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

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. 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 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.

Keywords: water resources; 'water-energy' nexus; climate change; computable general equilibrium model

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; UN, 2014). In particular, higher temperatures and evaporation will negatively affect water supply and, simultaneously, increase water demand by the agricultural and energy sectors (UN, 2014).

Projections from the Intergovernmental Panel on Climate Change (IPCC, 2013) 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 et al., 2017a; IPCC, 2013). 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 et al., 2017b; 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)[1].

The reduced availability of water resources is expected to exacerbate the existing competition among different sectors, notably agriculture, energy and urban uses (UN, 2014), as well as among countries sharing common river basins (IEA, 2016; UN, 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 43% of total freshwater withdrawals in Europe (UN, 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 (UN, 2014).

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

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 (UN, 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; UN, 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; UN, 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 et al., 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 and Damania, 2017) or focussed on the agricultural sector (e.g., Calzadilla et al., 2014, 2013a). 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 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 2 is devoted to a literature review on water-oriented CGE models. Section 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 4 presents and describes the considered scenarios regarding competition for water resources between sectors and countries. Section 5 presents and analyses the main results. Finally, Section 6 discusses the simulated impacts, assesses their policy implications and concludes.

2. Literature review

The complex interconnections between water resources and the economy is mostly examined through integrated hydro-economic models (Brouwer et al., 2008). 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 and Lanzi, 2014).

Berck et al., 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 and 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, 2017); broader regions, such as the Mediterranean (Roson and Sartori, 2015, 2014); and the world (Calzadilla et al., 2013a, 2010; Dellink et al., 2017; Roson and Damania, 2017; Roson and van der Mensbrugghe, 2012). Most of these studies considered the climate change scenarios from the IPCC 'SRES scenarios' (Nakicenovic et al., 2000). Impacts arising from the most recent Representative Concentration Pathways (RCPs; van Vuuren et al., 2011) or Shared Socioeconomic Pathways (SSPs; Kriegler et al., 2012) climate change scenarios have not yet been extensively analysed (Roson and 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 and Hewings, 2011; Luckmann et al., 2016; Rivers and Groves, 2013; Zhao et al., 2016); water-related taxes and subsidies (Berrittella et al., 2008; Cazcarro et al., 2011; Qin et al., 2012; Zhong et al., 2017); water use efficiency improvements (Calzadilla et al., 2011; Liu et al., 2017); public investments in the water sector (Llop and Ponce-Alifonso, 2012; Luckmann et al., 2014); introduction of water markets (Berrittella et al., 2007; Hassan and Thurlow, 2011; Solís and Zhu, 2015; Tirado et al., 2010); and sectoral reallocation of water resources (Juana et al., 2011; Seung et al., 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., 2008; Dellink et al., 2011), water infrastructure disruption (Rose et al., 2011), income and population growth pressures on freshwater resources (Jiang et al., 2014; Nechifor and Winning, 2017; Watson and Davies, 2011), and economic growth strategies (Cazcarro et al., 2015). A particular additional form of approaching water in CGE models is through the 'virtual water' concept[2], 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 and Thurlow, 2011), in the agricultural and water supply sectors (Berrittella et al., 2007; Watson and Davies, 2011) or, alternatively, in all economic sectors (Faust et al., 2015; Koopman et al., 2017; Luckmann et al., 2016; Roson and Damania, 2017). Few water-oriented CGE analyses only consider water as an intermediate input provided by the distribution and supply sectors (Llop and 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 et al., 2014, 2013a, 2013b, 2010; 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, 2013b; Roson and 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 and Zhu, 2015; Zhan et al., 2015), or isolating water to

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[2] 'Virtual water' consumption is the direct and indirect usage of water associated with the production or consumption of any good or service (Allan; J.A., 1992).

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 et al., 2016; Cakmak et al., 2008; Roe et al., 2005), hydrological models (Smajgl, 2006), agent-based models (Smajgl et al., 2009) and revealed preference models (Pérez-Blanco et al., 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 et al., 2013a, 2011) or multifactor productivity (e.g. Galeotti and Roson, 2012; Roson and Damania, 2017; Roson and 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 and Roson, 2012), Switzerland (Faust et al., 2015) and the world (Roson and Damania, 2017), respectively.

Even though this review on water-oriented CGE studies is not exhaustive, the revised literature clearly shows the 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.

