/4/044005

Guerreiro, S. B., Birkinshaw, S., Kilsby, C., Fowler, H. J., & Lewis, E. (2017). Dry getting drier − the future of transnational river basins in Iberia. Journal of Hydrology: Regional Studies, 12(May), 238–252. https://doi.org/10.1016/j.ejrh.2017.05.009

Guerreiro, S. B., Kilsby, C., & Fowler, H. J. (2017). Assessing the threat of future megadrought in Iberia. International Journal of Climatology, 37(15), 5024–5034. https://doi.org/10.1002/joc.5140

Guerreiro, S. B., Kilsby, C. G., & Fowler, H. J. (2016). Rainfall in Iberian transnational basins: a drier future for the Douro, Tagus and Guadiana? Climatic Change, 135(3–4), 467–480. https://doi.org/10.1007/s10584-015-1575-z

Hagemann, S., Chen, C., Clark, D. B., Folwell, S., Gosling, S. N., Haddeland, I., … Wiltshire, A. J. (2013). Climate change impact on available water resources obtained using multiple global climate and hydrology models. Earth System Dynamics, 4(1), 129–144. https://doi.org/10.5194/esd-4-129-2013

Hall, L. M. H., & Buckley, A. R. (2016). A review of energy systems models in the UK: Prevalent usage and categorisation. Applied Energy, 169, 607–628. https://doi.org/10.1016/j.apenergy.2016.02.044

Hamiche, A. M., Stambouli, A. B., & Flazi, S. (2016). A review of the water-energy nexus. Renewable and Sustainable Energy Reviews, 65, 319–331. https://doi.org/10.1016/j.rser.2016.07.020

Hamududu, B., & Killingtveit, A. (2012). Assessing Climate Change Impacts on Global Hydropower. Energies, 5(12), 305–322. https://doi.org/10.3390/en5020305

Hardin, G. (1968). The Tragedy of the Commons. Science, 162(3859), 1243 LP-1248.

Harou, J. J., Pulido-Velazquez, M., Rosenberg, D. E., Medellín-Azuara, J., Lund, J. R., & Howitt, R. E. (2009). Hydro-economic models: Concepts, design, applications, and future prospects. Journal of Hydrology, 375(3–4), 627–643. https://doi.org/10.1016/j.jhydrol.2009.06.037

Hassan, R., & Thurlow, J. (2011). Macro-micro feedback links of water management in South Africa: CGE analyses of selected policy regimes. Agricultural Economics, 42(2), 235–247. https://doi.org/10.1111/j.1574-0862.2010.00511.x

Hertel, T. (Ed). (1997). Global Trade Analysis. Modeling and Aplications. Cambridge: Cambridge University Press.

Hertig, E., & Tramblay, Y. (2017). Regional downscaling of Mediterranean droughts under past and future climatic conditions. Global and Planetary Change, 151, 36–48. https://doi.org/10.1016/j.gloplacha.2016.10.015

Hijioka, Y., Kainuma, M., Masui, T., Matsuoka, Y., & Nishimoto, H. (2008). Global GHG emission scenarios under GHG concentration stabilization targets. J. Glob. Environ. Eng., 13, 97–108.

Hoffman, K. C., & Wood, D. O. (1976). Energy System Modeling and Forecasting. Annual Review of Energy, 1(1), 423–453. https://doi.org/10.1146/annurev.eg.01.110176.002231

Hourcade, J. C., Jaccard, M. K., Bataille, C., & Ghersi, F. (2006). Hybrid modeling: New answers to old challenges. The Energy Journal, International Association for Energy Economics, 2(S), 1–12.

Howells, M., Rogner, H., Strachan, N., Heaps, C., Huntington, H., Kypreos, S., … Roehrl, A. (2011). OSeMOSYS: The Open Source Energy Modeling System: An introduction to its ethos, structure and development. Energy Policy, 39(10), 5850–5870. https://doi.org/http://dx.doi.org/10.1016/j.enpol.2011.06.033

IEA. (2011). Renewable Energy: Markets and Prospects by Technology. International Energy Agency, Paris.

IEA. (2015). World Energy Outlook 2015. OECD Publishing, Paris. https://doi.org/10.1787/weo-2015-en

IEA. (2016). World Energy Outlook 2016 - Water energy nexus. Paris: International Energy Agency. https://doi.org/dx.doi.org/10.1787/weo-2016-en

IEA. (2017). Renewables 2017. Analysis and forecasts to 2022. International Energy Agency. Paris. https://doi.org/10.1787/re_mar-2017-en

IMF. (2013). World Economic Outlook Database. Retrieved from http://www.imf.org/external/pubs/ft/weo/2013/01/weodata/index.aspx

INAG, DGEG, & REN. (2007). Programa nacional de barragens com elevado potencial hidroeléctrico [National Programme for Dams with High Hydroelectric Potential]. Lisboa: INAG - National Water Institute, DGEG - General Directorate for Energy and Geology and REN - National Transmission Operator [In Portuguese].

INE. (2014). Gross production of electric energy (kWh) by Geographic localization (NUTS - 2013) and Type of electricity production. Retrieved from http://www.ine.pt. Accessed January 2018

INE. (2016a). National accounts - Input-Output Tables 2013. Retrieved from http://www.ine.pt/. Accessed April 2017

INE. (2016b). Statistical data. Labour market - Unemployment. Retrieved from http://www.ine.pt/. Accessed January 2016

INE. (2016c). Gross value added (B.1g) at current prices (Base 2011 - *€) by Geographic* localization (NUTS - 2013) and Activity branch (A3); 2008. Retrieved from https://www.ine.pt/. Accessed September 2016

IPCC. (1996). Second assessment report: Climate change 1995. Geneva: IPCC.

IPCC. (2000). IPCC Special Report on Emissions Scenarios (SRES). A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. (N. Nakicenovic & R. Swart, Eds.). Cambridge: Cambridge University Press.

IPCC. (2007a). Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. (Core Writing Team, R. . Pachauri, & A. Reisinger, Eds.). Geneva, Switzerland: IPCC.

IPCC. (2007b). Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Change, Report of the Intergovernmental Panel on Climate. (S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, … H. . Miller, Eds.). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

IPCC. (2011). Special Report on Renewable Energy Sources and Climate Change Mitigation. (O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, … C. von Stechow, Eds.). United Kingdom and New York, NY, USA: Cambridge University Press.

