The economic impact of climate-induced regional water constraints in the Spanish energy sector[1]

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Abstract

Freshwater is becoming a limited resource in some parts of the world as a result of increasing demands (due to population growth and urbanization) and decreasing water resources (due to climate change and pollution). There is increasing competition for this limited resource between the agriculture, residential, industrial and energy sectors. Therefore, there is a need for an integrated analysis of some of these sectors to achieve efficient allocations of these resources. This paper provides an integrated analysis of the impacts of climate-induced water scarcity on the Spanish energy sector. An existing energy model is modified by including water consumption by energy technologies and regional water constraints. The effects on energy technology investments, operation schedules, foreign dependence and distribution are analyzed. The results show that ignoring water constraints can lead to sub-optimal decisions in energy investments, operation and import decisions.

Keywords: Energy, water, economic impact

1 Introduction

The nexus between two scarce and strategic resources, water and energy, is direct and well known. Water is needed to cool thermal power plants, to irrigate biofuels, or to produce electricity in hydro power plants. On the other hand, energy is required to pump underground water, to potabilize (or desalinate) it, to distribute it to users and to treat it.

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This relationship is becoming much more relevant lately. The increase of world's population, together with economic development, is increasing global demands for water and energy, and therefore intensifying the possible conflicts that may arise among them.

The International Energy Agency estimates that world energy demand will increase between 35 and 45% in 2035, something that will require massive investments in generation and transport infrastructures, and will also increase the pressure over fossil resources, which will still supply between 75 and 80% of the global energy demand.

As for the amount of global water, it is roughly constant (about 1.4 billion km^3) (Gleick & Palaniappan, 2010). Of the total about 97.5% is saline water in oceans and only 2.5% is freshwater suitable for human agriculture and domestic needs. Of the 2.5% about 70% is trapped in glaciers and ice caps. Moreover, the freshwater available per capita is decreasing due to the increase in population, economic development and lifestyle changes. Already, around 1.2 billion or one fifth of the global population live in regions of physical water scarcity which is defined as less than 1,000 cubic meters of annual water supply per person (UNESCO, 2012). In addition to physical water scarcity, another problem is human access to existing water resources as a result of the regional distribution, local infrastructure and water policies (United Nations Development Programme (UNDP), 2006). Accessible freshwater resources are further decreasing due to pollution, groundwater depletion and climate change (resulting in receding glaciers, reduced stream and river flows, and shrinking lakes). In locations where water stress is increasing, competition between the agriculture, urban, industrial and energy sectors for water is also increasing.

Hoff (Hoff, 2011) estimates an increase of 70% in world agriculture production by 2050 and a 50% increase in primary energy production by 2035. The International Energy Agency in the World Energy Outlook 2012 (IEA, 2012) estimates the world energy production in 2010 to be responsible for 15% of total withdrawals, predicted to increase by 20% by 2035. Water consumption is expected to increase by 85% as a result of higher efficiency plants with advanced cooling as well as biofuel expansion.

Thus, the demand for energy, water and food is expected to increase in some regions of the world as a result of life style changes, population increase and migration to urban centers. At the same time our finite sources of water are expected to decrease in some regions as a result of climate change and pollution. The regions where these two situations overlap will need to plan and manage their resources in order to meet the demand while managing the corresponding tradeoffs in the economic, agricultural, industrial, environmental and residential sectors. The situation is further complicated by the interdependencies of the sectors, and calls for an integrated management approach.

This paper proposes a first look at this integrated management for Spain, modeling together water and energy in order to understand what are the implications for the energy sector of a climate-induced water scarcity. Section 2 reviews briefly the state of the art on this issue. Section 3 describes the methodology used for this integrated analysis, and Section 4 presents some preliminary results. Section 5 offers some conclusions.

2 State of the art

There have been several quantitative analyses on the use of water for energy services as well as energy for water services. These serve as useful inputs to models and to get a sense of how the two sectors are inter-connected. Table 1 summarizes the sources of various quantitative studies on water use for energy production used to create Figure 1. As seen in the figure the range of values vary considerably from study to study.