3. Methodology

3.1. The model

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 in a soft-link approach with a technology bottom-up model. It relies on the model comprehensively described in Labandeira 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 (Teotonio et al., 2017), and, along with labour and capital, raw water as the third primary factor of production (see Appendix A for further details on 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, 2013)[3].

The main motivation for this research is that climate change will increase water scarcity and it will exacerbate competition for water resources, where the 'water-energy' nexus through the electricity sector is acknowledged as a major challenge for the near future (IEA, 2016). Considering that CGE models do not include the technological detail of the power sector, using solely a CGE approach would not deliver an accurate assessment of the impacts of competition for water between the power sector and the remaining economic sectors. Indeed, it has been highlighted in literature that one of the drawbacks of CGE models is to capture technology

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[3] 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, 2013).

complexity, which should be a central point for simulation exercises of energy and climate change scenarios (see for instance Labandeira et. al., 2009; Fortes et al., 2014; Krook-Riekkola et. al., 2017). Furthermore, due to the lack of time resolution, the seasonal (e.g. hydro) or daily (e.g. solar) variability of renewable resources, which impacts the power mix and the electricity prices, is neglected by CGE models. These limitations of the CGE models can be overcome by bottom-up models of the energy sector that provide a more precise configuration of the power mix and inherent electricity generations costs and prices. For this reason, a soft-link between these two models was established, thus minimizing the economic model drawbacks in assessing the impacts of water availability on the energy sector so as to better capture the effects of increased competition for scarcer water resources. Accordingly, we use an integrated modelling framework by linking the CGE model with the TIMES_PT model, in which: i) TIMES_PT is run to assess the impacts of water availability by providing, for each scenario, the corresponding power mix and electricity generation costs; and ii) these are introduced as external conditions to the CGE model[4] in order to simulate the economy-wide impacts of changes in water resources availability in the light of the 'water-energy' nexus. The two models are, thus, run separately and linked by exchanging data.

TIMES_PT is an optimisation technology-rich bottom-up model (see Fortes et al., 2019). It computes the least cost combination of technologies for the whole energy system that satisfies a given energy services demand (e.g. heating and cooling in residential and services sector, private passengers and freight mobility, cement, paper, iron steel production, among others). TIMES_PT is constituted by more than 2000 technologies, covering the supply and demand side. The availability of renewable resources is disaggregated in 12 annual time-slices (day, night and peak hours for each of the four seasons), reproducing the daily and seasonal variability of the natural resources and including the seasonal availability of hydrological resources (for more information on TIMES-PT, please refer to Fortes et al., 2019). The impact of water availability on the power sector was assessed using TIMES_PT by changing the hydropower capacity factor (HCF) model input parameters, following Teotónio et al. (2017).

In the CGE model 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[5]. This disaggregation of the "Electricity" sector was made according to the cost structure (capital, fuel and labour costs) and the output shares of

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[4] 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.

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

each representative generation technology, as given by the TIMES_PT model. Hence, it was necessary to convert physical units (GWh) from 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.

With this linking approach between TIMES_PT and the CGE, we minimize the CGE model drawbacks when assessing the impacts of water availability on the energy sector. Nevertheless, there are some limitations in this modelling framework that need to be mentioned. On the one hand, although both models rely on common assumptions regarding expected economic development, population growth and energy demand per sector in the BaU scenario (see Section 4.1) as well as energy import prices, they are underpinned by distinct methodologies (bottom-up versus top-down). Therefore, the results from both models may differ (e.g. energy consumption and energy mix by final users, energy prices, etc.) for the counterfactual scenarios (i.e. water availability scenarios). We avoided any interactive procedure in order to reduce concessions needed between the different models' assumptions in this simulation framework, as set for instance by Labandeira et. al. (2009), Fortes et al. (2014) and Krook-Riekkola et. al. (2017). On the other hand, in this research the driver of simulations and shocks is the water-energy nexus and focused on hydro-technology. Consequently, substitution effects from electricity demand to other energy sources are limited (see Section 5 for details on results from the CGE model) and, therefore, the soft link between both models is limited to the impacts on the power sector in TIMES_PT, which are translated to the CGE without the need for any interactive procedure. However, this approach will not be adequate for policies and shocks with a broader impact (e.g. energy and carbon taxes).

