Adaptation to climate-induced regional water constraints in the Spanish energy sector: an integrated assessment

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Abstract

The energy sector depends on water in all phases of its life-cycle, including raw material extraction, power plant cooling, irrigation of biofuel crops and directly in hydropower generation. In the coming decades, several regions of the world are expected to experience a decrease in water resource availability, in part due to climate change. The dependence of the energy sector on water resources calls for an active effort to adapt to the possible scenarios. This paper presents a novel model that addresses the direct impacts of regional and temporal water shortages on energy operation and investment decisions. The paper investigates the costs and benefits of adapting the energy sector to climate-induced water scarcity. The results show that the increase in costs for an energy plan that considers future water stress is relatively small as compared to one which ignores it. A plan which ignores water constraints, however, may lead to significant economic damages when actually exposed to water shortages. The results also highlight the value of the availability

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of water for the energy sector, which is significantly higher than existing prices. The paper concludes that the potential benefits to be gained by integrating energy and water models can be considerable.

Keywords: Energy, water, climate change, adaptation, economic impact

1 Introduction

The International Energy Agency (International Energy Agency (IEA), 2015) estimates that the world energy use will increase by one third by 2040. However, most of the increase will come from Non-OECD (Organisation for Economic Co-operation and Development) countries. In Spain, an energy use peak was reached in 2007, followed by a decline due to the economic crisis, as well as demographic, economic and energy efficiency changes. Forecasts show GDP growth rates of 0.8% in 2015 decreasing to 0.5% by 2020 (Organisation for Economic Co-operation and Development (OECD), 2016) (Trading Economics, 2016). Population is expected to decline by 1 million inhabitants by 2024 and by 5 million by 2064 (Institute Nacional de Estadística (INE), 2014). The energy future is unpredictable with future forecasts for 2020 estimating gross final energy consumption to vary between scenarios from 10% to -5% compared to 2005 values, while electricity generation is expected to increase between 20% to 40% compared to 2005 (Ministerio de Industria, Turismo y Comercio, Gobierno de España, 2010) (International Energy Agency (IEA), 2015). The electricity expansion is expected to come mostly from increased natural gas and renewables in the form of wind and solar. With the push for decarbonization, increased energy efficiency, uncertainty about nuclear policies, electric vehicle integration, biofuel alternatives to transport fuels and variable oil prices, the future energy mix is unpredictable with several possibilities for Spain.

In the water sector the main challenges in Spain relate to climate change-related declining water resources in the southeastern river basins (CEDEX, 2012). Already, Spain ranks as one of the most water-stressed nations in the European Union, with several southeastern river basins categorized as severely stressed, exploiting more than 40% of the available renewable resources in 2012 (European Environment Agency (EEA), 2012). In all its future scenarios (Pessimistic, optimistic and business as usual) for 2020, 2030 and 2040, the World Resource Institute forecasts water stress in Spain's southeastern basins to become "Extremely high" with water use to available resource ratios higher than 80% (World Resources Institute (WRI), 2016). In addition, Spain's water infrastructure suffers from water losses of up to 20% (Lallana, 2003) (Environmental Resources Management (ERM), 2013).

The existing water withdrawals by the energy sector (not including hydropower) in Spain are estimated at 25% of total withdrawals, while water consumption is estimated at 1.4% of total consumption (Hardy, Garrido, & Juana, Evaluation of Spain's Water Energy Nexus, 2012). Energy policies and subsequent growth of different energy technologies will have a huge impact on these percentages. For example, bioethanol and biodiesel consume almost 100 times more water than that needed for nuclear, concentrated solar power (CSP) and coal fired power plants. In turn, nuclear, CSP and coal plants consume several times more water than combined cycle natural gas plants, while wind and solar PV hardly consume any water.

Preparation for the possible changes in technologies, as well as the need to replace old equipment, will require massive investments in generation and transport infrastructures in the coming years. But, given the time scales involved, these investments must be planned taking into account the significant way in which climate change may affect them. On the one hand, climate change mitigation policies will require a large part of the investments to be directed towards low-carbon technologies. On the other hand, investment plans need to be adapted to changes in the climate, which will affect both energy demand and supply (IPCC, 2014).

One of the major elements through which the change in climate will affect energy supply and demand is the change in the temporal and regional availability of water as well as changes in water temperature (van Vliet, et al., 2013) (van Vliet, et al., 2012). Water is used in the energy sector in many ways, but mostly for cooling thermal power plants, for generating hydroelectricity, and for irrigating biofuels. A change in the availability of water would therefore clearly affect these technologies. Indeed, cooling methods are already shifting from traditional once-through cooling cycles to closed loop tower and pond cooling cycles, which are more water consumptive but withdraw less water (Martin, 2012). In the International Energy Agency (IEA), New Policies Scenario, from 2010 to 2035, global water withdrawals by the energy sector increase by about 20% while water consumption increases by up to 85% as a result of higher efficiency plants with advanced cooling methods, as well as due to the expansion of biofuel crops (IEA, 2012). These important implications of changes in water consumption and withdrawals patterns need be taken into consideration in future energy decisions and strategies in Spain.

Increased evapotranspiration and decreased runoff due to climate change will have a significant impact on decreasing hydroelectricity production in several regions of the world including Spain (van Vliet, et al., Global river discharge and water temperature under climate change, 2013) (World Bank, 2014). The agriculture sector, which is the largest consumer of water globally, will need to grow considerably, in order to meet the needs of the increasing global population to about 9 billion in 2050. Some studies estimate increases of almost 70% in world agriculture production by 2050 (Hoff, 2011). In Spain, changing trends in agriculture irrigation practices, in response to increased efforts for higher efficiency, can lead to significantly different agriculture water demands. Shifting from rain-fed to irrigation systems can lead to four times more water demand from agriculture as compared to only upgrading existing systems to pressurized drip irrigation systems (Daccache, Ciurana, Diaz, & Knox, 2014). The importance of correctly accounting for water availability and demands in future energy systems is thus critical, and has already prompted a large research effort into what is generally called the water-energy nexus.

Many recent case studies show that ignoring this interdependency in planning decisions can lead to serious consequences for both sectors. A case study on California (Stokes & Horvath, 2009), a region which has been suffering from a serious drought for the past several years, shows that if California were to meet its future freshwater needs using desalination the process would use 52% of the entire state's energy budget.

We see similar consequences when considering water intensive biofuels as alternatives to traditional fossil fuels in the transport sector. As part of the push for renewable energy expansion, the 2020 European Union renewable energy targets (Renewable Energy Directive 2009/28/EC) initially set a 10% goal for biofuels in the transport sector. A report from 2014 (European Forum for Renewable Energy Sources (EUFORES), 2014) showed that by 2012 Spain was lagging behind in this area (with only 0.4% renewables in the transport sector compared to the 2012 goal of 7.6%). However, while biofuels may address emissions issues, given the high water consumption intensity of biofuels the impacts on water resources can be significant. A study from Spain (Carrillo & Frei, 2009) shows the water impacts of different biofuel percentages in future energy mixes. The biofuels considered include the cultivation and production of biomass to produce bioethanol, biodiesel and biogas. The study shows that increasing the percentage of biofuels in the transport sector from 3% to 5.75%, from 2005 to 2030, would increase the water consumption of the sector more than 4 times (Carrillo & Frei, 2009). They further reported that if all the biofuel demand was locally cultivated and produced it would double the total water consumption of the entire Spanish population. This clearly shows that it makes little sense to promote this type of biofuels[†].

Therefore, we see that investments in future energy systems need to account for the water-energy nexus, and in particular, for the impact of climate-induced water constraints on these systems. Planning methodologies and models must address this element to create resilient strategies for the energy sector. Unfortunately, as discussed later, current practices and models tend to ignore water constraints in an integrated way. This paper presents the results from a new, integrated water-energy model that includes spatially and temporally disaggregated water demands

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[†] In addition to the water requirements, biofuels often displace existing croplands into grasslands and forests, which are carbon sinks absorbing high levels of CO_2. This indirect landuse change (ILUC) is shown to offset emissions savings and resulted in the passing of the EU Directive 2015/1513 (ILUC Directive) limiting the share of biofuels to 7% form the previous 10%.

and constraints, and is therefore capable of addressing some of the shortcomings of existing planning models. The results show the costs and benefits of energy planning with adaptation strategies to account for climate-induced water scarcity. Spain is used as a representative example of a region expected to suffer from significant climate-induced water scarcity in the next few decades.

Section 2 reviews the state of the art and the development of contemporary water-energy models. Section 3 describes the methodology used to create the current model while Section 4 discusses the strategy used in analyzing the benefits of utilizing an adaptation strategy. Section 5 presents the results of a case study applied to the Spanish energy system and Section 0 offers some conclusions and policy recommendations.

2 State of the art

Realizing the importance of the water-energy nexus in adapting to climate change, the past few years have seen an increase in efforts by governments, planners and scientists to address the issues using integrated methods.

The first step was to quantify the amount of water consumed by different energy technologies and incorporate these parameters into existing energy models in order to estimate the volume of water consumed by the system. The volume of water consumed could then be compared to the amount of water available for energy production in the region. Using this method a number of "water-energy" models were created which are described below.

The MARKAL/TIMES energy models developed by the IEA were adjusted to incorporate water usage for a case study in New York City by the Brookhaven

National Laboratory (Bhatt, Crosson, Horak, & Reisman, 2009) as well as for other United States regions (Bhatt, Friley, & Politis, 2013). The World Bank has also incorporated water into the TIMES Energy model (SATIM) developed by the Energy Research Center, at the University of Cape Town, for South Africa (Rodriguez, 2013). A similar project, the TIAM-FR model (Bouckaert, Selosse, Dubreuil, Assoumou, & Maizi, 2012) has been created at MINES ParisTech, which incorporates water consumption parameters in the TIMES energy model. The Center for Naval Analyses developed a new mixed-integer linear programming model of the power sector accounting for water used by thermal cooling (CNA Analysis & Solutions, 2014). However, none of these models consider actual physical water availability constraints and only use the energy models to account for how much water is being consumed, but not to react to water constraints. The decisions made by these models therefore do not reflect real water scarcity.