IPCC. (2013a). Annex III: Glossary [Planton, S. (ed.)]. In T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, … P. M. Midgley (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (pp. 1447–1466). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. https://doi.org/10.1017/CBO9781107415324.031

IPCC. (2013b). Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. (T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, … P. M. Midgley, Eds.). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

IPCC. (2014a). Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. (C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, … L. L. White, Eds.). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. https://doi.org/10.1017/CBO9781107415324.004

IPCC. (2014b). Climate Change 2014: Mitigation of Climate Change. Working Group III contribution to the IPCC 5th Assessment Report. Chapter 5 - Drivers , Trends and Mitigation. Final draft.

IPCC. (2014c). Climate Change 2014 Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. (Core Writing Team R.K. Pachauri and L.A. Meyer, Ed.). IPCC, Geneva, Switzerland.

IPCC. (2014d). Summary for Policymakers. In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, … J. C. Minx (Eds.), Climate Change 2014, Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

IRENA. (2012). Renewable Energy Technologies: Cost Analysis Series. Volume 1: Power Sector (No. Issue 3/5). Abu Dhabi: International Renewable Energy Agency. https://doi.org/10.1007/978-3-319-08512-8_7

IRENA. (2018). Renewable Power Generation Costs in 2017. Abu Dhabi: International Renewable Energy Agency. https://doi.org/10.1007/SpringerReference_7300

Jaccard, M., Nyboer, J., Bataille, C., & Sadownik, B. (2003). Modeling the cost of climate policy: Distinguishing between alternative cost definitions and long-run cost dynamics. Energy Journal, 24(1), 49–73. https://doi.org/10.5547/ISSN0195-6574-EJ-Vol24-No1-3

Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O. B., Bouwer, L. M., … Yiou, P. (2014). EURO-CORDEX: new high-resolution climate change projections for European impact research. Regional Environmental Change, 14(2), 563–578. https://doi.org/10.1007/s10113-013-0499-2

Jacobeit, J., Hertig, E., Seubert, S., & Lutz, K. (2014). Statistical downscaling for climate change projections in the Mediterranean region: methods and results. Regional Environmental Change, 14(5), 1891–1906. https://doi.org/10.1007/s10113-014-0605-0

Jain, S., & Singh, V. (2003). Water Resources Systems Planning and Management. Amsterdam: Elsevier.

Jiang, L., Wu, F., Liu, Y., & Deng, X. (2014). Modeling the impacts of urbanization and industrial transformation on water resources in China: An integrated hydro-economic cge analysis. Sustainability (Switzerland), 6(11), 7586–7600. https://doi.org/10.3390/su6117586

Jochem, E., & Schade, W. (2009). Adaptation and Mitigation Strategies Supporting European Climate Policy. Munich: Fraunhofer Institute for Systems and Innovation Research.

Juana, J. S., Strzepek, K. M., & Kirsten, J. F. (2011). Market efficiency and welfare effects of inter-sectoral water allocation in South Africa. Water Policy, 13(2), 220 LP-231.

Kao, S. C., Sale, M. J., Ashfaq, M., Uria Martinez, R., Kaiser, D. P., Wei, Y., & Diffenbaugh, N. S. (2015). Projecting changes in annual hydropower generation using regional runoff data: An assessment of the United States federal hydropower plants. Energy, 80, 239–250. https://doi.org/10.1016/j.energy.2014.11.066

Kemfert, C., & Welsch, H. (2000). Energy-Capital-Labor Substitution and the Economic Effects of CO2 Abatement: Evidence for Germany. Journal of Policy Modeling, 22(6), 641–660. https://doi.org/10.1016/S0161-8938(98)00036-2

Khan, Z., Linares, P., & García-González, J. (2017). Integrating water and energy models for policy driven applications. A review of contemporary work and recommendations for future developments. Renewable and Sustainable Energy Reviews, 67, 1123–1138. https://doi.org/10.1016/j.rser.2016.08.043

Kilsby, C. G., Tellier, S. S., Fowler, H. J., & Howels, T. R. (2007). Hydrological impacts of climate change on the Tejo and Guadiana Rivers. Hydrology and Earth System Sciences, 11(3), 1175–1189. https://doi.org/10.5194/hess-11-1175-2007

Koesler, S., Swales, K., & Turner, K. (2016). International spillover and rebound effects from increased energy efficiency in Germany. Energy Economics, 54, 444–452. https://doi.org/10.1016/j.eneco.2015.12.011

Koopman, J., Kuik, O., Tol, R., & Brouwer, R. (2015). Water scarcity from climate change and adaptation response in an international river basin context. Climate Change Economics, 06(01), 1550004. https://doi.org/10.1142/S2010007815500049

Koopman, J., Kuik, O., Tol, R. S. J., & Brouwer, R. (2017). The potential of water markets to allocate water between industry, agriculture, and public water utilities as an adaptation mechanism to climate change. Mitigation and Adaptation Strategies for Global Change, 22(2), 325–347. https://doi.org/10.1007/s11027-015-9662-z

Kottek, M., Grieser, J., Beck, C., Rudolf, B., & Rubel, F. (2006). World map of the Köppen-Geiger climate classification updated. Meteorologische Zeitschrift, 15(3), 259–263. https://doi.org/10.1127/0941-2948/2006/0130

Koutroulis, A. G., Papadimitriou, L. V., Grillakis, M. G., Tsanis, I. K., Wyser, K., & Betts, R. A. (2018). Freshwater vulnerability under high end climate change. A pan-European assessment. Science of the Total Environment, 613–614, 271–286. https://doi.org/10.1016/j.scitotenv.2017.09.074

Kriegler, E., O'Neill, B. C., Hallegatte, S., Kram, T., Lempert, R. J., Moss, R. H., & Wilbanks, T. (2012). The need for and use of socio-economic scenarios for climate change analysis: A new approach based on shared socio-economic pathways. Global Environmental Change, 22(4), 807–822. https://doi.org/10.1016/j.gloenvcha.2012.05.005

Krook-Riekkola, A., Berg, C., Ahlgren, E. O., & Söderholm, P. (2017). Challenges in top-down and bottom-up soft-linking: Lessons from linking a Swedish energy system model with a CGE model. Energy, 141. https://doi.org/10.1016/j.energy.2017.09.107

Kundzewicz, Z. W., Mata, I. J., Arnell, N. W., Döll, P., Jimenez, B., Miller, K., … Shiklomanov, I. (2008). The implications of projected climate change for freshwater resources and their management. Hydrological Sciences Journal, 53(1), 3–10. https://doi.org/10.1623/hysj.53.1.3