Despite the fact that we use the TIMES-PT partial equilibrium model to overcome the CGE limitations with regard to the specification of the power sector, it should be mentioned that TIMES_PT outcomes are driven by its cost-effective nature – ignoring micro-economic behaviour and general equilibrium interactions between agents and sectors. Moreover, electricity prices are represented by the technologies' generation costs and, thus, TIMES_PT does not simulate the behaviour of the current Iberian electricity Market (MIBEL), a spot hourly/daily market matching the marginal bids from suppliers and buyers in a wholesale market known as electricity pool. However, considering that we are simulating impacts for the long run and, furthermore, evolution trends (growth/reduction of electricity price) rather than the exact price, this does not constitute a problem.

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[6]. 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 "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. This assumption implies that the Government will have additional revenues, which will increase the public budget, and may be used to finance the current provision of public goods and services or to attend new expenditures (e.g. related to climate change impacts). The implication of this extra revenue is not significant as this represents only a fraction of the total public budget.

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 and Roson and 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 3.1), water consumption data refers to 2009

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[6] "It is assumed that the substitution possibilities between inputs for raw water extraction is small and, hence, that a Leontief function best represents "raw water" use, which is further justified by the lack of data concerning the elasticities of substitution between capital, energy and labour for the extraction of "raw water". This assumption implies that the impact on prices arising from any disruption in water availability will be higher. Accordingly, our results will be rather conservative in the sense that we are assuming higher costs and impacts than these would be if a CES function would have been considered."

(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[7] (see Brenhas et al., 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 B.

4. Scenarios

4.1. The business-as-usual scenario for 2050

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 (including energy efficiency technological change; from Teotónio et al., 2017), gross domestic product (GDP; APA, 2015), population (APA, 2015) and international fossil fuel prices (IEA, 2015). In particular, the Electricity sector's total output was broken-down according to (i) the cost structure (capital, fuel and labour costs) and ii) the output shares of each representative generation technology projected for 2050 using the TIMES_PT model (Teotónio et al., 2017). Raw water intensities computed for 2008 (see Section 3.2) are assumed to be kept constant for 2050 (a conservative assumption). The resulting sectoral gross value-added (GVA) breakdown is in accordance with existing projections for the year 2050 in Portugal (APA, 2012).

4.2. Water competition 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

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[7] 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 et al., 2012), so, this was not considered in the analysis.

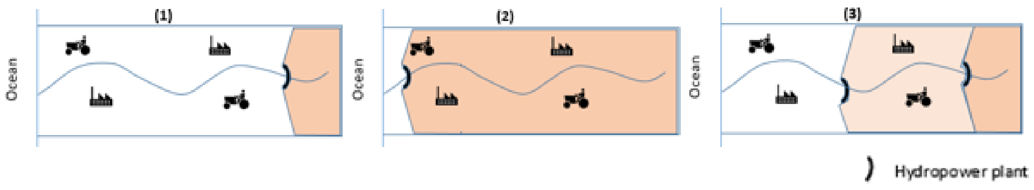
scenarios is developed considering three main assumptions: competition for water resources between users, competition for water resources between countries and climate change scenarios (RCP4.5 and RCP 8.5). This section describes the scenarios building process and their main assumptions.

As for 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): All economic sectors (hydropower generation and the other production sectors) bear the same overall impacts of climate change on water resources availability in Portugal, i.e. there is no competition for water between the hydropower generation sector and other production sectors (as shown in Table 3). Note that these latter other production sectors do compete with each for the scarcer "raw water" production factor, implying an efficient allocation of water resources among them (based on sectoral marginal costs and benefits from water use).
- Scenario 'Total competition' (Comp_): Only hydropower generation bears the impacts of climate change on water resources availability in Portugal, i.e. there is competition for water between the hydropower generation sector and the other production sectors that increase their water consumption in an attempt to maintain pre-climate change activity levels (as shown in Table 3). Hence, hydropower generation bears the cumulative effects of i) reduced water availability associated with climate change and ii) adaptation of the other production sectors (that compete, as before, with each other for the "raw water" production factor). The (Comp_) scenario breaks-down into two sub scenarios, which differ on the assumptions for international competition between Portugal and Spain. The 'Comp_PT' scenario considers there is no competition between the two countries, i.e. Portugal bears the effects of climate change in both countries and the effects of inter-sectoral competition in Portugal only. The 'Comp_PT-SP' scenario considers that there is international competition, i.e. Portugal bears the effects of climate change and inter-sectoral competition in Portugal and Spain."

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 1).