Some models have been developed which also represent the water system and water limitations. The National Renewable Energy Laboratory (NREL) has developed a model which uses limited water-rights for new energy investments in an innovative method to analyze the water-energy nexus (Cohen, Macknick, Averyt, & Meldrum, 2014). However, the model does not consider water availability during the actual operation of the energy system, only during the purchase of water-rights. Bartos & Chester (Bartos & Chester, 2014) present a water-energy model applied to the US state of Arizona which considers both the energy and water systems. The model however does not consider physical water constraints or availability, and only considers water demands from various resources. The model does not 'react' to actual water constraints but is used to meet various efficiency goals.

A model which considers the energy and water systems as well as water constraints has been developed by Bhattacharya & Mitra, (Bhattacharya & Mitra, 2013) which uses a modified a version of the International Institute for Applied Systems Analysis's (IIASA) model, MESSAGE. The limitation of the model is that it considers the resource demands and availability at an annual level for an aggregated single region, and cannot therefore address critical regional and temporal differences in water and energy demands and availabilities.

There have also been attempts to model the water-energy nexus by bundling individual sector-specific systems such as the series of projects by the Stockholm Environment Institute (SEI) and the CLEWS initiative, related to water, energy, land use and food modeling 2014 (SEI, 2012) (Welsch, Hermann, & Howells, 2013). These models are soft-linked and run iteratively with the results of one model fed into the other, and therefore lack a joint global optimization.

As a result of a lack of water availability constraints, regional and temporal synchronization of the water and energy sectors, and hydropower-hydrological cycle coupling, existing models are not able to simulate correctly the adaptation of energy systems to climate-induced water scarcity. None of the models reviewed before is able to simultaneously represent the temporal and spatial distribution of potential water scarcity (typically at the watershed level) synchronized with overlapping energy systems (which may be interconnected among watersheds). These drawbacks prevent proper adaptation and optimization of the energy system to react to changes in water availability.

Another key element to consider in water-energy models is the value of the availability of water, both temporally and geographically, in a broader regional economic context. The value of water can also be used by planners to review existing water prices and the opportunities for a water market as an adaptation tool for energy systems. Analyzing the costs of water constraints in the energy sector can also assist in decisions at a larger scale, in which technology changes in other sectors can be seen as potential options to free water for the energy sector.

Therefore, there is still a need for models that are able to address simultaneously the key issues mentioned before, so that they can provide a realistic picture of the interaction between water and energy when adapting to climate change. This paper presents a model that addresses some of these issues and is used in a case study in Spain. The following section describes the methodology used.

3 Methodology

Figure 1 shows a diagram of the methodology used to develop the model. An already existing energy model, MASTER_SO (López-Peña, Linares, & Pérez'Arriaga, 2013) was used as a starting point. The MASTER_SO is a long-term partial-equilibrium, bottom-up, linear-programming model for the energy sector. It satisfies a given demand for energy services for a chosen year, by optimizing energy investments and operation, subject to emissions constraints while minimizing the total cost. The model has been programmed in GAMS (Brooke, Kendrick, Meeraus, Raman, & Rosenthal, 1998) and considers the entire lifecycle of the energy production from energy extraction all the way to the final user.

The original model assumes a single node energy sector with well-connected transport and distribution networks for oil, gas and electricity. The original model also assumes that geographic features and locations within the system do not have any impacts on energy production. This assumption of uncongested energy transfers across the country will be impacted by the expected future expansion in distributed generation accompanying the growth of renewables (Ruiz-Romero, Colmenar-Santos, Gil-Ortega, & Molina-Bonilla, 2013) (Montoya, Aguilera, & Manzano-Agugliaro, 2014). While independent micro or mini grids and smart cities will probably reduce the capacity to share energy across regions, the impacts from a water perspective are not expected to be so critical given that most distributed energy systems will be mostly based on water-efficient wind and solar photovoltaics. Thus, distributed generation is expected to decrease both the local water requirements as well as the overall energy requirements of the central grid. Future developments of the model could improve the representation of the grid to address these issues more directly.

The model can be run allowing new investments or not. When we allow new investments we are able to analyze the costs of investing and planning for the future. When we do not allow investments we are able to simulate the operational costs of the system under a previously determined installed capacity.

The year 2050 was chosen as the year to simulate, since this allowed considering significant changes in water availability due to climate change, while at the same time maintaining current assumptions about possible energy technology availability, potential and costs. The assumptions considered regarding available energy technologies, costs, or emission levels are consistent with the Energy Roadmap 2050 of the European Commission, which require a significant decarbonization of the energy sector in Europe, and therefore imposes large reductions in allowable carbon emissions. In particular, the electricity sector must be carbon-free, and therefore only investments in nuclear or renewables are allowed in this sector.

First, the existing MASTER_SO model was modified by including water consumption and water withdrawal parameters for each energy production process. Alternative water efficient energy production technologies were also introduced into the model as options available to planners to adapt to climate change. These alternative technologies use closed-loop, dry and hybrid cooling methods at higher costs and less thermal efficiency to save water. Table 1 lists some of the studies which were used to create Figure 2, which shows some of the water consumption parameters used. As seen in the figure, the large range is due to the fact that water consumption by energy technologies depends on a number of factors such as the ambient temperature, the water temperature and the choice of energy technology, which vary from region to region and from time period to time period.

The second necessary step was to disaggregate the model into water basins. Contrary to energy, water cannot be easily transferred among watersheds, and therefore an analysis of water scarcity must always include detail at watershed level.

This also allows including a constraint limiting the amount of water used per basin per time period. These constraints can then be used to evaluate the opportunity cost of water for the energy system by analyzing the shadow prices, obtained as the dual variable of the water constraint for each period and region.

In order to reflect adequately the geographically-related water scarcity, energy production capacity and demand were divided into the fifteen river basins shown in Table 2. The energy system was still considered to be a well-connected single node network spanning across river basin boundaries.

Nuclear power plants, oil refineries and regasification power plants were distributed according to their individual geographic locations. Thermal power plants were distributed using the online data repository Enipedia (TU Delft). Special regime technologies (cogeneration, solar PV, solar thermal, wind, and mini hydro) were distributed using data from the Comisión Nacional de Energía (CNE, 2013).

The existing water resources in each basin were analyzed based on historical data and reports from the Spanish Ministry of Environment (Ministerio de Medio Ambiente, Gobierno de España, 2000) & (Ministerio de Medio Ambiente, Gobierno de España, 2013). The resources reported represent the sum of final surface and groundwater runoff in the natural environment per river basin after accounting for precipitation and runoff as a function of temperature. The Ministry of the Environment also reports the part of the natural resources available for use, calculated after accounting for the environmental, social, geopolitical, technical and management restrictions upon natural resources. Legislation regarding water allocation priorities and environmental flows has been evolving since its formalization in the 1985 Water Act. Up till 2008, environmental regulations were simpler, requiring fixed percentages of total annual or multi-year average flows (10% in most basins) for the environment (Costejá, Font, Rigol, & Subirats, 2002) (Sanz & Schmidt, 2012)[‡]. This has been the approach followed in our study.

Next, the changes in the availability of water resources as a result of climate change were analyzed based on the predictions made by the Centro de Estudios y

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[‡] After the Boletin Oficial del Estado (BOE) order ARM/2656/2008 the Ministry of Environment made it mandatory for inter-communitarian river basin management plans to use a detailed methodology (developed by the Ministry and a broad group of experts, research centers, universities and water authorities) to calculate both annual and seasonal environmental flow requirements as well as flood regimes and rates of change limits. The methodology recommended by the Ministry combines hydrological modelling (applicable at the basin level) with habitat modelling for several target species in specific river segments. The regulations also recommend site specific assessments of lakes and wetlands.

Experimentación de Obras Públicas (CEDEX, 2012). In order to demonstrate the impacts of climate change two, 'Intergovernmental Panel on Climate Change' (IPCC), emission scenarios from the Special Report on Emissions Scenarios (SRES) (IPCC, 2000) were chosen and the corresponding changes (averages for the period 2041-2070) in water resources are shown in Table 3 below. As seen in the table the "severe" scenario predicts significant reductions in water availability of about 60 % in some of the basins such as "Tinto, Odiel y Piedras".

Another important development in the original model was to represent the impact of the changes in water availability (in this case, changes in runoff) on the hydroelectricity production in each basin. A complete representation of the topology of hydro production in all basins was considered out of the scope of the current study due to the large data requirements. Instead, the reservoirs in each basin were aggregated into a single representative one, and the electricity production potential was then linearly correlated to water availability using historical hydroelectricity production from the Spanish System Operator, Red Eléctrica (Red Eléctrica de España, 2014). Figure 3 shows the regression functions obtained. The estimation of these relationships uses a very simple linear relationship, however, aggregating the reservoirs already leads to a loss of several details involving the topology and individual non-linear characteristics of single reservoirs, leading to limited benefits, if any, from more complicated relations.

The model is also limited by the quality of data available. As discussed earlier, the ranges of data for water consumption parameters are considerably large. The water available for energy has also been represented by constant values based on average resource and demand values for each basin. In spite of these limitations the model serves well for a comparative analysis of different scenarios since the errors and limitations are applied uniformly across model runs.

With these changes, the model is now ready to simulate the impact of water scarcity on the energy sector. To assess the costs and benefits of adaptation to climate change and its impacts on water availability the following strategy was used.