Labandeira, X., Labeaga, J., & Rodríguez, M. (2009). An integrated economic and distributional analysis of energy policies. Energy Policy, 37(12), 5776–5786. https://doi.org/10.1016/j.enpol.2009.08.041

Labandeira, X., Linares, P., & Rodríguez, M. (2009). An Integrated Approach to Simulate the Impacts of Carbon Emissions Trading Schemes. The Energy Journal, 30(Special Issue 2: Climate Change Policies After 2012), 217–237. https://doi.org/10.2307/41323217

Labriet, M., Cabal, H., Lechón, Y., Giannakidis, G., & Kanudia, A. (2010). The implementation of the EU renewable directive in Spain. Strategies and challenges. Energy Policy, 38(5), 2272–2281. https://doi.org/10.1016/j.enpol.2009.12.015

Labriet, M., Drouet, L., Vielle, M., Haurie, A., Kanudia, A., & Loulou, R. (2010). Coupled Bottom-Up and Top-Down Modelling to Investigate Cooperative Climate Policies. Montreal: Les Cahiers du GERAD.

Lanz, B., & Rausch, S. (2011). General equilibrium, electricity generation technologies and the cost of carbon abatement: A structural sensitivity analysis. Energy Economics, 33(5), 1035–1047. https://doi.org/10.1016/j.eneco.2011.06.003

Leggett, J., Pepper, W. J., Swart, R. J., Edmonds, J., Filho, L. G. M., Mintzer, I., … Watson, J. (1992). Emissions Scenarios for the IPCC: an Update. In Climate Change 1992: The Supplementary Report to The IPCC Scientific Assessment (pp. 68–95). Cambridge University Press.

Lehner, B., Czisch, G., & Vassolo, S. (2005). The impact of global change on the hydropower potential of Europe: a model-based analysis. Energy Policy, 33(7), 839–855. https://doi.org/10.1016/j.enpol.2003.10.018

Lehner, B., Döll, P., Alcamo, J., Henrichs, T., & Kaspar, F. (2006). Estimating the Impact of Global Change on Flood and Drought Risks in Europe: A Continental, Integrated Analysis. Climatic Change, 75(3), 273–299. https://doi.org/10.1007/s10584-006-6338-4

Lehner, F., Coats, S., Stocker, T. F., Pendergrass, A. G., Sanderson, B. M., Raible, C. C., & Smerdon, J. E. (2017). Projected drought risk in 1.5°C and 2°C warmer climates. Geophysical Research Letters, 44(14), 7419–7428. https://doi.org/10.1002/2017GL074117

Leibowicz, B. D., Krey, V., & Grubler, A. (2016). Representing spatial technology diffusion in an energy system optimization model. Technological Forecasting and Social Change, 103, 350–363. https://doi.org/http://dx.doi.org/10.1016/j.techfore.2015.06.001

Liu, Y., Hu, X., Zhang, Q., & Zheng, M. (2017). Improving agricultural water use efficiency: A quantitative study of Zhangye City using the static CGE model with a ces water-land resources account. Sustainability (Switzerland), 9(2). https://doi.org/10.3390/su9020308

Liu, Y., & Lu, Y. (2015). The Economic impact of different carbon tax revenue recycling schemes in China: A model-based scenario analysis. Applied Energy, 141(1), 96–105. https://doi.org/10.1016/j.apenergy.2014.12.032

Llop, M., & Ponce-Alifonso, X. (2012). A never-ending debate: demand versus supply water policies. A CGE analysis for Catalonia. Water Policy, 14(4), 694 LP-708.

Lobanova, A., Koch, H., Liersch, S., Hattermann, F. F., & Krysanova, V. (2016). Impacts of changing climate on the hydrology and hydropower production of the Tagus River basin. Hydrological Processes, 30(26), 5039–5052. https://doi.org/10.1002/hyp.10966

López-Moreno, J. I., Beniston, M., & García-Ruiz, J. M. (2008). Environmental change and water management in the Pyrenees: Facts and future perspectives for Mediterranean mountains. Global and Planetary Change, 61(3), 300–312. https://doi.org/10.1016/j.gloplacha.2007.10.004

López-Moreno, J. I., Fassnacht, S. R., Heath, J. T., Musselman, K. N., Revuelto, J., Latron, J., … Jonas, T. (2013). Small scale spatial variability of snow density and depth over complex alpine terrain: Implications for estimating snow water equivalent. Advances in Water Resources, 55, 40–52. https://doi.org/10.1016/j.advwatres.2012.08.010

López-Moreno, J. I., Vicente-Serrano, S. M., Angulo-Martínez, M., Beguería, S., & Kenawy, A. (2010). Trends in daily precipitation on the northeastern Iberian Peninsula, 1955-2006. International Journal of Climatology, 30(7), 1026–1041. https://doi.org/10.1002/joc.1945

Loulou, R., & Goldstein, G. (2005). Documentation for the TIMES model. Part I - TIMES concepts and theory. Energy Technology Systems Analysis Programme (ETSAP).

Luckmann, J., Flaig, D., Grethe, H., & Siddig, K. (2016). Modelling Sectorally Differentiated Water Prices - Water Preservation and Welfare Gains Through Price Reform? Water Resources Management, 30(7), 2327–2342. https://doi.org/10.1007/s11269-015-1204-7

Luckmann, J., Grethe, H., McDonald, S., Orlov, A., & Siddig, K. (2014). An integrated economic model of multiple types and uses of water. Water Resources Research, 50(5), 3875–3892. https://doi.org/10.1002/2013WR014750

Luis, M., González-Hidalgo, J. C., Longares, L. A., & Stepánek, P. (2009). Seasonal precipitation trends in the Mediterranean Iberian Peninsula in second half of 20th century. International Journal of Climatology, 29, 1312–1323. https://doi.org/10.1002/joc

Macknick, J., Newmark, R., Heath, G., & Hallett, K. C. (2012). Operational water consumption and withdrawal factors for electricity generating technologies: A review of existing literature. Environmental Research Letters, 7(4). https://doi.org/10.1088/1748-9326/7/4/045802

Mahmood, A., & Marpaung, C. (2014). Carbon pricing and energy efficiency improvement -- Why to miss the interaction for developing economies? An illustrative CGE based application to the pakistan case. Energy Policy, 67, 87–103. https://doi.org/10.1016/j.enpol.2013.09.072

Majone, B., Villa, F., Deidda, R., & Bellin, A. (2016). Impact of climate change and water use policies on hydropower potential in the south-eastern Alpine region. Science of the Total Environment, 543, 965–980. https://doi.org/10.1016/j.scitotenv.2015.05.009

MAOTE. (2015). Compromisso para o Crescimento Verde [Commitment to Green Growth]. Lisboa: Ministry of the Environment, Spatial Planning and Energy.