Figure 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 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:

Step 1. Water resources availability in the eight main river basins in Portugal[8] 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

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[8] Minho, Lima, Cávado, Douro, Vouga, Mondego, Tejo and Guadiana river basins

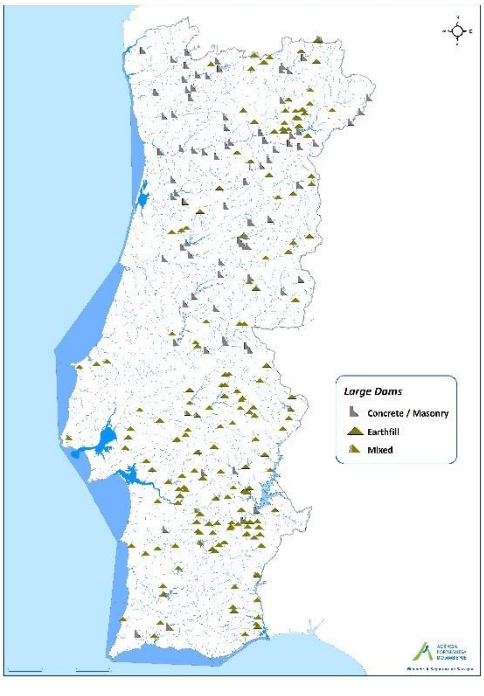
to the river mouth (see Table 1). The relevant water resources for the hydropower sector in Portugal correspond to the sum of water resources coming from Spain and those from the interior river basins upstream of the hydropower plants. Note that water coming from Spain represents around two thirds of the relevant water resources for hydropower generation in Portugal, highlighting the interdependence of Portugal and Spain in water resources management.

Table 1. Water resources per river basin, in Portugal (total flow; hm^3/year)

Water origin	Spain	Portugal			Total flow (5)=(1)+(4)	Water resources available for hydropower generation in Portugal (6)=(1)+(2)
Location in the riverbasin	Total (1)	Upstream (interior) (2)	Downstream (coastal) (3)	Total (4)=(2)+(3)		
Minho	8 217	0	1 059	1 059	9 276	0
Lima	1 442	405	156	562	2 004	1 848
Cavado	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
Tejo	8 163	472	1 305	1 777	9 940	8 636
Guadiana	1 214	191	1 461	1 653	2 867	1 405
Total	19 160	11 263	18 640	29 903	49 062	30 423

Calculations based on data from APA, 2016a; MARETEC, 2016

Figure 2. Large dams in Portugal



Source: APA, 2017

Step 2. Sustained by the Regional Accounts (INE, 2017), 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 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 3.2) and territorial disaggregation of economic activities (we assume the coastal vs. interior territorial disaggregation for 2008 as there is no available data for 2050). Table 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 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			0.020			

Calculations based on data from APA, 2016a; Eurostat, 2016; INE, 2017. Total water consumption corresponds to the sum of raw water and distributed water consumption.

Note: 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.

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 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, 2017, 2016) as well as the energy mix projected for 2050 (Bailera and 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 et al., 2011). Table 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.

Table 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	-5.25%	-5.25%
			RCP 8.5	-32.82%	-32.82%
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	-5.54%	0.00%*
			RCP 8.5	-34.63%	0.00%*
		Competition in Portugal and Competition between Portugal and Spain (Comp_PT-SP)	RCP 4.5	-8.49%	0.00%*
			RCP 8.5	-52.83%	0.00%*

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).

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.

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.

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 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[9]. 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 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%	15.9%	11.5%
	Wind power	31.3%	31.6%	31.6%	31.6%	31.9%	32.0%	32.2%
	Solar photovoltaic	29.9%	33.9%	34.0%	34.8%	35.4%	35.5%	37.3%
	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%

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 5.2 and 5.3 describe the economy-wide effects at the macroeconomic and sectoral level, respectively.

5.2. Macroeconomic impacts

At the macroeconomic level (see Table 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

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[9] 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.

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[10]. 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).