4 Assessment Strategy

The purpose of this paper is to investigate the benefits of using an integrated energy model to adapt to climate-induced water scarcity in comparison to a non-integrated energy model which does not take into account water scarcity. The non-integrated model represents existing trends and methods of energy planning. In order to achieve this comparison the model considers two different types of possible scenarios:

i. Scenario “Unconstrained”: This scenario represents the traditional non-integrated energy models which ignore water constraints and therefore consider water to be an unlimited resource. In this scenario the energy system is not constrained by water limits and the water consumption by different energy technologies has no impact on the decisions made by the model.

ii. Scenarios “Stressed” (Moderate & Severe): These scenarios represent the new integrated water-energy model which takes both spatial and temporal water constraints into account and therefore adapts endogenously to predicted changes in water availability.

The scenarios mentioned above describe possible futures and in a first iteration we run the model to see what optimal strategies are proposed for meeting future demand scenarios which consider water stress versus a scenario which ignores water constraints. In this iteration the model is allowed to invest in new technologies to satisfy additional demands and tackle water constraints if any. The results provide an estimate of the predicted costs needed to satisfy future demands. This first run allows us to evaluate the extra cost induced by water scarcity: the reduced availability water in certain basins may prevent the most economical energy strategy to be adopted by the model, hence resulting in a higher total cost than in the "Unconstrained" scenario.

In the next iteration, we evaluate the benefits of adaptation as the costs of non-adaptation. To do so, we take the investment strategy proposed by the model in the first iteration as fixed and run it again, but this time not allowing for new investments. This allows us to evaluate the impacts of water shortages on the strategy proposed by the model for the "Unconstrained" scenario. As discussed further in Section 5, water intensive technologies, such as nuclear or cogeneration power plants, sited in water-scarce locations will now have limited performance. The original investment strategy decided under the "Unconstrained" scenario may have sited these technologies, counting on them to be the cheapest or most efficient sources of energy. However, water constraints under the "Stressed" scenario may make these technologies unavailable; forcing the use of more expensive technologies in other locations or curtailing energy demand if not enough alternatives were planned for. Hydropower production will be less than expected and final energy delivery technologies choices will need to be adjusted.

5 Results and Discussion

5.1 New capacity investments

First we compare the investments made and their geographical distribution, using the two scenarios “Unconstrained” and “Stressed”, as shown in Figure 4. We use the “Severe Stress” scenario here to demonstrate more clearly the differences between the unconstrained and water stressed case. The previous installed capacity (yellow) is based on data collected from various sources as mentioned in Section 3 and is the same for both scenarios. The upper chart in Figure 4, corresponding to the ‘Unconstrained’ scenario, shows that the model makes some investments in the four water stressed basins. The lower chart corresponds to the ‘Stressed’ scenario and we see how, in this case the model avoids making investments in water scarce basins where water-consumptive technologies would not be able to operate. As mentioned before, and in order to be consistent with the requirements of the EU Energy Roadmap 2050, only low-carbon technologies were allowed for new investments.

It should be remarked that according to existing regulations (Garrido & Llamas, 2008) (Estrela, 2014) water is first provided to residential users followed by the agriculture sector and then the energy sector. A combination of: the emissions scenario considered; the corresponding regional water availability impacts; historical demands and predictions for future increases; as well as existing regulations; lead to the extreme case of no regional freshwater available for the energy sector in certain basins in 2050.

As seen in Table 4 the ‘Unconstrained’ scenario invests in technologies which are water consumptive, such as cogeneration, in basins where those water resources may not be available. The amount of water intensive new capacity, built in these water stressed basins was 8.6 GW, which was about 10% of the total new investments (86 GW). Since water is the only constraint in the model guiding the choice of capacity location, the choices made in the 'Unconstrained' scenario are arbitrary. New capacity location choices for the "Unconstrained" scenario were therefore checked to make sure they were not unusually biased towards water stressed basins, nor significantly higher than the distribution of previous capacity in any location. In the 'Stressed' scenario, in the water-stressed basins, the model only invests in water–efficient, small-hydro capacity, since there is no water available for the energy sector.

5.2 Water availability and consumption for energy sector

Figure 5 shows the distribution of water resources available (blue) for the energy sector and the planned consumption of water resources (red) by the energy sector for the two scenarios (allowing for new investments). The upper chart of Figure 5 corresponds to the 'Unconstrained' scenario and as seen in this case the optimum plan, ignoring water constraints, would consume water in all the different basins. In the lower chart corresponding to the 'Stressed' scenario, the model redistributes its operation decisions to avoid the water stressed basins. It should be noted that the model accounts for both water consumption and withdrawal. However, only the former is shown here.

5.3 The costs and benefits of adaptation

5.3.1 Costs of adapting to water stress

In this section the predicted costs of planning for future energy demands are compared when considering different degrees of water scarcity. The planned costs of the model, when it is run for three different scenarios (no water constraints, moderate water stress and severe water stress) are compared in Table 5. Table 6 shows the same changes as percentages.

As expected, with additional constraints (from water stress) the overall planned costs of the system increase, but in an almost negligible way. The increase when planning for moderate water stress is about 300 million Euros (0.1% of total) and about 1 billion Euros (0.4% of total) for the severe water stress scenario.

A large part of this increase comes from adaptive planning for water stress by investing in water efficient technologies. A decrease in hydro power production is expected in the water stressed scenarios and this decrease is replaced by investments in wind power. In the moderate scenario an additional 2 GW and in the severe scenario an additional 6 GW of wind power are built. With increased intermittent generation the expected costs of electricity transmission also increases.

Another notable change is in the operation of final energy delivery technologies which constitute a large part of the total costs. As seen in Table 5 and Table 6 the water stressed scenarios have lower "final energy delivery technology" operation costs. Some of the shifts in final energy delivery technologies are shown in Table 7. For example in residential water heating the most cost effective technologies available for the model are electric resistive heating and the most expensive is using a biomass furnace. With additional wind power installed the scenarios with water stress are able to shift to this technology. The unconstrained water scenario uses biomass since the tradeoffs of installing more wind or other technologies to generate electricity are less favorable than using the existing biomass capacity at a higher cost. We see a similar shift in space heating for commercial building services as well.

5.3.2 The benefits of adapting to water stress

The next step was to take the investment plans proposed by each scenario and expose them to simulated water stressed situations. In these runs the model was not allowed to invest in new technology and was limited to the sum of the previously installed capacity and planned new capacity according to the scenario chosen. This allowed us to calculate the cost of not having adapted energy planning to water scarcity, or alternatively, the benefits of adaptation in terms of avoided costs. Table 8 shows some of the major contributors to total costs and the differences between the different scenarios. As seen in the tables, taking water stress into account during the planning phase provides a better capability to adapt and a more efficient system, with cost savings in both the moderate and severe water stress simulations.

In the moderate water stress case the overall system savings are 0.6 billion Euros while in the severe water shortage scenario we come to an extreme case in which there is non-served energy and the savings reach significant levels depending on the value given to non-served energy (22 billion Euros in this case). Of course, this is an upper limit and given enough time, the system would be able to build enough capacity, although probably at a higher cost than when planned ahead.

With energy capacity already installed, a large part of the savings comes from optimizing the final energy delivery technologies using the available energy capacity. When we compare the planned costs of "final energy delivery technology" operations from Table 5 we see that when the unconstrained energy plan was exposed to water shortages there was an increase in final energy delivery technology costs. In contrast the plans constrained by water shortages perform the same if not better when exposed to actual water shortages.

Table 9 shows the changes in some of the "final energy delivery technology" choices used by the original "Unconstrained" plan versus exposing the plan to different degrees of simulated water stress. It can be observed, for example in residential refrigeration, that the model switches to higher efficiency but more expensive refrigeration technologies, since it needs to account for the decrease in available energy output. This lack of available energy occurs as a result of not investing in enough electricity power capacity during the planning phase, when water shortages were ignored and available hydropower energy availability was overestimated. We see a similar result in commercial building services space heating in which "final energy delivery technologies" shift from the cheaper and more efficient electricity resistive heating to natural gas boilers. In addition to a lack of electric generation capacity planning this shift to natural gas based heating may also be explained by the water efficiency of regasification technologies.

Table 10 shows the corresponding changes in power plant energy outputs for the original "Unconstrained" plan and the resulting outputs when the plan is exposed to moderate and severe water stress. As discussed above we see that hydropower energy potential was overestimated. Water shortages also limit the availability of energy production from biomass fed power plants which need water for cooling. To replace some of this capacity we see an increase in regasification outputs to feed natural gas demands which can replace certain electricity-based end products such as the space heating example described above.

Thus, from Table 6 we see that the cost of adapting to potential climate-change-induced water scarcity is about 0.1% (0.3 billion Euros) for moderate water stress and 0.4% (1 billion Euros) for severe water stress. This increase in costs occurs as a result of additional investments in water-efficient technologies, optimization of power plant locations and the corresponding changes in final energy delivery technology choices, transmission and imports.

On the other hand, the benefits of adapting to climate change can be significant. Table 8 shows savings of 0.2% (0.6 billion Euros) in the moderate water stress scenario and up to 8% (22 billion Euros) in the severe water stress scenario. The unconstrained scenario, unable to plan for water scarcity, invests in the wrong technologies in the wrong places and these become unavailable for use when there is not enough water. The total non-served energy for the unconstrained water plan exposed to severe water stress was 2.2 TWh of the total demand, about 1600 TWh. The social cost of not meeting this demand can change from system to system (Linares & Rey, 2013). In the original model the cost of Non-Served Energy was assigned at a rate of 10,000 Euro/MWh. This parameter will have a significant impact on the final results but is useful in demonstrating the differences shown here.