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, Análisis y Evaluación de las Relaciones Entre el Agua y la Energía en España, 2010) (Hardy & Garrido, Challenges and Opportunities related to the Spanish Water-Energy Nexus, 2012)	HARD_2010	Spain
8	(Hardy, Garrido, & Juana, Evaluation of Spain´s Water'Energy Nexus, 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, 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

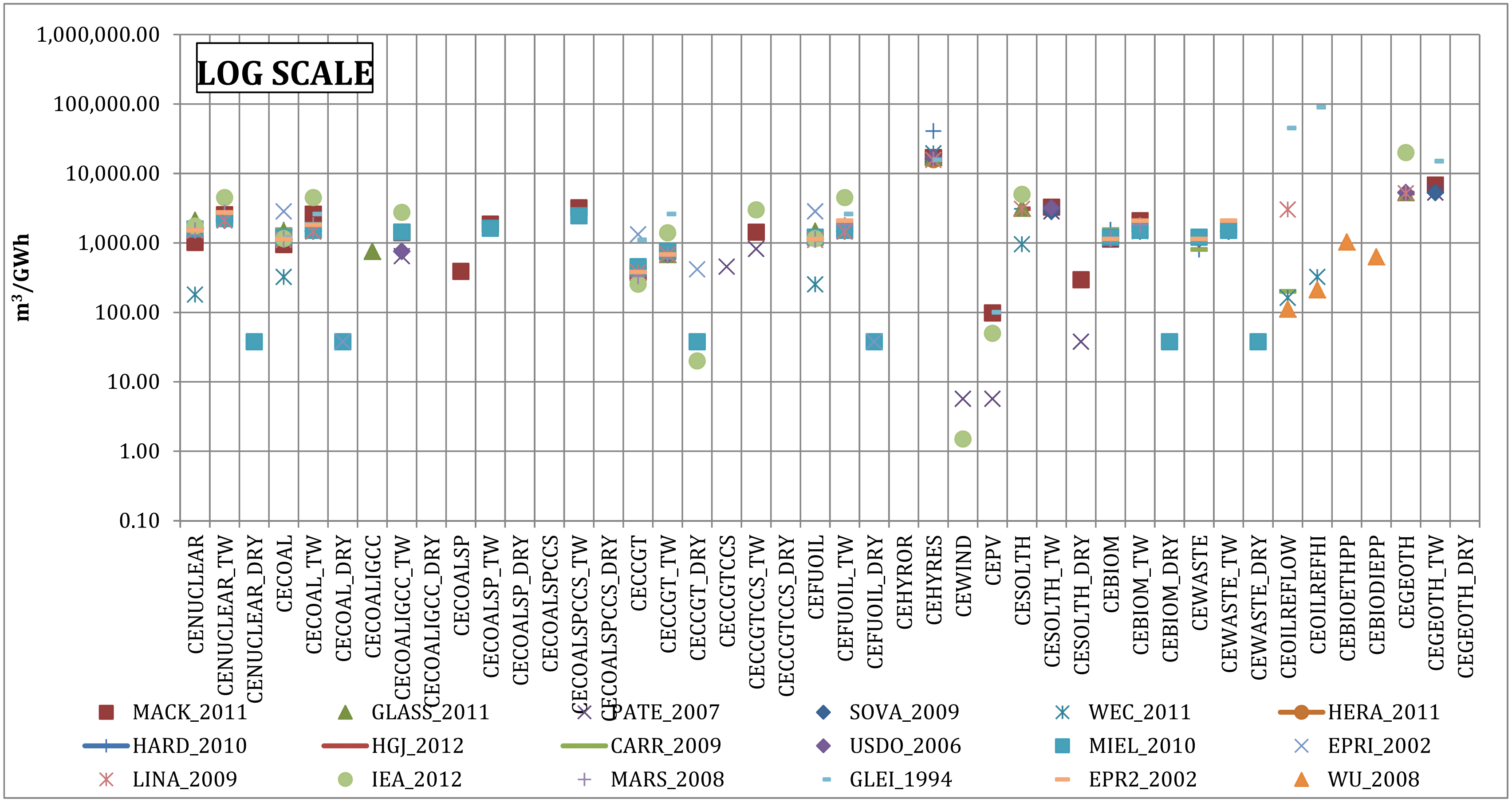

Figure 1: Range of water consumption values (m3/GWh) for various energy conversion technologies

But, in general, all these studies are static and aggregated. On the one hand, they assess the need of water to produce energy, but assuming a fixed energy demand, and without endogenous technological changes. This prevents, among others, to determine the impact of a change in the availability of water in the energy system, since it does not account for the reaction of this system to those changes. On the other hand, only a few studies consider the constraint of having limited water availability.