The macroeconomic impacts under the no competition for water (between hydropower and the other production sectors) and stronger climate change impacts scenario (RCP 8.5_No_Comp) are significant, as mentioned before. In this case all sectors must accept a reduction in total available water and, therefore, production sectors compete to reach efficient water allocations based on the differences between sector's marginal cost of water abatement (or marginal productivities). As a result, there will be a significant reduction in GDP (-3.2%), which results mainly from the strong negative impacts on labour intensive sectors, such as the primary and services sectors (see also next sections). This also explains the strong increase in unemployment rates (+28.2%) and decrease in public consumption (-18.4%), which is related to the reduction in revenues (e.g. lower revenues from taxes on consumption and mainly social contributions). The trade balance shows a strong negative impact (17.5% increase in trade deficit), and results from the important share of primary and services (tourism) sectors on the trade balance. Welfare changes positively because, as unemployment increases significantly, real wages decrease and, therefore, the opportunity cost of leisure (on which agents' utility/welfare partly depends) also decreases. Hence, more time is devoted to leisure, thereby slightly increasing agents' welfare. Finally, CO2 emissions decrease significantly in all cases. The differences between scenarios are minor because the share of natural gas in the power sector (the unique fossil fuel that remains in the BaU by 2050; 9.3%) across the different scenarios is quite similar (ranging between 9.4% in the RCP4.5_Comp_PT-SP scenario and 11.8% in the RCP8.5_Comp_PT-SP scenario). The reason for this stability in shares is the need for a backup technology supporting a power sector that is mainly based on renewables, which faces issues related to intermittency in power supply.

Table 5. Macroeconomic impacts of climate change and competition scenarios, compared to the business-as-usual scenario (BaU2050)

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[10] 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.

	% 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%
CO2 emissions	-62.9%	-62.8%	-62.8%	-63.0%	-62.2%	-61.7%

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 4). As a consequence, small economic impacts are found at the macroeconomic (see Table 5) as well as sectoral levels (see Figure 3 and Appendix C). 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 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). Figure 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 7 summarizes the inherent impacts on water consumption (both raw and distributed water).

Table 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 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)

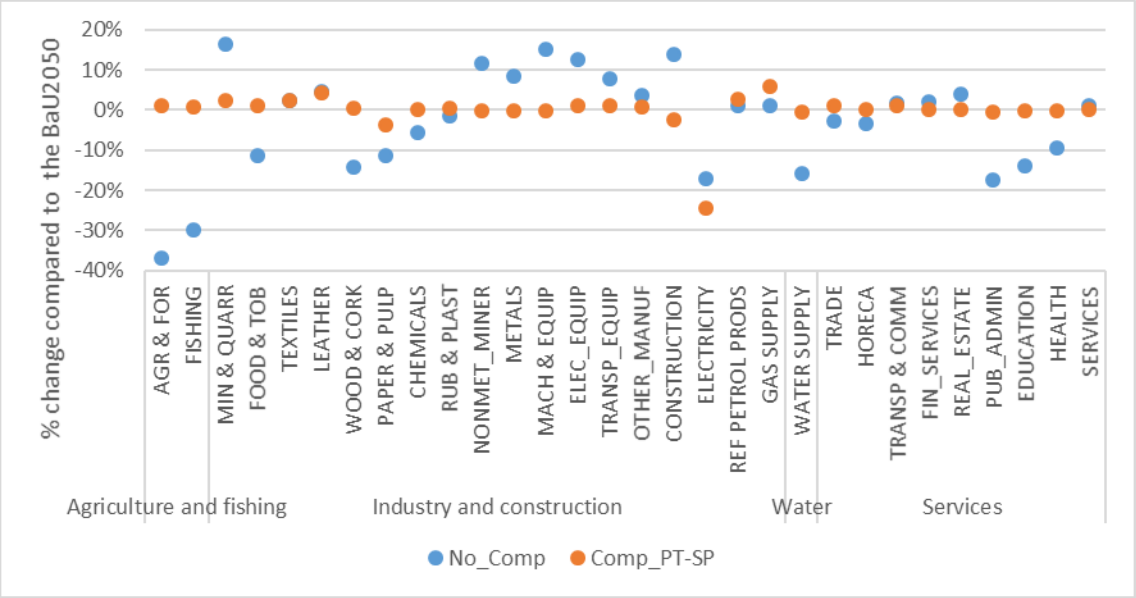

Table 7. Sectoral impacts of climate change (RCP 8.5) and competition (No_Comp; Comp_PT_SP) scenarios on water consumption (% change compared to the business-as-usual scenario)

Economic sector	BaU2050 (% of total consumption)		% change compared to the BaU2050			
			No_Comp		Comp_PT-SP	
	Raw water	Distributed	Raw	Distributed	Raw	Distributed

		water	water	water	water	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%

5.3.1. 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.

5.3.2. 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[11]. 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).

5.3.3. 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 -

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[11] 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.

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 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.