5.3.3 The shadow price of water for energy

Another output that indicates the cost of water scarcity (or the benefits of adaptation) is the shadow price or value of the availability of water to the energy sector. These values are shown in Figure 6. As can be expected, the 'Unconstrained' scenario with no water constraints has no opportunity cost for water. Including water constraints allows planners to evaluate the value of water for the energy sector for different time periods and different regions. As shown in the figure the prices can reach as high as 50 Euro/m3 of water. These prices are considerably higher than the current water prices in Spain which range from 0.02 Euro/m3 for superficial water, 0.12 Euro/m^3 for subterranean sources and 0.50 Euro/m^3 for desalinated water sources (Ministerio de Medio Ambiente, 2007). The high value of water in certain regions and periods can be seen as an opportunity for trade with other sectors to help the energy system adapt to future water shortages. After similar analysis in other sectors, central planners can also use these values to assist in optimal water resource allocation decisions to maximize net-benefits in a region.

5.3.4 Sensitivity Analysis

As mentioned before, the data used for this study are subject to significant uncertainties, with sometimes large ranges. A sensitivity analysis was carried out to analyse the influence of uncertainty in the data. Four critical parameters: water availability; water consumption by energy technologies; carbon dioxide emissions limits; and hydroelectric energy production were used in the analysis. We compare the impacts of variations in each of the parameters on the final costs of four different scenarios from this study (Unlimited Plan, Moderate Stress Constrained Plan, Unlimited Plan performance in moderate water stress and Constrained Plan performance in moderate stress). As a baseline we use the current values used in this study. In increments and decrements of 5% and 10% we compared the variations in each parameter up to +80% and -80% of the baseline values.

The baseline value used for the availability of water for the energy sector in 2050 without climate change is about 20,000 hm^3. The variability in water availability data as a result of different climate change scenarios used in this study had a range of between -12% (-2,500 hm^3) to -35% (-7,000 hm^3) from the baseline. For annual hydro energy production the baseline used was 24.7 TWh, which had a range of values (based on possible changes in water levels in reservoirs) between -11% (-3.2 TWh) to -38% (-10.6 TWh). Water consumption parameters for different energy technologies (based on different studies) had the highest variability for those technologies which consumed the least water (example Wind) with standard deviations of up to 150%. However, for technologies with higher water consumption the standard deviation ranged up to 70%. Finally, for CO_2 emissions limits, the baseline value uses a limit of 150 million tons of CO_2 emissions, based on a rough average assumption of the different possible scenarios from the European 2050 roadmap. Spain's emissions evolved from 218 million tons in 1990 to 354 million tons in 2005 and then decreased to 270 million tons in 2011. Thus, the variability considered between +80% and -80% in the sensitivity analysis captures the variability of the different parameters for a range of possible futures.

The results of the variability analysis are shown in Figure 7 and Figure 8. Figure 7 shows the sensitivity of the results during the planning phase when new investments are permitted. Both the unlimited (black) and constrained (red) scenarios show the most sensitivity to carbon emission limits and the availability of hydro energy. Water availability and water consumption by energy technologies shown in Figures 7(a) and 7(d) do not influence the unlimited scenario because in this scenario the model does not take into account water availability as a constraint. For the constrained scenario, the impacts are not significant because the model invests and operates already existing capacity located in the water rich basins. In general we notice that the less constrained unlimited scenario is able to find a lower optimum solution.

Figure 8 shows the sensitivity analysis of the different scenarios during the performance phase when the different plans are exposed to water stress. In this case we see in general that the unlimited scenario (black) is now more constrained than the constrained (red) scenario and gives a poorer optimum. That is, the limitations for adaptation of the unconstrained scenario are revealed to be even larger when we introduce uncertainty in the inputs.

In Figure 8(a) we see that the unlimited scenario is more sensitive to decreases in water availability, with total costs increasing dramatically after a decrease in water availability of about 30% and above, which is within the range of uncertainty for that data set. The water constrained model on the other hand is more robust and is not affected by water availability reductions, until about a 75% decrease in water resources. The results remain most sensitive to the uncertainties in the CO_2 emission limits (Figure 8(b)) and hydroelectric production potential (Figure 8(c)) parameters. Finally, similar to water availability (Figure 8(a)), we see that the uncertainties in water consumption parameters (Figure 8(d)) for the unlimited scenario can lead to increases in system costs, when approaching about 50% which is well within the range of variability of this parameter. The constrained scenario plan is much more robust, remaining stable for even high variations in the water consumption parameters.

The sensitivity analysis thus shows that the model is in general most sensitive to parameters directly related to energy production such as carbon emissions and the contribution of hydro energy to the system. Regarding water availability and water consumption by energy technologies, the analysis shows the robustness of integrated analysis in the face of uncertain water conditions, while ignoring water stress can lead to drastic impacts as a result of conditions well within the range of future uncertainty. In fact, the sensitivity analysis reinforces the robustness of the integrated planning and the benefits it provides in terms of adaptation to uncertain circumstances.

6 Conclusions and Policy Implications

The main conclusion of this study is that ignoring water demands and constraints in the energy sector can lead to significant costs under certain climate change scenarios. Ignoring future water stress when making energy capacity investment decisions can lead to overestimating future hydropower resources, underinvesting in sufficient capacity and misplacing water intensive technologies such as cogeneration or solar thermal in water-stressed basins. Some of this capacity subsequently may become unavailable when exposed to water shortages. In these expected water scarce regions, such water-intensive technologies need to be replaced by water-efficient technologies. In the worst case, in months and locations when high demands overlap with low water availability, energy demands may need to be curtailed, leading to non-served energy. The reduced capacity availability also leads to an increase in foreign energy dependence. Altogether, the costs of not planning for possible future water-stressed situations induced by climate change may range from 0.2% to 8% of the system costs for the Spanish case, more than doubling the cost of adaptation.

Another way to estimate these costs is to look at the opportunity costs i.e. assessing the extent to which energy costs would be reduced if more water were available.

The shadow prices estimated for water show that for particular basins and periods, the value of water for the energy sector can reach up to 40 times the existing prices, which are less than 1 Eur/m^3. These differences point to the advantages of using water markets to optimally distribute water resources between different sectors, and to help with the adaptation of the energy sector to climate change.

Incorporating future water stress at the planning stage is shown to be profitable. The extra cost of the energy investments required to cope with future water scarcity is about 0.1% (0.3 billion Euros) to 0.4% (1 billion Euros) of the total system costs, while the losses if ignoring water shortages range from 0.2% (0.6 billion Euros) to 8% (22 billion Euros) in the current case study. The cost-benefit analysis is thus clear in the interest of planning ahead for climate-induced water scarcity.

To achieve this, new models capable of representing integrated policies need to be developed. In this case study, some of these issues were addressed by disaggregating Spain into water basins and distributing the current installed capacity accordingly. Other key developments were the representation of actual water resources and the determination of the changes in hydro-energy production potential with changes in water availability.

Several other interesting insights were also deduced from the results. The decrease in the use of fossil fuels in the electricity sector due to the decarbonization requirements also contributes to the adaptation of the energy sector to water shortages, since often low-carbon technologies, such as wind or solar photovoltaics also have low water requirements.

This leads to another complication brought about by the increase of intermittent technologies. Additional backup is required to account for the variable production output of intermittent technologies such as wind or solar. This backup, under a low-carbon scenario, would be hydropower. However, reduced hydro production as a result of climate change, calls for the backup by other low-carbon technologies.

Of course, when considering all these implications it is important to be aware of the large uncertainties associated with the scenarios used for the year 2050. These uncertainties are present in the energy and water demands, the developments and costs of future energy technologies and changes in water availability as a result of climate change. Furthermore, the values used for the water consumption parameters by energy technologies are based on the median values from a number of different studies which had a large range. A sensitivity analysis was conducted to test the impacts of the uncertainties on the final results. It was found that the model is most sensitive to changes in the CO_2 emission limits and the amount of hydroelectric potential. The results were less sensitive to changes in water availability and the water consumption parameters of the energy technologies. Another important conclusion from the sensitivity analysis was the robustness of the integrated-planning strategy. It was found that taking water constraints into consideration resulted in an energy system plan which was more robust in the face of possible climate change related water shortages, with stable and consistent total costs. An energy system plan which does not consider water constraints on the other hand, becomes unstable (with drastic cost increases) when future water availability decreases by 30% or more, which is within the range of possible future scenarios. Similarly, the results for the water constrained scenario plan remain stable with changes in the water consumption parameters for the energy technologies, while the unconstrained scenario plan starts to show significant cost increases with variations in this parameter of 50% or more.

Keeping in mind the uncertainties, the results show the importance and impacts of incorporating water constraints and climate-related changes on energy planning, policies and strategies. Given the strong interdependencies between the energy and water sectors, it is clear that in order to capture the complete benefits of adapting to climate change, it is important to also include the feedback loops of energy-consumption from an endogenous "optimizable" water sector system. The current model is limited to representing only the energy sector with exogenous water availability inputs. Future work can expand the model to also include a representation of the physical water system allowing for a more complete analysis of the interrelationships between water and energy. Research is underway on this complete integration.

While the need for integrated assessments becomes clearer an even bigger challenge lies in the implementation and execution of integrated policies. Over the decades, water and energy resources have traditionally been managed independently, each developing its own specific regulatory instruments and policy frameworks to manage their corresponding needs governed by inherently different physical, economic, social, spatial and temporal characteristics. Governance and legislation varies over the lifetime and lifecycle of both resources, ranging from national or federal oversight for regulated activities (such as electricity transmission) or publicly owned entities (such as water bodies) to market based and privately owned activities (such as energy generation and electricity retail). Thus, along with the integration of water and energy planning models, it is equally important to address the development and integration of cross-sector policy and regulation instruments that will enable the implementation of integrated assessment results into actual systems.