MARETEC. (2016). MOHID. Retrieved from http://www.maretec.mohid.com/. Accessed September 2016

Martinsen, T. (2011). Introducing technology learning for energy technologies in a national CGE model through soft links to global and national energy models. Energy Policy, 39(6), 3327–3336. https://doi.org/https://doi.org/10.1016/j.enpol.2011.03.025

Masui, T., Matsumoto, K., Hijioka, Y., Kinoshita, T., Nozawa, T., Ishiwatari, S., … Kainuma, M. (2011). An emission pathway for stabilization at 6 Wm−2 radiative forcing. Climatic Change, 109(1), 59. https://doi.org/10.1007/s10584-011-0150-5

Mekonnen, M. M., & Hoekstra, A. Y. (2012). The blue water footprint of electricity from hydropower. Hydrology and Earth System Sciences, 16(1), 179–187. https://doi.org/10.5194/hess-16-179-2012

Melo, J. de, & Tarr, D. (1992). A general equilibrium analysis of foreign exchange shortages in a developing country. Economic Journal, 91, 891–906.

Messner, S., & Schrattenholzer, L. (2000). MESSAGE–MACRO: linking an energy supply model with a macroeconomic module and solving it iteratively. Energy, 25, 267–282.

Michaelides, S., Karacostas, T., Sánchez, J. L., Retalis, A., Pytharoulis, I., Homar, V., … Nisantzi, A. (2017). Reviews and perspectives of high impact atmospheric processes in the Mediterranean. Atmospheric Research, (July), 0–1. https://doi.org/10.1016/j.atmosres.2017.11.022

Mideksa, T. K., & Kallbekken, S. (2010). The impact of climate change on the electricity market: A review. Energy Policy, 38(7), 3579–3585. https://doi.org/10.1016/j.enpol.2010.02.035

Milliman, J. D. (2001). River Inputs. In Encyclopedia of Ocean Sciences, Second Edition. Elsevier B.V.

Milly, P. C. D., Dunne, K. A., & Vecchia, A. V. (2005). Global pattern of trends in streamflow and water availability in a changing climate. Nature, 438, 347–350. https://doi.org/10.1038/nature04312

Mourato, S., Moreira, M., & Corte-Real, J. (2014). Water Availability in Southern Portugal for Different Climate Change Scenarios Subjected To Bias Correction. Journal of Urban and Environmental Engineering, 8(1), 109–117. https://doi.org/10.4090/juee.2014.v8n1.109117

Mukheibir, P. (2013). Potential consequences of projected climate change impacts on hydroelectricity generation. Climatic Change, 121(1), 67–78. https://doi.org/10.1007/s10584-013-0890-5

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., … Zhang, H. (2013). Anthropogenic and natural radiative forcing. In T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, … P. M. Midgley (Eds.), Climate Change 2013 the Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA.: Cambridge University Press. https://doi.org/10.1017/CBO9781107415324.018

Nakata, T. (2004). Energy-economic models and the environment. Progress in Energy and Combustion Science, 30(4), 417–475. https://doi.org/10.1016/j.pecs.2004.03.001

Nakata, T., Silva, D., & Rodionov, M. (2011). Application of energy system models for designing a low-carbon society. Progress in Energy and Combustion Science, 37(4), 462–502. https://doi.org/10.1016/j.pecs.2010.08.001

Nash, L. L., & Gleick, P. H. (1993). The Colorado River Basin and Climatic Change: The Sensitivity of Streamflow and Water Supply to Variations in Temperature and Precipitation. US Environmental Protection Agency. Washington, D.C.

Nechifor, V., & Winning, M. (2017). Projecting irrigation water requirements across multiple socio-economic development futures – A global CGE assessment. Water Resources and Economics, 20(February), 16–30. https://doi.org/10.1016/j.wre.2017.09.003

Nguene, G., Fragnière, E., Kanala, R., Lavigne, D., & Moresino, F. (2011). SOCIO-MARKAL: Integrating energy consumption behavioral changes in the technological optimization framework. Energy for Sustainable Development, 15(1), 73–83. https://doi.org/10.1016/j.esd.2011.01.006

Nunes, P., Seixas, J., & Pacheco, N. R. (2008). Vulnerability of water resources, vegetation productivity and soil erosion to climate change in Mediterranean watersheds. Hydrological Processes, 22, 3115–3134. https://doi.org/10.1002/hyp

OECD/IEA. (2015a). Energy Technology Perspectives 2015. Paris: International Energy Agency.

OECD/IEA. (2015b). Energy Technology Perspectives 2015. Paris: International Energy Agency. https://doi.org/10.1016/j.energy.2014.04.084

OECD. (2015). The Economic Consequences of Climate Change. Paris: OECD Publishing. https://doi.org/10.1787/9789264235410-en

OECD. (2016). Policy Guidance on Resource Efficiency. Paris: OECD Publishing. https://doi.org/10.1787/9789264257344-en.

Okagawa, A., & Ban, K. (2008). Estimation of substitution elasticities for CGE models. (Discussion Papers In Economics And Business (no. 08-16)). Osaka School of International Public Policy.

Orlowsky, B., & Seneviratne, S. I. (2012). Global changes in extreme events: Regional and seasonal dimension. Climatic Change, 110(3–4), 669–696. https://doi.org/10.1007/s10584-011-0122-9

Ozturk, T., Ceber, Z. P., Türkeş, M., & Kurnaz, M. L. (2015). Projections of climate change in the Mediterranean Basin by using downscaled global climate model outputs. International Journal of Climatology, 35(14), 4276–4292. https://doi.org/10.1002/joc.4285

Paltsev, S. (2004). MIT Joint Program on the Science and Policy of Global Change Improving the Refining Sector in EPPA. Joint Program Technical Note TN #4. https://doi.org/10.1016/j.enpol.2013.04.026

Paltsev, S., Reilly, J. M., Jacoby, H. D., Eckaus, R. S., Mcfarland, J., Sarofim, M., … No, R. (2005). The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4. MIT Joint Program on the Science and Policy of Global Change Report No. 125.