5.3.4. Services

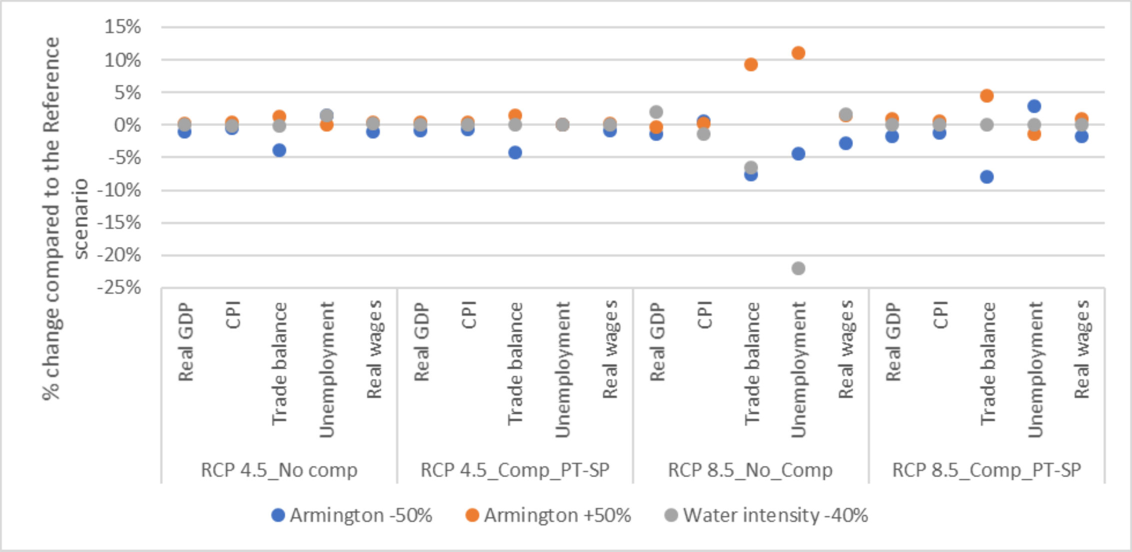
Many activities belonging to the services sector are amongst the most important consumers of distributed water and electricity and, therefore, their activity levels are impacted by climate change. Non-tradable services, notably the health, education and public administration sectors, are the most affected 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.

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 4 presents the impacts on key macroeconomic variables. The most noticeable impacts occur for the RCP8.5_No_Comp scenario. Given the lower/higher degree of openness to international trade (represented by a 50% reduction/increase in trade elasticities, respectively), the trade balance deficit improves/deteriorates more as compared to the Reference scenario. Furthermore, a higher degree of openness will increase the unemployment rate, as compared to the Reference scenario (the opposite occurring for a lower degree of openness). On the other hand, the 40% reduction in water intensity leads to positive economic impacts, notably a higher real GDP, less unemployment, higher real wages and a lower trade deficit, as lower water consumption counterbalances the diminished water availability resulting from climate change.

Figure 4. Sensitivity analysis – Macroeconomic impacts of alternative Armington trade elasticities and sectoral water intensities



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 trans-boundary 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 trans-boundary 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 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 trans-boundary 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. To do so, a soft-link between a top-down CGE model and bottom-up model of the energy sector was developed. This integrated modelling framework minimizes the limitations of the CGE model in the assessment of the impacts of water availability on the energy sector, associated with the lack of technological detail in this kind of models. Furthermore, it allows for a more exact simulation of the power mix and generation costs and prices. Still, the following limitations of this approach should be acknowledged. First, the bottom-up model of the energy sector has, itself, some limitations that condition results, notably by assuming that decisions are based on cost-effectiveness criteria and disregarding market behaviour and agents' preferences. Second, as the two models rely on different methodologies (top-down and bottom-up), their results may diverge. To avoid possible inconsistencies and the need for adjustments between the models, the relationship between the two was unidirectional (i.e. with the bottom-up model feeding the top-down CGE model).

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 trans-boundary 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 presented in this paper are highly affected by the impacts of climate change on precipitation and run-off, which vary according to the region. Impacts of climate change on the European hydropower sector will diverge in different European latitudes. For instance, Lehner et al. (2005) assessed that, by 2070, expected decreases in hydropower gross potential range between 20% and 50% for Mediterranean countries and that expected increases in hydropower gross potential are over in 30% in Northern European countries. Climate conditions in the Iberian Peninsula are Mediterranean (see Teotónio et al., 2017), characteristic for Southern Europe and the Mediterranean basin and that are considered a 'hot spot' region for climate change (see Teotónio et al.,2017). Hence, our results are applicable to other Mediterranean countries with a relatively large share of hydropower in the power mix (such as Turkey or Italy, where hydropower represents, respectively, more than 25% and 20% of total power production (World Bank/IEA, 2019)). Nonetheless, results provided by this analysis 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 and Sartori, 2015), -2.5% in Israel (Baum et al., 2016) and -1.1% in Spain (Galeotti and 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 et al., 2013a) 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 trans-boundary riverbasins[12], 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, 2016b), 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[13] (disregarding the effects of increased efficiency). The performed sensitivity analysis, 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