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Table 1: Sources for water consumption per GWh data

No.	Name	Code	Region
1	(Glassman, Wucker, Isaacman, & Champilou, 2011)	GLASS_2011	USA
2	(WEC, 2010)	WEC_2010	World
3	(Grubert, Beach, & Webber, 2012)	GRUB_2012	Texas
4	(Sovacool & Sovacool, 2009)	SOVA_2009	USA
5	(Pate, Hightower, Cameron, & Einfeld, 2007)	PATE_2007	USA
6	(Herath, Deurer, Home, Singh, & Clothier, 2011)	HERA_2011	New Zealand
7	(Hardy & Garrido, 2010) (Hardy & Garrido, 2012)	HARD_2010	Spain
8	(Hardy, Garrido, & Juana, 2012)	HGJ_2012	Spain
9	(Carrillo & Frei, 2009)	CARR_2009	Spain
10	(USDOE, 2006)	USDO_2006	USA
11	(Mielke, Anadon, & Narayanamurti, 2010)	MIEL_2011	USA
12	(Macknick, Newmark, Heath, & Hallett, 2011)	MACK_2011	USA
13	(Poole, Younos, & Hill, 2009)	POOL_2009	USA
14	(EPRI, 2002)	EPRI_2002	USA_CAL
15	(Linares & Sáenz de Miera, Implications for Water of the World Energy Scenarios, 2010)	LINA_2009	World
16	(IEA, 2012)	IEA_2012	World
17	(Marsh, 2008)	MARS_2008	Australia
18	(Gleick, Water and Energy, 1994)	GLEI_1994	World
19	(Electric Power Research Institute, 2002)	EPR2_2002	USA
20	(Wu, Mintz, Wang, & Arora, 2008)	WU_2008	USA

Table 2: River basins used in the model

Galicia Costa
Miño-Sil
Cantabrico Occidental
Cantabrico Oriental
Duero
Tajo
Guadiana
Tinto, Odiel Y Piedras
Guadalquivir
Guadalete Y Barbate
Cuencas Mediterraneas Andaluzas
Segura
Jucar
Ebro
Distrito Fluvial de Cataluña

Table 3: CEDEX Climate Change Scenarios

River Basin	Variation in Water Available (%) (2041-2070)	
	Moderate Stress IPCC SRES A2 CGCM2-FIC	Severe Stress IPCC SRES A2 ECHAM4-FIC
Galicia Costa	-14	-37
Miño-Sil	-11	-28
Cantabrico Occidental	-20	-38
Cantabrico Oriental	-11	-34
Duero	-10	-37
Tajo	-13	-50
Guadiana	-19	-58
Tinto, Odiel y Piedras	-8	-65
Guadalquivir	-7	-55
Guadalete y Barbate	-12	-56
Cuencas Mediterraneas Andaluzas	-13	-41
Segura	-11	-44
Jucar	-11	-32
Ebro	-14	-27
Distrito Fluvial de Cataluña	-5	-11

Table 4: New capacity investments in water stressed basins

Model	Water Stressed Basins	Technology	New Cap (GW)	Water Consumption (hm^3/GWh)
Unconstrained	Guadalquivir	Solar PV	0.1335	5.1E-05
	Guadalete Y Barbate	Cogeneration	5.2928	1.4E-03
		Wind	0.0246	1.4E-06
		Solar PV	0.2124	5.1E-05
	Cuencas Mediterraneas Andaluzas	Mini Hydro	0.1103	0
		Wind	0.0566	1.4E-06
		Solar PV	0.4316	5.1E-05
		Solar Thermal	1.072	3.5E-03
	Segura	Wind	0.0566	1.4E-06
		Solar PV	0.1311	5.1E-05
		Solar Thermal	1.0763	3.5E-03
Severe Stress	Guadalquivir	Small hydro	0.1905	0

Table 5: Summary of planned costs (billion Euros) for unconstrained water, moderate water stress, and severe water stress

Summary Item	Unconstrained	Moderate Stress	Severe Stress
Total System Costs	270.36	270.68	271.42
New Energy Conversion Capacity	20.14	20.36	20.91
Final Energy Technology Operation	170.04	169.98	169.76
Energy Transport/Transmit	16.20	16.34	16.69
Primary Energy Imports	13.05	13.05	13.07
Transformed Energy Imports	47.34	47.34	47.33

Table 6: Percentage changes of planned costs for moderate water stress and severe water stress compared to the unconstrained scenario

Summary Item (%)	Moderate Stress	Severe Stress
Total System	0.1	0.4
New Energy Conversion Capacity	1.1	3.8
Final Energy Technology Operation	0.0	-0.2
Final Energy Consumed	0.0	0.2
Total Electricty Generated	0.1	0.8
Energy Transport/Transmit	0.9	3.0
Primary Energy Imports	0.0	0.1
Transformed Energy Imports	0.0	0.0

Table 7: Example of planned optimal "final energy delivery technology" outputs for residential hot water and general service space heating for unconstrained water, moderate stress and severe stress

Sector	Final Energy Delivery Technology	Cost (M€/GWh)	Unconstrained (TWh)	Moderate (TWh)	Severe (TWh)
Residential Hot Water	Natural gas boiler condensation	0.03	20.5	20.7	21.5
	Electric resistive. Central electricity	0.01	3.7	4.4	6.4
	Electric resistive. Distributed electricity	0.01	0.0	0.0	0.2
	Biomass furnace	0.05	33.1	32.3	28.7
	Solar thermal	0.11	9.5	9.5	9.5
Commericial Building Services Heating	Natural gas boiler low temperature	0.05	13.9	13.7	12.9
	Electric resistive heating. Central electricity	0.01	50.7	50.8	51.1
	Electric resistive heating. Distributed electricity	0.01	0.3	0.4	0.7

Table8

Table 8: Summary of costs (billion Euros) when exposing original plans for "Unconstrained" water, "Moderate Stress", and "Severe Stress" to simulated moderate and severe water stress conditions

Cost Type	Simulated Water Stress Moderate			Simulated Water Stress Severe		
	Plan Unconstrained	Plan Moderate Stress	% Difference	Plan Unconstrained	Plan Severe Stress	% Difference
Total System Costs	249.90	249.32	0.2	272.72	249.91	8.4
Primary Energy Imports	13.05	13.07	-0.1	13.17	13.06	0.8
Energy Transport/Transmit	16.24	16.77	-3.2	16.26	16.76	-3.0
Transformed Energy Imports	47.33	47.33	0.0	47.50	47.34	0.4
Non-Supplied Energy	0.0	0.0	NA	22.1	0.0	NA
Final Energy Tech Operation Costs	170.10	169.25	0.5	170.52	169.61	0.5

Table 9: Comparison of optimal "final energy delivery technology outputs" for original "Unconstrained" plan with plan exposed to simulated moderate and severe water stress conditions

Sector	Final Energy Delivery Technology	Cost (M€/Unit)	Unconstrained Plan (TWh)	Expose to Moderate Stress (TWh)	Expose to Severe Stress (TWh)
Residential Refridgeration	Fridges conventional, consuming centralised electricity	109.07	6.1	4.8	1.6
	Fridges high efficiency, consuming centralised electricity	125.44	5.5	6.5	7.7
	Fridges conventional, consuming distributed electricity	109.07	0.7	0.2	0.0
	Fridges high efficiency, consuming distributed electricity	125.44	0.7	1.0	2.4
Commercial Building Services Heating	Natural gas boiler low Temperature	0.05	13.9	16.2	23.7
	Electric resistive heating. central electricity	0.01	50.7	48.6	42.9
	Electric resistive heating. distributed electricity	0.01	0.3	0.6	0.2

Table 10: Comparison of energy production outputs for for original "Unconstrained" plan with plan exposed to moderate water stress and plan exposed to severe water stress

Power Plant Type	Unconstrained Plan (TWh)	Expose to Moderate Stress (TWh)	Expose to Severe Stress (TWh)
Total	663	654	648
Hydro Run of River	11.8	10.4	7.3
Hydro Reservoir	16.2	14.4	10.1
Cogeneration	160.7	160.7	156.5
Regasification	455.4	455.5	459.9
Biomass	19.0	13.1	14.2