Pandey, R. (2002). Energy policy modelling: Agenda for developing countries. Energy Policy, 30(2), 97–106. https://doi.org/10.1016/S0301-4215(01)00062-3

Papadimitriou, L. V., Koutroulis, A. G., Grillakis, M. G., & Tsanis, I. K. (2016). High-end climate change impact on European runoff and low flows - Exploring the effects of forcing biases. Hydrology and Earth System Sciences, 20(5), 1785–1808. https://doi.org/10.5194/hess-20-1785-2016

Pascale, S., Lucarini, V., Feng, X., Porporato, A., & ul Hasson, S. (2016). Projected changes of rainfall seasonality and dry spells in a high greenhouse gas emissions scenario. Climate Dynamics, 46(3), 1331–1350. https://doi.org/10.1007/s00382-015-2648-4

Paxian, A., Hertig, E., Seubert, S., Vogt, G., Jacobeit, J., & Paeth, H. (2015). Present-day and future mediterranean precipitation extremes assessed by different statistical approaches. Climate Dynamics, 44(3), 845–860. https://doi.org/10.1007/s00382-014-2428-6

Pepper, W. J., Leggett, R. J., Swart, R. J., Wasson, J., Edmonds, J., & Mintzer, I. (1992). Emission Scenarios for the IPCC An Update, Assumptions, Methodology, and Results. US Environmental Protection Agency. Washington, D.C.

Pereira-Cardenal, S. J., Madsen, H., Arnbjerg-Nielsen, K., Riegels, N., Jensen, R., Mo, B., … Bauer-Gottwein, P. (2014). Assessing climate change impacts on the Iberian power system using a coupled water-power model. Climatic Change, 126(3–4), 351–364. https://doi.org/10.1007/s10584-014-1221-1

Pereira, A. M., Pereira, R. M., & Rodrigues, P. G. (2016). A new carbon tax in Portugal: A missed opportunity to achieve the triple dividend? Energy Policy, 93, 110–118. https://doi.org/10.1016/j.enpol.2016.03.002

Pérez-Blanco, C. D., Standardi, G., Mysiak, J., Parrado, R., & Gutiérrez-Martín, C. (2016). Incremental water charging in agriculture. A case study of the Regione Emilia Romagna in Italy. Environmental Modelling and Software, 78, 202–215. https://doi.org/10.1016/j.envsoft.2015.12.016

Pfenninger, S., Hawkes, A., & Keirstead, J. (2014). Energy systems modeling for twenty-first century energy challenges. Renewable and Sustainable Energy Reviews, 33, 74–86. https://doi.org/10.1016/j.rser.2014.02.003

PNAEE. (2017). Plano Nacional de Acção para a Eficiência Energética - Resultados [National Energy Efficiency Action Plan - Results]. Retrieved from http://www.pnaee.pt/pnaee#resultadospnaee. Accessed July 2016

Pollitt, H., Barker, A., Barton, J., Pirgmaier, E., Polzin, C., Lutter, S., … Stocker, A. (2010). A scoping study on the macroeconomic view of sustainability - Final report for the European Commission, DG Environment. Cambridge: Cambridge Econometrics.

Ponce, R., Bosello, F., & Giupponi, C. (2012). Integrating water resources into computable general equilibrium models – a survey. Fondazione Eni Enrico Mattei. Nota di lavoro 2012.057.

Proença, S. (2013). Impact Assessment of Energy and Climate Policies A Hybrid Bottom-up General Equilibrium Model (HyBGEM) for Portugal. PhD Thesis. Instituto Superior de Economia e Gestão. Universidade Técnica de Lisboa. Lisboa.

Proença, S., & St. Aubyn, M. (2013). Hybrid modeling to support energy-climate policy: Effects of feed-in tariffs to promote renewable energy in Portugal. Energy Economics, 38, 176–185. https://doi.org/10.1016/j.eneco.2013.02.013

Prudhomme, C., Giuntoli, I., Robinson, E. L., Clark, D. B., Arnell, N. W., Dankers, R., … Wisser, D. (2014). Hydrological droughts in the 21st century, hotspots and uncertainties from a global multimodel ensemble experiment. Proceedings of the National Academy of Sciences, 111(9), 3262–3267. https://doi.org/10.1073/pnas.1222473110

Pulquério, M., Garrett, P., Santos, F. D., & Cruz, M. J. (2014). On using a generalized linear model to downscale daily precipitation for the center of Portugal: an analysis of trends and extremes. Theoretical and Applied Climatology, 120(1), 147–158. https://doi.org/10.1007/s00704-014-1156-5

Qin, C., Jia, Y., Su, Z. (Bob), Bressers, H. T. A., & Wang, H. (2012). The economic impact of water tax charges in China: a static computable general equilibrium analysis. Water International, 37(3), 279–292. https://doi.org/10.1080/02508060.2012.685554

Rasilla, D. F., Garmendia, C., & García-Codron, J. C. (2013). Climate change projections of streamflow in the Iberian peninsula. International Journal of Water Resources Development, 29(2), 184–200. https://doi.org/10.1080/07900627.2012.721716

RCM 20/2013. (2013). Resolução do Conselho de Ministros n.º 20/2013 [Resolution of Council of Ministers no. 20/2013]. Diário da República, 1.ª série — N.º 70 — 10 de abril de 2013. https://doi.org/10.3000/17252555.L_2009.140.eng

RCM 56/2015. (2015). Resolução do Conselho de Ministros n.º 56/2015 [Resolution of Council of Ministers no. 56/2015]. Diário da República, 1.ª série — N.º 147 — 30 de julho de 2015.

REN. (2015). Hydropower Capacity Factor in Portugal, 1971-2014 (Personal communication). Redes Energéticas Nacionais.

REN. (2016). Caracterização da RNT para efeitos de acesso à rede [Characterization of the National Transmission Network for network access purposes]. Lisboa: Redes Energéticas Nacionais [In Portuguese]. Retrieved from http://www.centrodeinformacao.ren.pt/PT/publicacoes/CaracterizacaoRNT/CaracterizacaodaRNT2015.pdf

REN21. (2011). Renewables 2011. Global Satus Report. Paris: REN21 Secretariat.