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[12] Notably concerning the fulfilment of the transnational treaties. In this case, the Albufeira Convention, that regulates the water use and exploitation of trans-boundary river basins between Portugal and Spain.

[13] 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.

the other production factors is null, like in e.g. Berrittella et al., 2007 and Gómez et al., 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 trans-boundary 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 A. 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 Table A. 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}.

Production

Figure A1 – Production structure of all sectors except "Electricity"

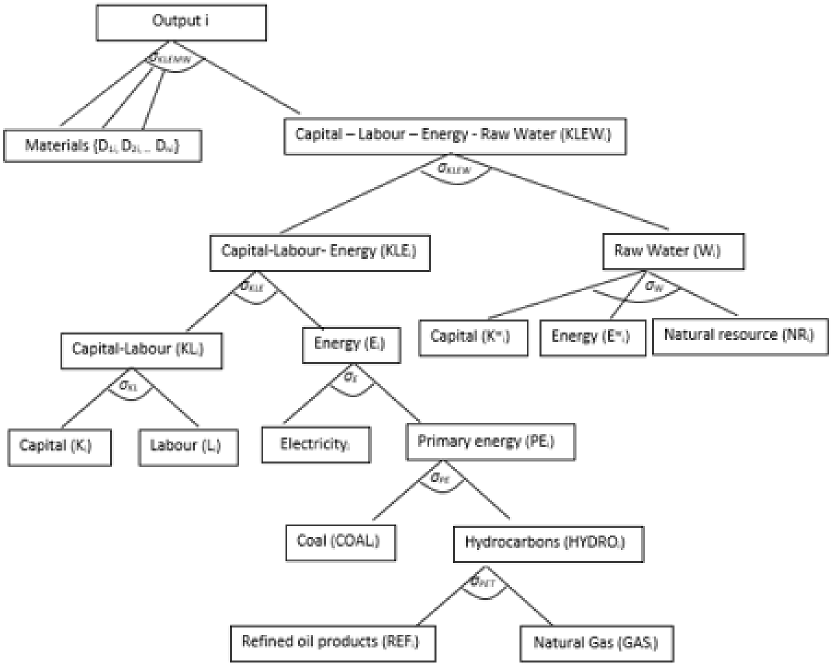
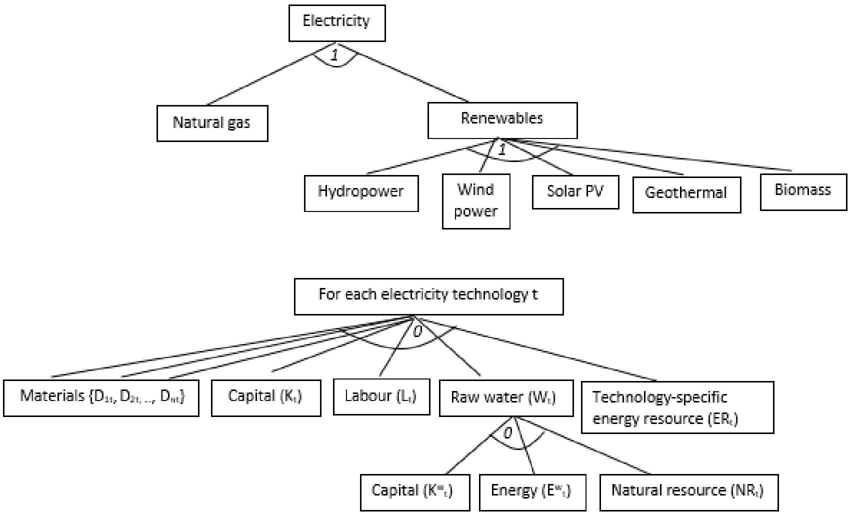


Figure A2 – Production structure of the "Electricity" production sector



Where "t" represents each electricity generation 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 A1. 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 Natural 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 - E$_i$ {composite input Electricity (Electricity) + Primary energy (PE)}

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

Eq. 7 - PE$_i$ {composite input COAL + HYDRO}

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

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 Natural 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.