In addition, water availability, or its changes, varies very significantly from region to region, even within the same country. Therefore, it is important to account for the geographic location of energy production in order to determine correctly the expected impacts. For this it is required to have simulation models for the energy sector that represent correctly the response of the system to changes in the availability of water, and that, on the other hand, feature a reasonable level of geographical disaggregation to represent realistically the different availability of water in different water basins.

Several sector specific models which address only energy (LEAP, MARKAL, MESSAGE) or only water (WEAP, BASINS) already exist and have been well documented. New models which try and integrate the capabilities of both types are currently in various stages of development.

There have been attempts to model the nexus by bundling individual sector specific systems such as the series of projects by the Stockholm Environment Institute (SEI), related to water, energy, land use and food modeling 2014 (SEI, 2012) (Welsch, Hermann, & Howells, 2013). The MARKAL/TIMES energy models developed by the International Energy Agency (IEA) have been adjusted to incorporate water systems for case studies in New York City by the Brookhaven National Laboratory 2009 (Bhatt, Crosson, Horak, & Reisman, 2009) (Bhatt, Friley, & Politis, Energy-Water Nexus Policy Modeling (ETSAP Workshop at IEA),

2013) and for South Africa 2013 (Rodriguez, 2013). The World Bank has incorporated water into the TIMES Energy model (SATIM) developed by the Energy Research Center, at the University of Cape Town, for South Africa. A similar project, an integrated nexus model, TIAM-FR 2012 (Bouckaert, Selosse, Dubreuil, Assoumou, & Maizi, 2012) has been created at MINES ParisTech. The Center for Naval Analyses (CNA) 2014 describes a new mixed-integer linear programming model of the power sector accounting for water used by thermal cooling (CNA Analysis & Solutions, 2014). The National Renewable Energy Laboratory (NREL) 2014 use water-rights in an innovative method to analyze the nexus (Cohen, Macknick, Averyt, & Meldrum, 2014). Bartos & Chester, 2014 (Bartos & Chester, 2014) (Bartos & Chester, 2014) present a water-energy nexus model applied to the US state of Arizona. Cardenal 2014 (Pereira-Cardenal, et al., 2014) present a coupled water-power model which assesses the impacts of climate change on the power system in Spain and Portugal. Bhattacharya & Mitra 2013, (Bhattacharya & Mitra, 2013) present a modified version of the International Institute for Applied Systems Analysis's (IIASA) model, MESSAGE, to capture the water and energy nexus.

The key conclusions and recommendations from an analysis of these projects are that water-energy nexus models need to consider both the geographical and temporal scope in the model. However, most of the models consider a single node electricity system and ignore watershed boundaries. Water scarcity is a regional concern and therefore energy capacity has to be disaggregated in order to identify which energy sources are going to suffer as a result of water shortage.

Models should also include seasonal variations, since the largest water or energy demands may coincide with scarcity periods, something not included in models using annual averages.

Finally, none of the models described have been applied to Spain, a country particularly interesting in this regard. The availability of water in Spain is subject to significant pressures, which may become more acute in a climate change scenario. On the other hand, the Spanish energy system, and in particular electricity generation, depends largely on the availability of water, and is therefore very sensible to climate-induced changes in water. Spain shows also a large regional diversity of uses and availability of water. For example, the Segura basin only has 1% of the Spanish water resources, whereas it uses 5% of them. On average, Spain is considered as a low to medium hydric stress region, whereas again, the Segura basin is a high-stress area.

Therefore, we found there was a need to develop a model able to handle all these requirements, and to apply it to Spain, in a context of climate-change-induced water scarcity. The following section describes the methodology used.

3 Methodology

As explained in the objectives the purpose of this paper is to show the influence of water constraints on the energy sector. For this purpose an already existing model, the MASTER_SO was used. The MASTER_SO is a long-term partial-equilibrium, bottom-up, linear-programming model. It satisfies a given demand of energy services for a chosen year by optimizing the energy production subject to emissions constraints, minimizing the total cost of energy services. This model has been programmed in GAMS and considers the entire lifecycle of the energy production from energy extraction all the way to the final user. For more details on the model refer to López-Peña et al (2013) (López-Peña, Linares, & Pérez'Arriaga, 2013).