REN21. (2014). The First Decade: 2004-2014, 10 Years of Renewable Energy Progress. Paris: REN21 Secretariat. https://doi.org/9783981593440

Reynaud, A. (2015). Modelling Household Water Demand in Europe. Insights from a Cross-Country Econometric Analysis of EU-28 countries 2015. Joint Research Centre - Institute for Environment and Sustainability. Luxembourg: Publications Office of the European Union. https://doi.org/10.2788/95638

Riahi, K., Grübler, A., & Nakicenovic, N. (2007). Scenarios of long-term socio-economic and environmental development under climate stabilization. Technological Forecasting and Social Change, 74(7), 887–935. https://doi.org/10.1016/j.techfore.2006.05.026

Riahi, K., Rao, S., Krey, V., Cho, C., Chirkov, V., Fischer, G., … Rafaj, P. (2011). RCP 8.5-A scenario of comparatively high greenhouse gas emissions. Climatic Change, 109(1), 33–57. https://doi.org/10.1007/s10584-011-0149-y

Rivers, N., & Groves, S. (2013). The Welfare Impact of Self-supplied Water Pricing in Canada: A Computable General Equilibrium Assessment. Environmental and Resource Economics, 55(3), 419–445. https://doi.org/10.1007/s10640-013-9633-3

Rivers, N., & Jaccard, M. (2005). Combining Top-Down and Bottom-Up Approaches To Energy-Economy Modeling Using Discrete Choice Methods. The Energy Journal, 26(1), 83–106.

Rodrigo, F., & Trigo, R. M. (2007). Trends in daily rainfall in the Iberian Peninsula from 1951 to 2002. International Journal of Climatology, 27, 513–529. https://doi.org/10.1002/joc

Roe, T., Dinar, A., Tsur, Y., & Diao, X. (2005). Feedback links between economy-wide and farm-level policies: With application to irrigation water management in Morocco. Journal of Policy Modeling, 27(8), 905–928. https://doi.org/10.1016/j.jpolmod.2005.05.007

Rose, A., Liao, S.-Y., & Bonneau, A. (2011). Regional Economic Impacts of a Verdugo Scenario Earthquake Disruption of Los Angeles Water Supplies: A Computable General Equilibrium Analysis. Earthquake Spectra, 27(3), 881–906. https://doi.org/10.1193/1.3610245

Rosenthal, R. (2012). *GAMS | A User's Guide*. (GAMS Development Corporation, Ed.). Washington, DC, USA.

Roson, R. (2006). Introducing imperfect competition in CGE models: Technical aspects and implications. Computational Economics, 28(1), 29–49. https://doi.org/10.1007/s10614-006-9034-6

Roson, R. (2017). Simulating the Macroeconomic Impact of Future Water Scarcity. Discussion Paper. World Bank, Washington, DC.

Roson, R., & Damania, R. (2017). Simulating the macroeconomic impact of future water scarcity. Journal of Policy Modeling, 39(6), 1–21. https://doi.org/10.1016/j.jpolmod.2017.10.003

Roson, R., & Sartori, M. (2014). Climate change, tourism and water resources in the Mediterranean. International Journal of Climate Change Strategies and Management, 6(2), 212–228. https://doi.org/10.1108/IJCCSM-01-2013-0001

Roson, R., & Sartori, M. (2015). System-Wide Implications of Changing Water Availability and Agricultural Productivity in the Mediterranean Economies. Water Economics and Policy, 01(01), 1450001. https://doi.org/10.1142/S2382624X14500015

Roson, R., & van der Mensbrugghe, D. (2012). Climate change and economic growth: impacts and interactions. International Journal of Sustainable Economy, 4(3), 270–285. https://doi.org/10.1504/IJSE.2012.047933

Roudier, P., Andersson, J. C. M., Donnelly, C., Feyen, L., Greuell, W., & Ludwig, F. (2016). Projections of future floods and hydrological droughts in Europe under a +2°C global warming. Climatic Change, 135(2), 341–355. https://doi.org/10.1007/s10584-015-1570-4

Rübbelke, D., & Vögele, S. (2012). Short-term distributional consequences of climate change impacts on the power sector: who gains and who loses? Climatic Change, 116(2), 191–206. https://doi.org/10.1007/s10584-012-0498-1

Rutherford, T. (1999). Applied General Equilibrium Modeling with MPSGE as a GAMS Subsystem: An Overview of the Modeling Framework and Syntax. Computational Economics, 14(1–2), 1–46. https://doi.org/10.1023/A:1008655831209

San José, R., Pérez, J. L., González, R. M., Pecci, J., Garzón, A., & Palacios, M. (2015). Impacts of the 4.5 and 8.5 RCP global climate scenarios on urban meteorology and air quality: Application to Madrid, Antwerp, Milan, Helsinki and London. Journal of Computational and Applied Mathematics, 293, 192–207. https://doi.org/10.1016/j.cam.2015.04.024

Santos, C. C. (2014). Analysing hydrological services provided by forests to support spatial planning and land management. PhD Thesis, University of Porto. Porto.

Santos, F. D., Forbes, K., & Moita, R. (2002). Climate Change in Portugal. Scenarios, Impacts and Adaptation Measures - SIAM Project. (R. M. Santos, F. D., Forbes, K., Ed.). Lisboa, Portugal: Gradiva.

Santos, F. D., & Miranda, P. (2006). Alterações Climáticas em Portugal - Cenários, Impactos e Medidas - Projecto SIAMII [Climate change in Portugal - Scenarios, Impacts and Adaptation Measures - SIAM II Project]. (F.D. Santos e P. Miranda, Ed.). Lisboa, Portugal: Gradiva.

Santos, J. A., Corte-Real, J., Ulbrich, U., & Palutikof, J. (2007). European winter precipitation extremes and large-scale circulation: a coupled model and its scenarios. Theoretical and Applied Climatology, 87(1), 85–102. https://doi.org/10.1007/s00704-005-0224-2

Saveyn, B., Van Regemorter, D., & Ciscar, J. C. (2011). Economic analysis of the climate pledges of the Copenhagen Accord for the EU and other major countries. Energy Economics, 33(December 2009), S34–S40. https://doi.org/10.1016/j.eneco.2011.07.024

Schaeffer, R., Szklo, A. S., Pereira de Lucena, A. F., Moreira Cesar Borba, B. S., Pupo Nogueira, L. P., Fleming, F. P., … Boulahya, M. S. (2012). Energy sector vulnerability to climate change: A review. Energy, 38(1), 1–12. https://doi.org/10.1016/j.energy.2011.11.056

Schaefli, B. (2015). Projecting hydropower production under future climates: a guide for decision-makers and modelers to interpret and design climate change impact assessments. Wiley Interdisciplinary Reviews: Water, 2(4), 271–289. https://doi.org/10.1002/wat2.1083