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

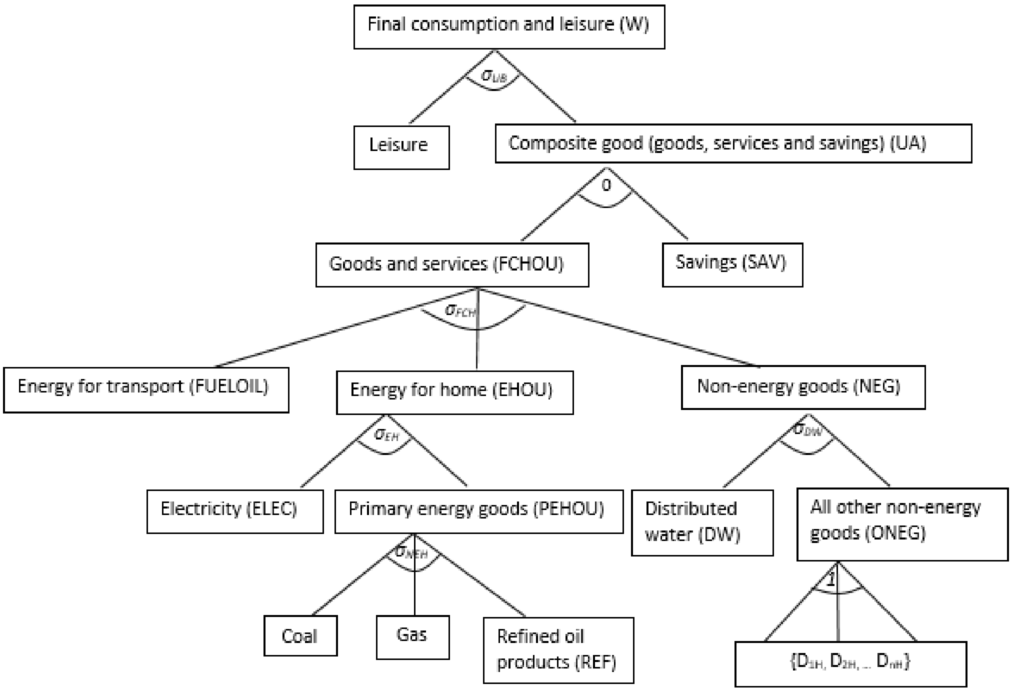
Eq. 13 - Armington nest for total supply {Output + Imports}

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

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

Consumption

Figure A3. 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)}

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

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 and Munson, 2008).

Table A1. Elasticities of substitution

	Production substitution elasticities								**International trade elasticities**	
	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: EC, 2013 and Aguiar et al., 2016

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 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 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 B. 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	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 C. Simulation results under RCP4.5 scenario

Economic activity	Production sector	Domestic production	
		No_Comp	Comp_PT-SP
Agriculture and fishing	AGR & FOR	-5.6%	0.2%
	FISHING	-4.6%	0.1%
Industry and construction	MIN & QUARR	1.2%	0.5%
	FOOD & TOB	-1.2%	0.2%
	TEXTILES	1.2%	0.5%
	LEATHER	1.6%	0.7%
	WOOD & CORK	-3.1%	0.2%
	PAPER & PULP	-1.3%	-0.5%
	CHEMICALS	0.3%	0.0%
	RUB & PLAST	-0.1%	0.1%
	NONMET_MINER	-0.1%	0.0%
	METALS	-0.1%	0.0%
	MACH & EQUIP	-0.1%	0.1%
	ELEC_EQUIP	0.7%	0.2%
	TRANSP_EQUIP	0.6%	0.2%
	OTHER_MANUF	0.3%	0.2%
	CONSTRUCTION	-1.2%	-0.4%
	ELECTRICITY	-3.8%	-4.4%
	REF PETROL PRODS	0.4%	0.5%
	GAS SUPPLY	0.4%	0.7%
Water	WATER SUPPLY	-2.1%	-0.1%
Services	TRADE	-0.3%	0.2%
	HORECA	0.1%	0.1%
	TRANSP & COMM	1.1%	0.2%
	FIN_SERVICES	0.3%	0.1%
	REAL_ESTATE	0.3%	0.1%
	PUB_ADMIN	1.1%	-0.1%
	EDUCATION	1.0%	0.0%
	HEALTH	0.7%	-0.1%
	SERVICES	0.2%	0.0%

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