The model considers a single node energy sector, that is, it considers the entire energy sector as well integrated by means of transportation and distribution networks for oil, gas and electricity. The model assumes that geographic features and locations within the system do not have any significant impacts. This assumption may not hold when water constraints are added to the equation.

The model is divided into twelve months, each of which is further divided into two working and non-working days. These are further divided into five load levels. The year chosen for the simulation has been 2050, since that allowed us to see already some changes in water availability due to climate change, while at the same time keeping many assumptions about energy technologies availability, potential and costs.

In order to account for water constraints, the existing MASTER_SO model was modified by including the water used by each energy production process as well as a constraint limiting the amount of water used to be less than the water available. The single node energy model was divided into fifteen river basins and the installed energy capacity was distributed by river basin. The assumptions considered regarding technologies, costs, or emission levels are consistent with the Energy Roadmap 2050 of the European Commission.

The fifteen river basins used in the model are shown in Table below.

Table 2: River Basins used in the Model

River Basin	**Names Used in Model**
Galicia Costa	01_Gal_Costa
Miño - Sil	02_Mino_Sil
Cantábrico Occidental	03_Cantbr_Oc
Cantábrico Oriental	04_Cantbr_Or
Duero	05_Duero
Tajo	06_Tajo
Guadiana	07_Guadiana
Guadalquivir	08_Tint_Od_Pdra
Tinto, Odiel y Piedras	09_Guadaluquivir
Guadalete - Barbate	10_Guad_Barbte
Cuencas Mediterráneas Andaluzas	11_C_Med_Andlz
Segura	12_Segura
Júcar	13_Jucar
Ebro	14_Ebro
Cuencas Internas de Cataluña	15_CICat

The existing energy capacity was divided amongst the different basins based on various data sources as described below:

- Nuclear power plants, oil refineries and regasification power plants were distributed according to their individual geographic locations.

- Thermal power plants were distributed using Enipedia (TU Delft), the online database of the Technical University of Delft (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).

Climate change scenarios were based on the predictions for water resources made by the Centro de Estudios y Experimentación de Obras Públicas (CEDEX) (CEDEX, 2012). Two emission scenarios were chosen with the corresponding changes in water resources as shown in Table 3 below.

Table 3: CEDEX Climate Change Scenarios

	Variation in Runoff (%) (2041-2070)		**Variation in Water Available (%) (2041-2070)**	
River Basin	**A2i**	**A2ii**	**A2i**	**A2ii**
	CGCM2-FIC	**ECHAM4-FIC**	**CGCM2-FIC**	**ECHAM4-FIC**
Galicia Costa	-4	-31	-14	-37
Miño-Sil	-6	-34	-11	-28
Cantabrico Occidental	-4	-27	-20	-38
Cantabrico Oriental	-2	-24	-11	-34
Duero	-13	-41	-10	-37
Tajo	-16	-48	-13	-50
Guadiana	-23	-58	-19	-58
Tinto, Odiel Y Piedras	-23	-58	-8	-65
Guadalquivir	-18	-55	-7	-55
Guadalete Y Barbate	-18	-55	-12	-56
Cuencas Mediterraneas	-15	-50	-13	-41

Andaluzas				
Segura	-10	-39	-11	-44
Jucar	-11	-28	-11	-32
Ebro	-6	-26	-14	-27
Distrito Fluvial de Cataluña	-2	-5	-5	-11

Finally, we should also mention how we have dealt with changes in water availability regarding hydro production. Basically, we have used a representative reservoir for each basin in which we aggregate all electricity production. We have calculated an energy coefficient for each basin (or for an aggregation of basins, when data was not available) to translate changes in water availability into changes in electricity production. These coefficients have been calculated by regressing total runoff and changes in reservoir levels (from Ministerio de Agricultura, Medio Ambiente y Alimentación) against hydro electricity production (from Red Electrica de España) The following figure shows the regression functions obtained.