Figure1

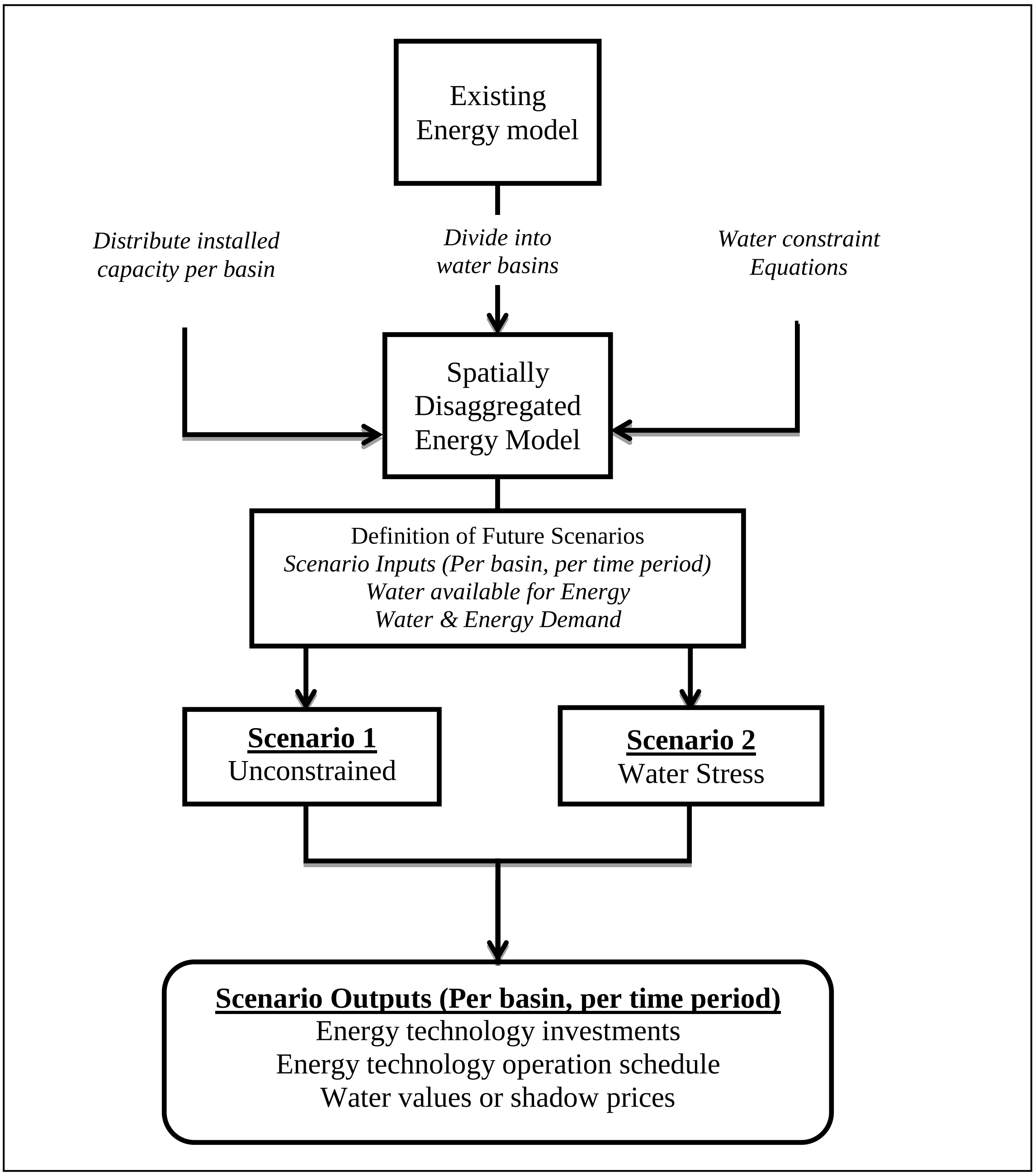

Figure 1: Schematic diagram of the methodology

Figure2

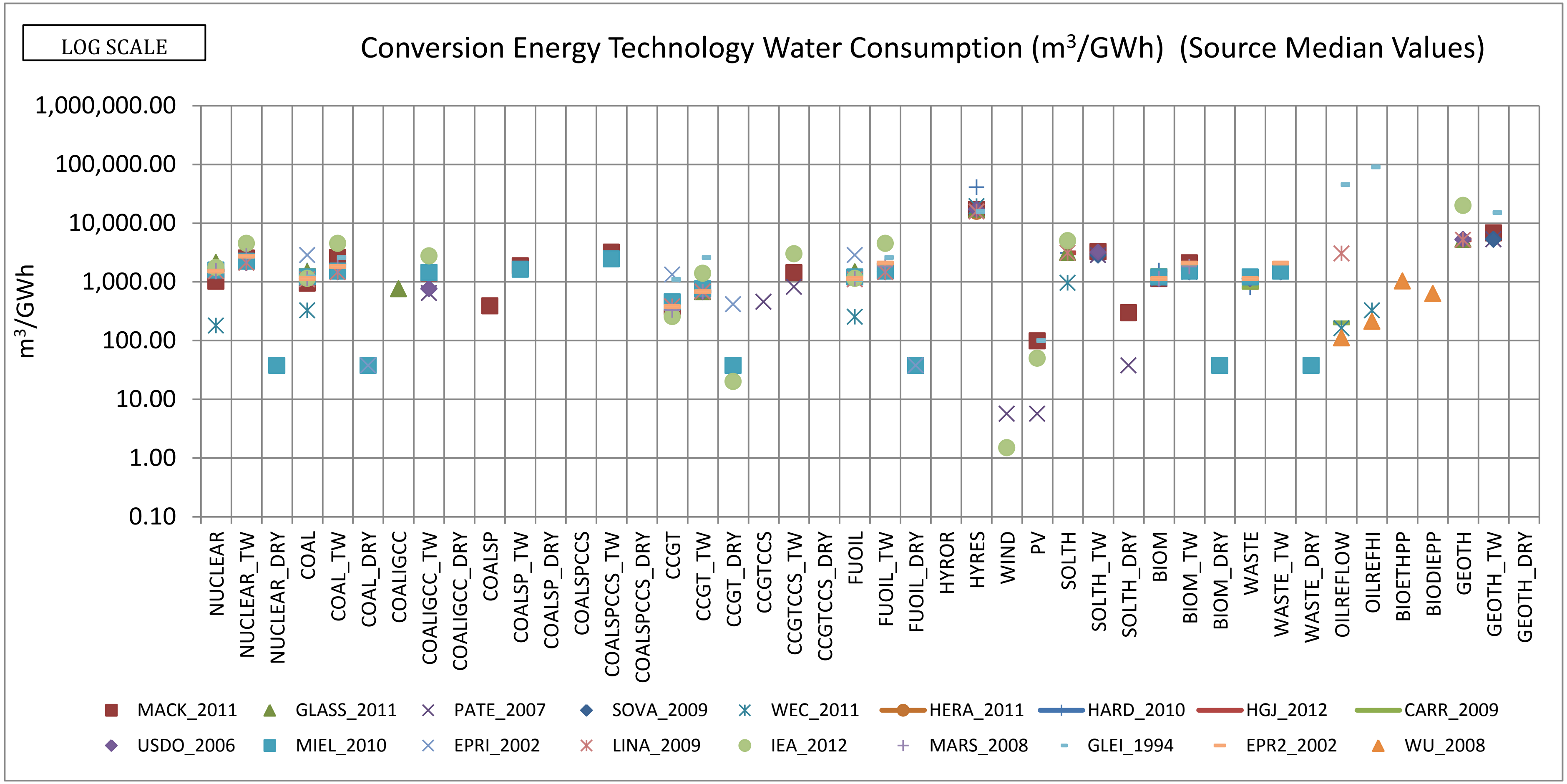

Figure 2: Range of water consumption values (m3/GWh) for various energy conversion technologies

Abbreviations: TW Tower Cooling, COALSP Coal Supercritical, IGCC Integrated Gasification Combined Cycle, CCS Carbon Capture Storage, CCGT Combined Cycle Gas Turbine, FUOIL Fuel Oil, SOLTH Solar Thermal, BIOM Bio Mass, OILREFHI Oil Refinery High Complex