Scherer, L., & Pfister, S. (2016). Global water footprint assessment of hydropower. Renewable Energy, 99, 711–720. https://doi.org/10.1016/j.renene.2016.07.021

Schneider, C., Laizé, C. L. R., Acreman, M. C., & Flörke, M. (2013). How will climate change modify river flow regimes in Europe? Hydrology and Earth System Sciences, 17(1), 325–339. https://doi.org/10.5194/hess-17-325-2013

Scoccimarro, E., Gualdi, S., Bellucci, A., Zampieri, M., & Navarra, A. (2016). Heavy precipitation events over the Euro-Mediterranean region in a warmer climate: results from CMIP5 models. Regional Environmental Change, 16(3), 595–602. https://doi.org/10.1007/s10113-014-0712-y

Seixas, J., Fortes, P., Dias, L., Dinis, R., Alves, B., Gouveia J., & S., S. (2012). Roteiro Nacional de Baixo Carbono: Portugal 2050 - Modelação de gases com efeito estufa, Energia e Resíduos [Low Carbon RoadMap: Portugal 2050 - Energy and Waste Greenhouse emissions]. Lisboa. Retrieved from http://www.apambiente.pt/_zdata/RNCB/EnergiaResiduos_10_07.pdf

Seljom, P., Rosenberg, E., Fidje, A., Haugen, J. E., Meir, M., Rekstad, J., & Jarlset, T. (2011). Modelling the effects of climate change on the energy system—A case study of Norway. Energy Policy, 39(11), 7310–7321. https://doi.org/10.1016/j.enpol.2011.08.054

Seung, C. K., Harris, T. R., Englin, J. E., & Netusil, N. R. (2000). Impacts of water reallocation: A combined computable general equilibrium and recreation demand model approach. The Annals of Regional Science, 34(4), 473–487. https://doi.org/10.1007/s001689900011

Simões, S., Cleto, J., Fortes, P., Seixas, J., & Huppes, G. (2008). Cost of energy and environmental policy in Portuguese CO2 abatement—scenario analysis to 2020. Energy Policy, 36(9), 3598–3611. https://doi.org/10.1016/j.enpol.2008.06.004

Simões, S. J., & Barros, A. P. (2007). Regional hydroclimatic variability and Brazil's 2001 energy crisis. Management of Environmental Quality: An International Journal, 18(3), 263–273. https://doi.org/10.1108/14777830710731734

Smajgl, A. (2006). Quantitative evalutaion of water use benefits – an integrative modeling approach for the Great Barrier Reef region. Natural Resource Modeling, 19(4), 511–538. https://doi.org/10.1111/j.1939-7445.2006.tb00192.x

Smajgl, A., Morris, S., & Heckbert, S. (2009). Water Policy Impact Assessment – Combining Modelling Techniques in the Great Barrier Reef Region. In A. Zerger & R. M. Argent (Eds.), MODSIM 2005 International Congress on Modeling and Simulation. Modeling and Simulation Society of Australia and New Zealand (pp. 1985–1991).

Solís, A. F., & Zhu, X. (2015). Water Markets: Insights from an Applied General Equilibrium Model for Extremadura, Spain. Water Resources Management, 29(12), 4335–4356. https://doi.org/10.1007/s11269-015-1063-2

Stagge, J. H., Rizzi, J., Tallaksen, L. M., & Stahl, K. (2015). Future Meteorological Drought: Projections of Regional Climate Models for Europe, Technical Report No. 25, (25). Retrieved from http://www.eu-drought.org/

Strachan, N., & Kannan, R. (2008). Hybrid modelling of long-term carbon reduction scenarios for the UK. Energy Economics, 30(6), 2947–2963. https://doi.org/10.1016/j.eneco.2008.04.009

Swan, L. G., & Ugursal, V. I. (2009). Modeling of end-use energy consumption in the residential sector: A review of modeling techniques. Renewable and Sustainable Energy Reviews, 13(8), 1819–1835. https://doi.org/10.1016/j.rser.2008.09.033

Tapiador, F. J., Hou, A. Y., de Castro, M., Checa, R., Cuartero, F., & Barros, A. P. (2011). Precipitation estimates for hydroelectricity. Energy & Environmental Science, 4, 4435–4448. https://doi.org/10.1039/c1ee01745d

Tarroja, B., AghaKouchak, A., & Samuelsen, S. (2016). Quantifying climate change impacts on hydropower generation and implications on electric grid greenhouse gas emissions and operation. Energy, 111, 295–305. https://doi.org/10.1016/j.energy.2016.05.131

Teotónio, C., Fortes, P., Roebeling, P., Rodriguez, M., & Robaina-Alves, M. (2017). Assessing the impacts of climate change on hydropower generation and the power sector in Portugal: A partial equilibrium approach. Renewable and Sustainable Energy Reviews, 74, 788–799. https://doi.org/10.1016/j.rser.2017.03.002

Thomson, A. M., Calvin, K. V, Smith, S. J., Kyle, G. P., Volke, A., Patel, P., … Edmonds, J. A. (2011). RCP4.5: a pathway for stabilization of radiative forcing by 2100. Climatic Change, 109(1), 77–94. https://doi.org/10.1007/s10584-011-0151-4

Tian, X., Dai, H., Geng, Y., Huang, Z., Masui, T., & Fujita, T. (2017). The effects of carbon reduction on sectoral competitiveness in China: A case of Shanghai. Applied Energy, 197, 270–278. https://doi.org/10.1016/j.apenergy.2017.04.026

Tirado, D., Lozano, J., & Gómez, C. M. (2010). Economic regional impacts of water transfers: the role of factor mobility in a case study of the agricultural sector in the Balearic Islands. Economía Agraria y Recursos Naturales, 10(2), 41–59. https://doi.org/10.7201/earn.2010.02.03

Tuladhar, S. D., Yuan, M., Bernstein, P., Montgomery, W. D., & Smith, A. (2009). A top–down bottom–up modeling approach to climate change policy analysis. Energy Economics, 31, S223–S234. https://doi.org/10.1016/j.eneco.2009.07.007

Turner, S. W. D., Ng, J. Y., & Galelli, S. (2017). Examining global electricity supply vulnerability to climate change using a high-fidelity hydropower dam model. Science of the Total Environment, 590–591, 663–675. https://doi.org/10.1016/j.scitotenv.2017.03.022