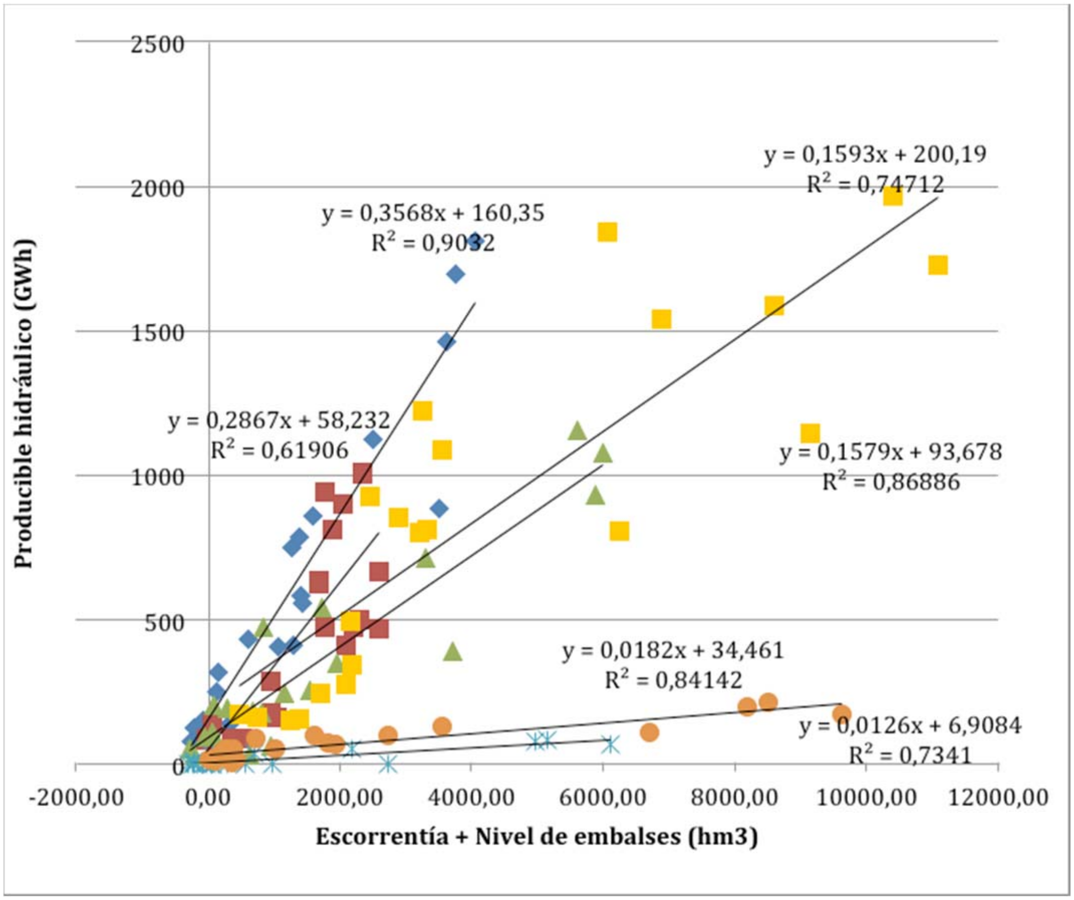

Figure 2: Correlation between runoff and reservoir levels with hydro production (Blue: Duero; Red: Ebro + Cataluña; Green: Tajo+Segura+Júcar; Yellow: MiñoSil+Cantábrico; Orange: Guadalquivir, Light blue: Guadiana)

Of course, the model is limited by the quality of data available. As discussed earlier the ranges of data for water consumption parameters are considerably large. Water available for energy has also been represented by constant values based on average resource and demand values per basin. However, we still feel that we are able to produce some approximations that illustrate the relevance of water for the energy sector.

4 Results

Several scenarios were run to compare the impacts of climate-induced water constraints on the energy sector. The following section lists the scenarios that were run and then discusses the results describing the impacts of water scarcity on operation and investment decisions. Other outputs such as costs, shadow prices, foreign dependency and water usage are also discussed.

The scenarios differ in the water availability and also in whether they allow for new investments in the energy sector or not. By allowing or not investments in the energy sector we want to assess the advantages of an adaptation strategy: if we allow for new investments we are allowing the system to adapt to the new, water-constrained situation, whereas when we fix the energy capacity installed we represent the situation in which water scarcity arrives by surprise.