Figure3

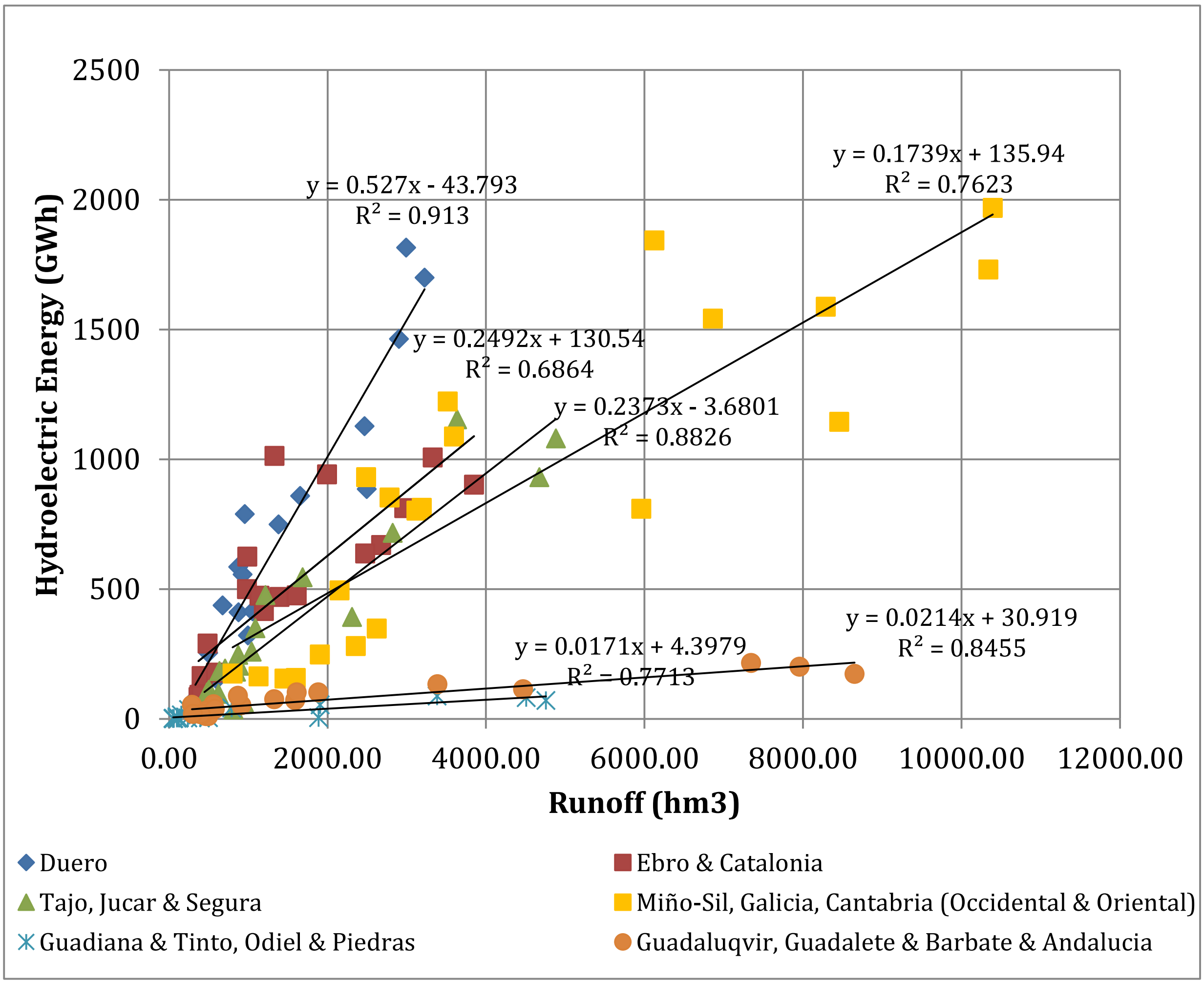

Figure 3: Correlations between runoff and hydroelectric production

Figure4

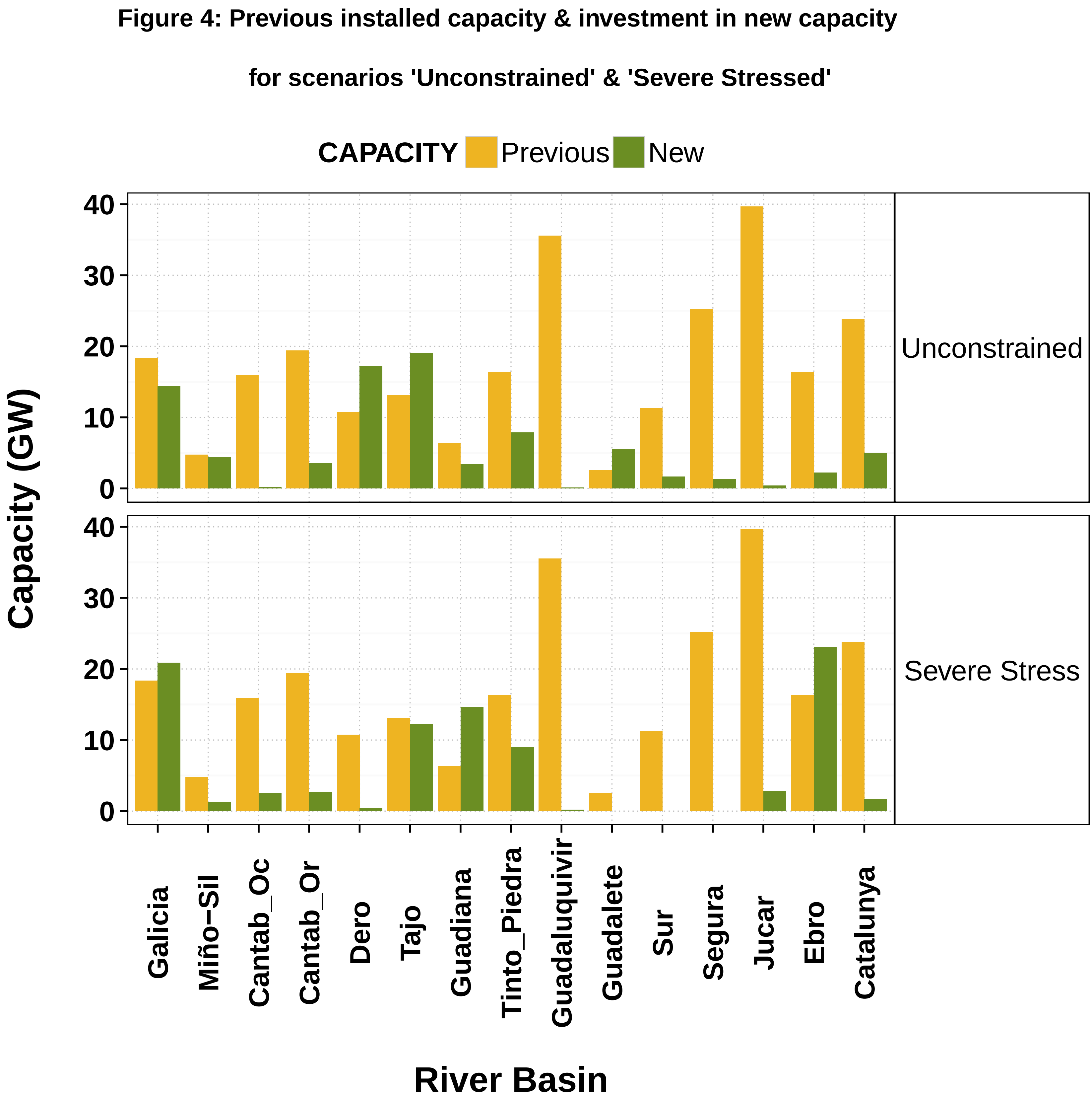
Figure 4: Previous installed capacity & investment in new capacity
for scenarios 'Unconstrained' & 'Severe Stressed'
CAPACITY
Previous
New
Capacity (GW)
0
10
20
30
40
Unconstrained
Severe Stress
Galicia
Miño–Sil
Cantab_Oc
Cantab_Or
Dero
Tajo
Guadiana
Tinto_Piedra
Guadaluquivir
Guadalete
Sur
Segura
Jucar
Ebro
Catalunya
River Basin

Figure5

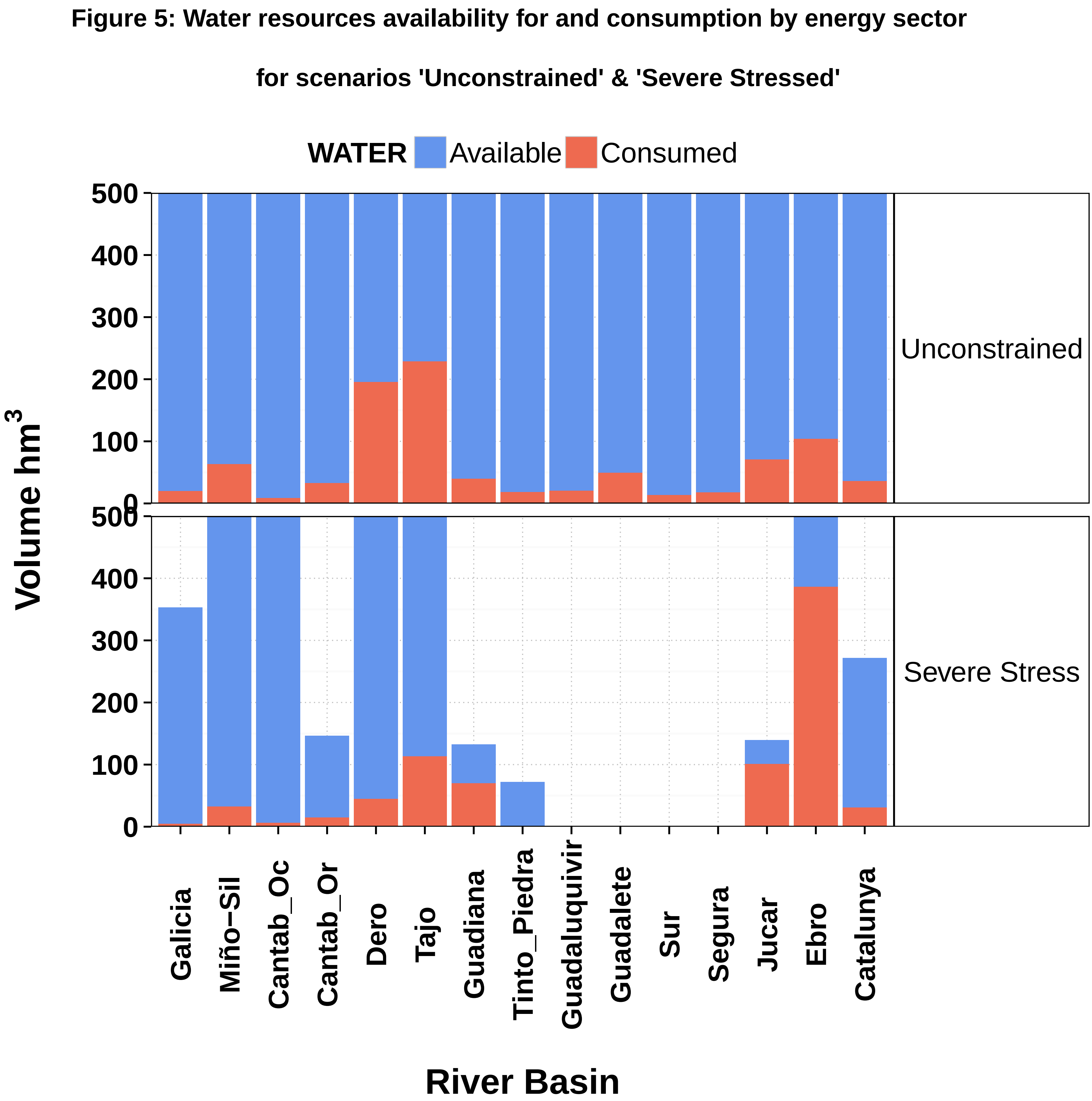
Figure 5: Water resources availability for and consumption by energy sector
for scenarios 'Unconstrained' & 'Severe Stressed'
WATER
Available
Consumed
Volume hm³
500
400
300
200
100
0
Unconstrained
Severe Stress
Galicia
Miño–Sil
Cantab_Oc
Cantab_Or
Dero
Tajo
Guadiana
Tinto_Piedra
Guadaluquivir
Guadalete
Sur
Segura
Jucar
Ebro
Catalunya
River Basin