Turral, H., Svendsen, M., & Faures, J. M. (2010). Investing in irrigation: Reviewing the past and looking to the future. Agricultural Water Management, 97(4), 551–560. https://doi.org/10.1016/j.agwat.2009.07.012

UN. (2016). GHG Inventories. National Inventory Submissions. Retrieved from http://unfccc.int/files/national_reports/annex_i_ghg_inventories/

Vaillancourt, K., Alcocer, Y., Bahn, O., Fertel, C., Frenette, E., Garbouj, H., … Waaub, J. P. (2014). A Canadian 2050 energy outlook: Analysis with the multi-regional model TIMES-Canada. Applied Energy, 132, 56–65. https://doi.org/10.1016/j.apenergy.2014.06.072

Valverde, P., Serralheiro, R., de Carvalho, M., Maia, R., Oliveira, B., & Ramos, V. (2015). Climate change impacts on irrigated agriculture in the Guadiana river basin (Portugal). Agricultural Water Management, 152, 17–30. https://doi.org/10.1016/j.agwat.2014.12.012

van Beeck, N. (1999). Classification of Energy Models. Tilburg University & Eindhoven University of Technology.

van Vliet, M. T. H., Donnelly, C., Strömbäck, L., Capell, R., & Ludwig, F. (2015). European scale climate information services for water use sectors. Journal of Hydrology, 528, 503–513. https://doi.org/10.1016/j.jhydrol.2015.06.060

van Vliet, M. T. H., van Beek, L. P. H., Eisner, S., Flörke, M., Wada, Y., & Bierkens, M. F. P. (2016). Multi-model assessment of global hydropower and cooling water discharge potential under climate change. Global Environmental Change, 40, 156–170. https://doi.org/10.1016/j.gloenvcha.2016.07.007

van Vliet, M. T. H., Vögele, S., & Rübbelke, D. (2013). Water constraints on European power supply under climate change: impacts on electricity prices. Environmental Research Letters, 8, 035010 (10pp). https://doi.org/10.1088/1748-9326/8/3/035010

van Vliet, M. T. H., Wiberg, D., Leduc, S., & Riahi, K. (2016). Power-generation system vulnerability and adaptation to changes in climate and water resources. Nature Climate Change, 6, 375–380.

van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., … Rose, S. K. (2011). The representative concentration pathways: An overview. Climatic Change, 109(1), 5–31. https://doi.org/10.1007/s10584-011-0148-z

van Vuuren, D. P., Hoogwijk, M., Barker, T., Riahi, K., Boeters, S., Chateau, J., … Kram, T. (2009). Comparison of top-down and bottom-up estimates of sectoral and regional greenhouse gas emission reduction potentials. Energy Policy, 37(12), 5125–5139. https://doi.org/10.1016/j.enpol.2009.07.024

van Vuuren, D. P., Stehfest, E., den Elzen, M. G. J., Kram, T., van Vliet, J., Deetman, S., … van Ruijven, B. (2011). RCP2.6: exploring the possibility to keep global mean temperature increase below 2°C. Climatic Change, 109(1), 95. https://doi.org/10.1007/s10584-011-0152-3

Vautard, R., Gobiet, A., Sobolowski, S., Kjellström, E., Stegehuis, A., Watkiss, P., … Jacob, D. (2014). The European climate under a 2 °c global warming. Environmental Research Letters, 9(3). https://doi.org/10.1088/1748-9326/9/3/034006

Watson, P. S., & Davies, S. (2011). Modeling the effects of population growth on water resources: A CGE analysis of the South Platte River Basin in Colorado. Annals of Regional Science, 46(2), 331–348. https://doi.org/10.1007/s00168-009-0326-3

WEC. (2016). World Energy Resources: Hydropower | 2016. London: World Energy Council.

Wei, T., & Liu, Y. (2017). Estimation of global rebound effect caused by energy efficiency improvement. Energy Economics, 66, 27–34. https://doi.org/10.1016/j.eneco.2017.05.030

Wing, I. (2006). The synthesis of bottom-up and top-down approaches to climate policy modeling: Electric power technologies and the cost of limiting US CO2 emissions. Energy Policy, 34(18), 3847–3869. https://doi.org/10.1016/j.enpol.2005.08.027

Wing, I. (2008). The synthesis of bottom-up and top-down approaches to climate policy modeling: Electric power technology detail in a social accounting framework. Energy Economics, 30(2), 547–573. https://doi.org/10.1016/j.eneco.2006.06.004

Wing, I., & Lanzi, E. (2014). Integrated Assessment of Climate Change Impacts. OECD Environment Working Papers, No. 66. OECD Publishing. https://doi.org/10.1787/5jz2qcjsrvzx-en

World Bank. (2018). World Bank Commodity Price Data. Retrieved from http://www.worldbank.org/en/research/commodity-markets. Accessed January 2018

WWAP. (2014). The United Nations World Water Development Report 2014: Water and Energy. Paris: United Nations World Water Assessment Programme. UNESCO.

Yu, X., Moreno-Cruz, J., & Crittenden, J. C. (2015). Regional energy rebound effect: The impact of economy-wide and sector level energy efficiency improvement in Georgia, USA. Energy Policy, 87, 250–259. https://doi.org/10.1016/j.enpol.2015.09.020

Zarfl, C., Lumsdon, A. E., Berlekamp, J., Tydecks, L., & Tockner, K. (2014). A global boom in hydropower dam construction. Aquatic Sciences, 77(1), 161–170. https://doi.org/10.1007/s00027-014-0377-0

Zeitoun, M., Goulden, M., & Tickner, D. (2013). Current and future challenges facing transboundary river basin management. Wiley Interdisciplinary Reviews: Climate Change, 4(5), 331–349. https://doi.org/10.1002/wcc.228

Zhan, J., Sun, Z., Wang, Z., Chen, J., & Li, Z. (2015). Simulated water productivity in Gansu Province, China. Physics and Chemistry of the Earth, 79–82, 67–75. https://doi.org/10.1016/j.pce.2015.02.003

Zhao, J., Ni, H., Peng, X., Li, J., Chen, G., & Liu, J. (2016). Impact of water price reform on water conservation and economic growth in China. Economic Analysis and Policy, 51, 90–103. https://doi.org/10.1016/j.eap.2016.06.003

Zhong, S., Shen, L., Liu, L., Zhang, C., & Shen, M. (2017). Impact analysis of reducing multi-provincial irrigation subsidies in China: a policy simulation based on a CGE model. Water Policy, 19(2), 216–232. https://doi.org/10.2166/wp.2017.052