Model Scenario	**Energy Investments Allowed**	**Water Available Quantity**
2_Nexus	Yes	Unlimited
4_WR_WT	Yes	Real Data (2014)
5_FXWRWT	No	Real Data (2014)
6_FXCCiWT	No	Climate Change A2i
7_FXCCiiWT	No	Climate Change A2ii
8_CCiWT	Yes	Climate Change A2i
9_CCiiWT	Yes	Climate Change A2ii

4.1 Current water scenario

Economic impact of water scarcity

We first compare the unlimited water “Nexus” scenario to the realistic water distribution, “WRWT”. Total costs for the “Nexus” and “WRWT” case are almost the same with a slight increase in WRWT due to the unavailability of energy in certain locations. Table 4 shows some of the outputs from the two models.

Table 4: Scenario “Nexus” vs. “WRWT”

Output	2_Nexus	3_WRWT
Total system costs (Giga Eur)	270.3196	270.359

Cost of final energy technologies (Giga Eur)	170.035	170.0472
Total Energy Dependence (%)	74.6056	74.8425
Electricity Generation Fixed Cost (GEur)	2.8097	2.8091
Electricity Generation Variable Cost(GEur)	0.2574	0.2573

Water Resources and Usage

In Figure 3 we can see that in the realistic case, four river basins (Guadalquivir, Guadalete y Barbate, Cuencas Mediterraneas Andaluzas and Segura) already use all their water resources for other uses (agriculture and residential) so there is no water available for energy. The water consumption due to energy production is simply shifted to other basins. Figure 4 shows the distribution of water availability during the year for the realistic case.