Figure6

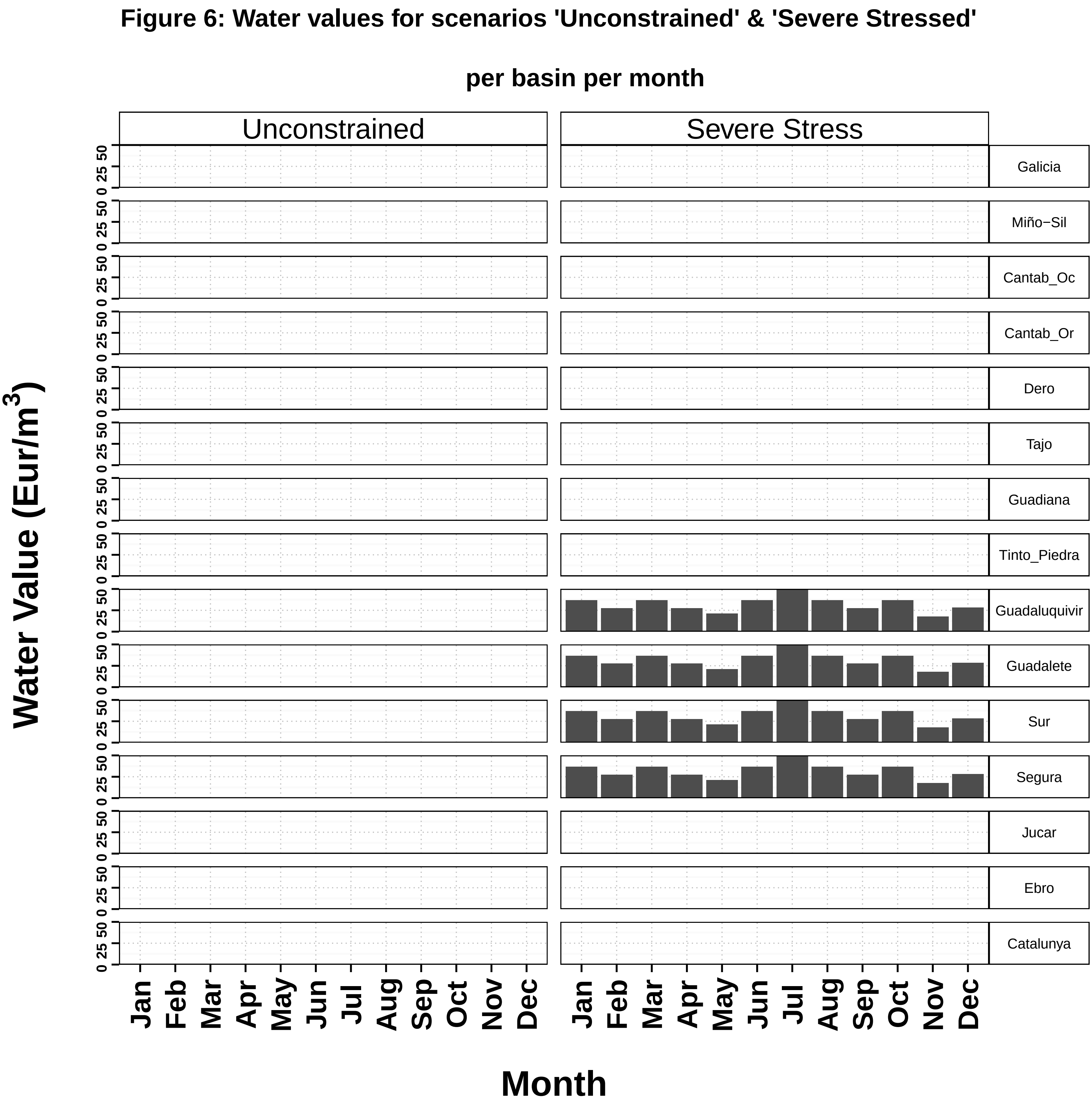
Figure 6: Water values for scenarios 'Unconstrained' & 'Severe Stressed'
per basin per month
Unconstrained
Severe Stress
Galicia
Miño−Sil
Cantab_Oc
Cantab_Or
Dero
Tajo
Guadiana
Tinto_Piedra
Guadaluquivir
Guadalete
Sur
Segura
Jucar
Ebro
Catalunya
0 25 50
Water Value (Eur/m3)
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month

Figure7

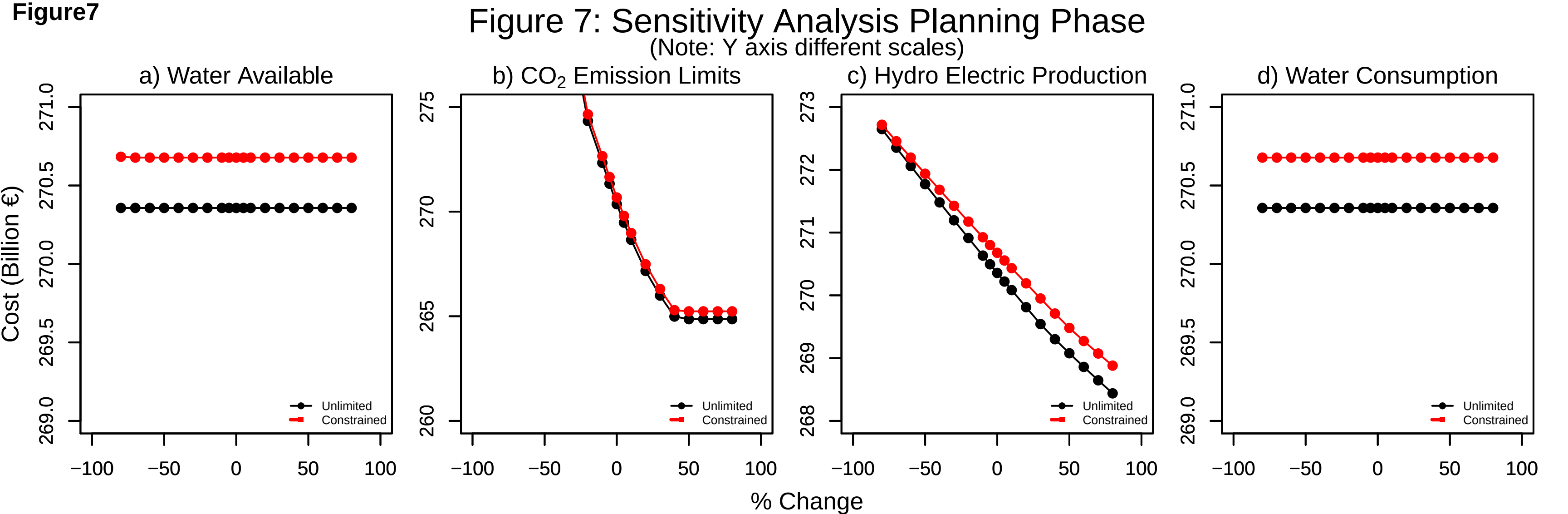

Figure 7: Sensitivity Analysis Planning Phase
(Note: Y axis different scales)
a) Water Available
b) CO_2 Emission Limits
c) Hydro Electric Production
d) Water Consumption
Cost (Billion €)
% Change
Unlimited
Constrained

Figure8

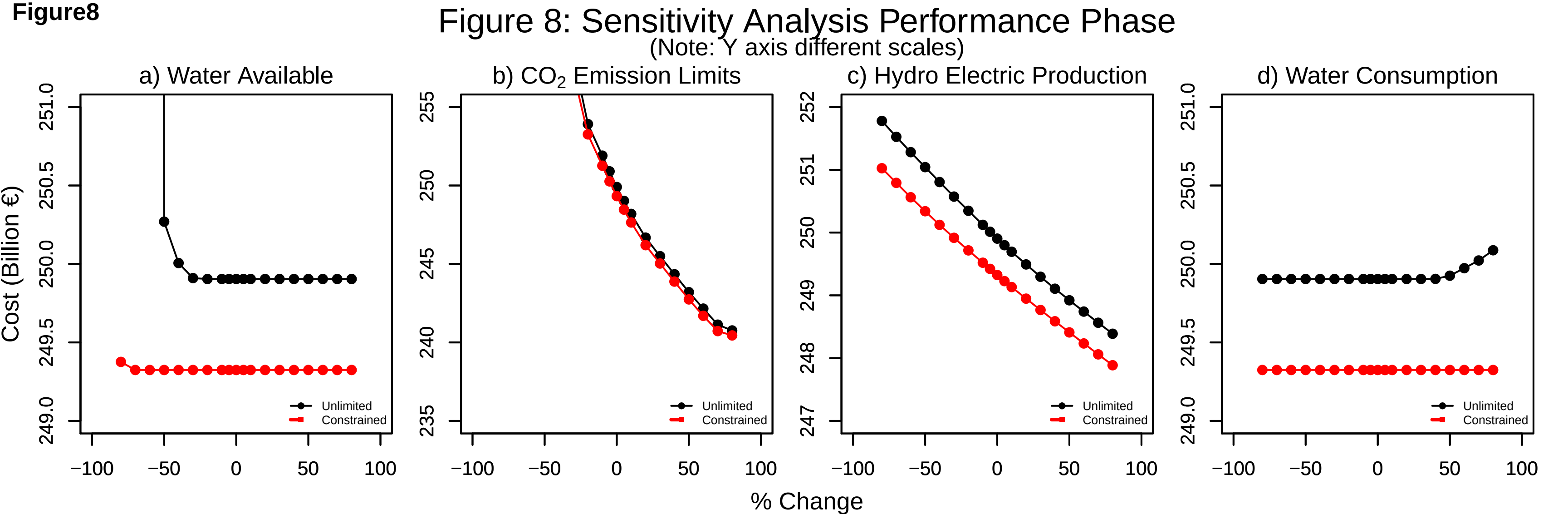
Figure 8: Sensitivity Analysis Performance Phase
(Note: Y axis different scales)
a) Water Available
b) CO_2 Emission Limits
c) Hydro Electric Production
d) Water Consumption
Cost (Billion €)
% Change
Unlimited
Constrained
249.0
249.5
250.0
250.5
251.0
235
240
245
250
255
247
248
249
250
251
252
−100
−50
0
50
100