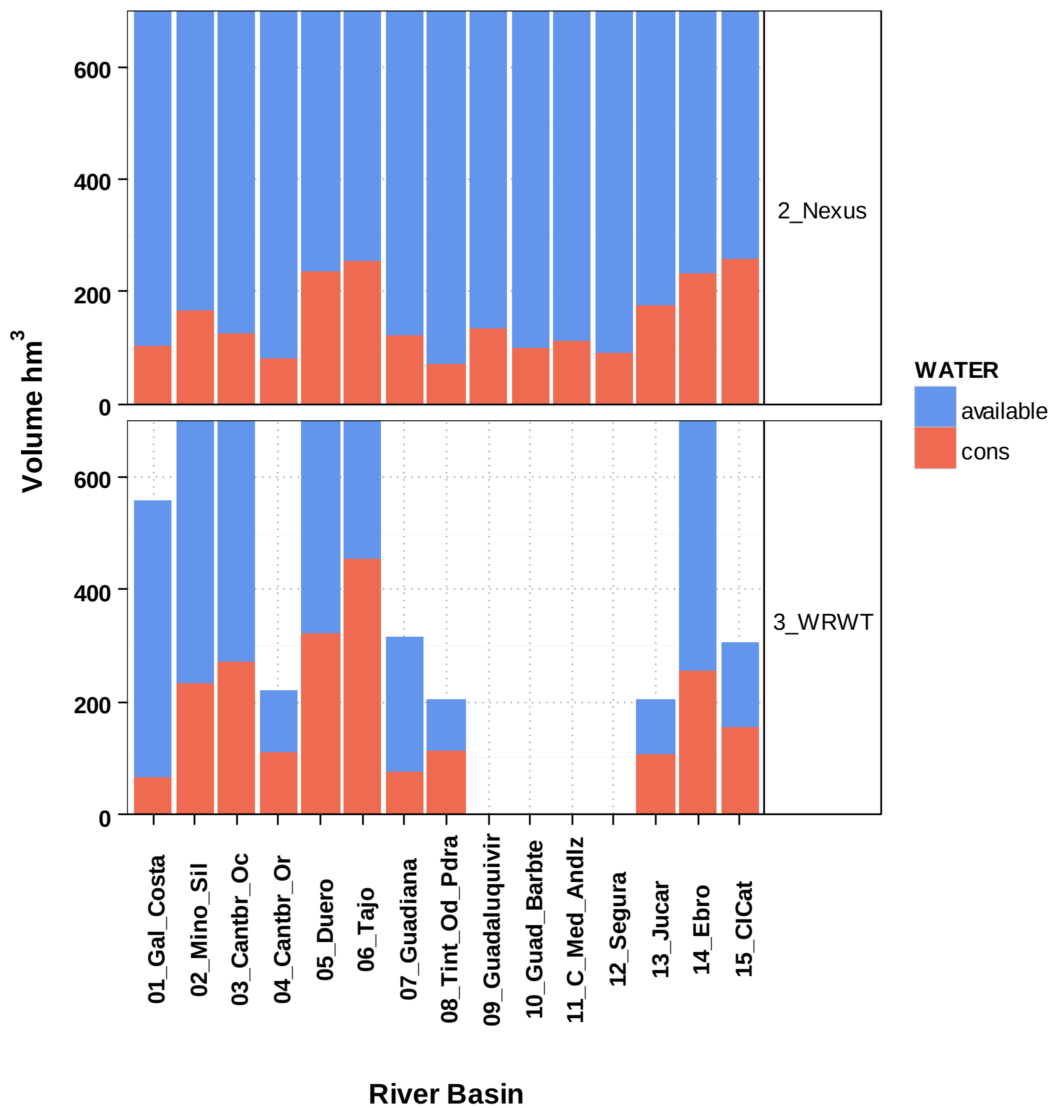

Figure 3: Water Resources Availability and Consumption for scenarios "Nexus" vs. "WRWT"

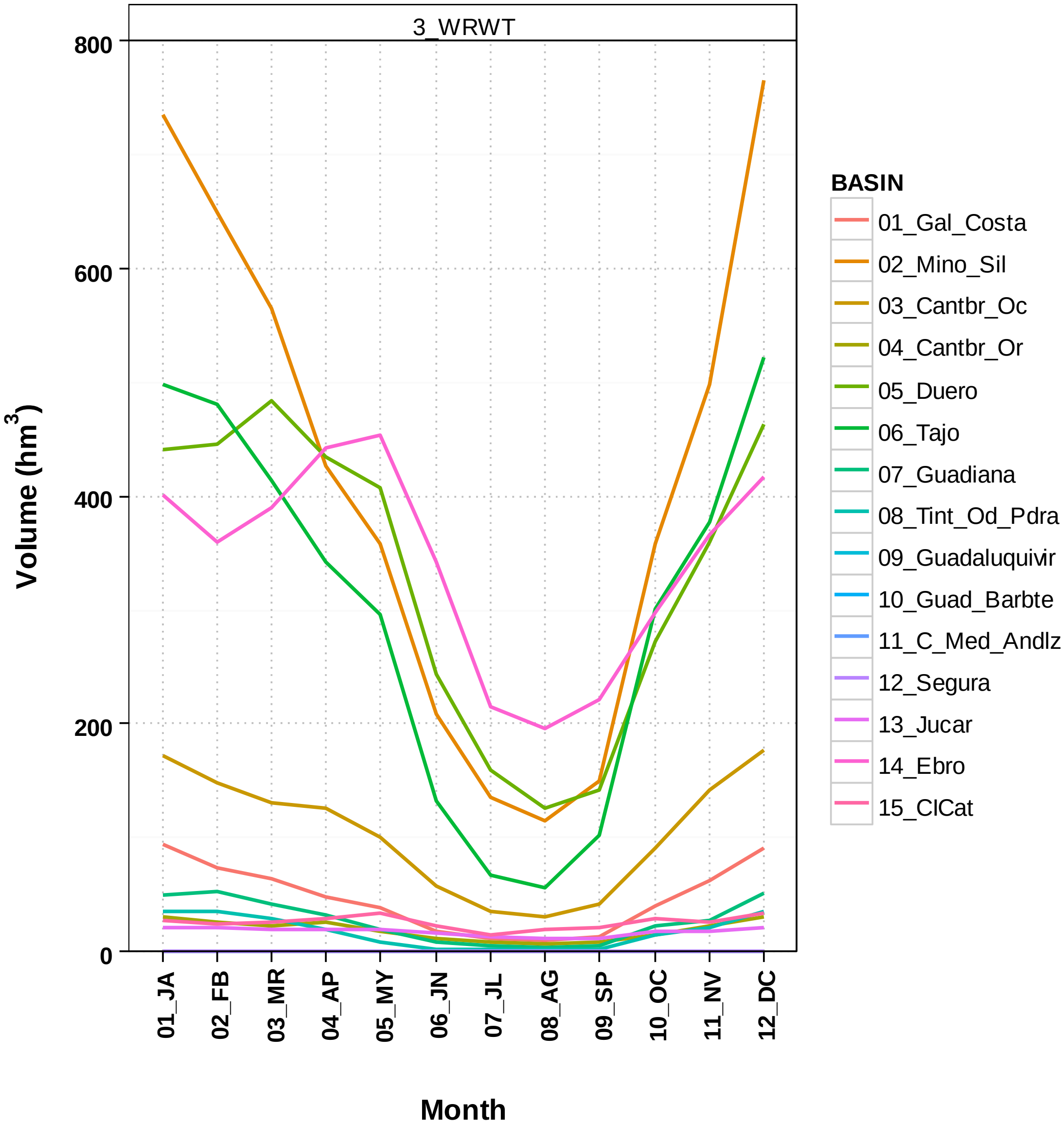

Figure 4: Water Resources Availability and Consumption for scenario “WRWT”

Investments

The distribution of the new installed capacity for each scenario is shown in Figure 5 below. As seen in the figure when water becomes limited in the case of scenario "WRWT" the new capacity is redistributed to reflect the water availability. The only capacity installed in the water stressed basin (Segura) is mini-hydro which does not consume any water.

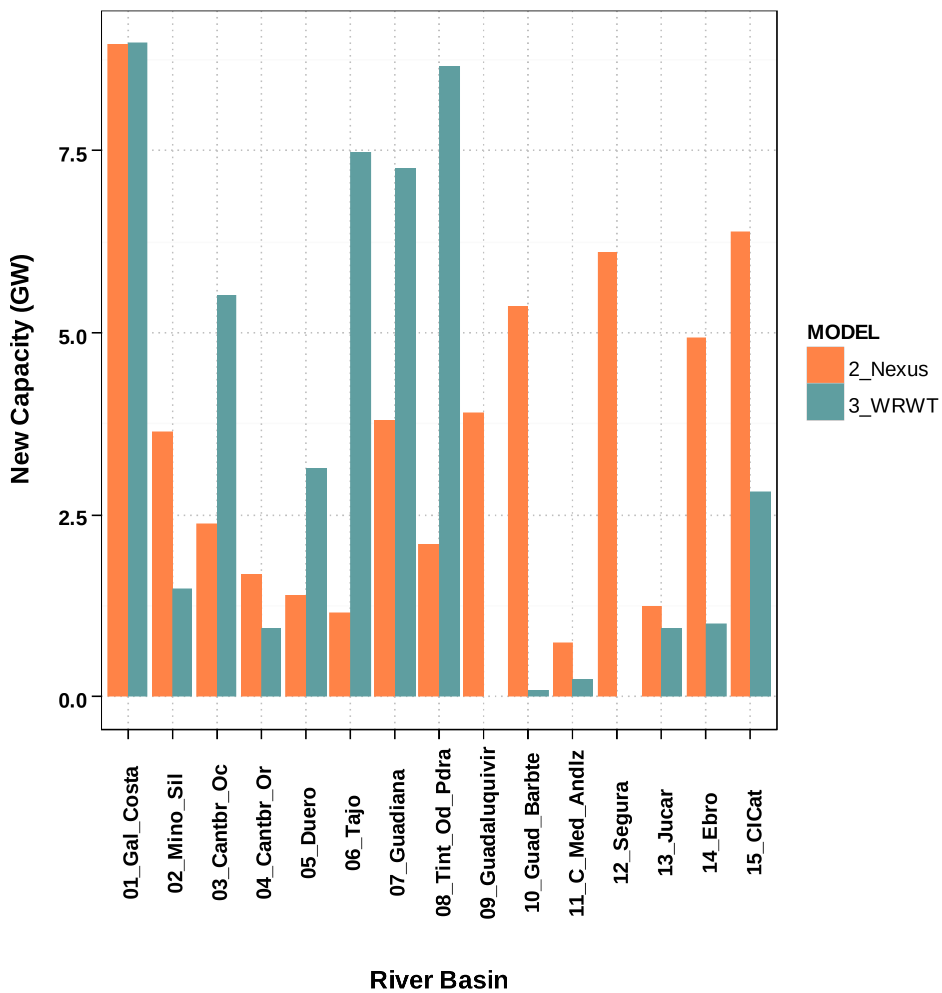

Figure 5: Investment in New Capacity for scenarios "Nexus" & "WRWT"

Water Values

The shadow price of water is shown in Figure 6 below. As seen in the figure, water only has a value when and where it is scarce. The “Nexus” scenario with unlimited water gives no value to water, while the “WRWT” scenario with limited water in four basins shows a corresponding price. This shadow price can in fact be quite high, higher than the price of water in agriculture or residential uses, and therefore enough to facilitate trades if that was a possibility.

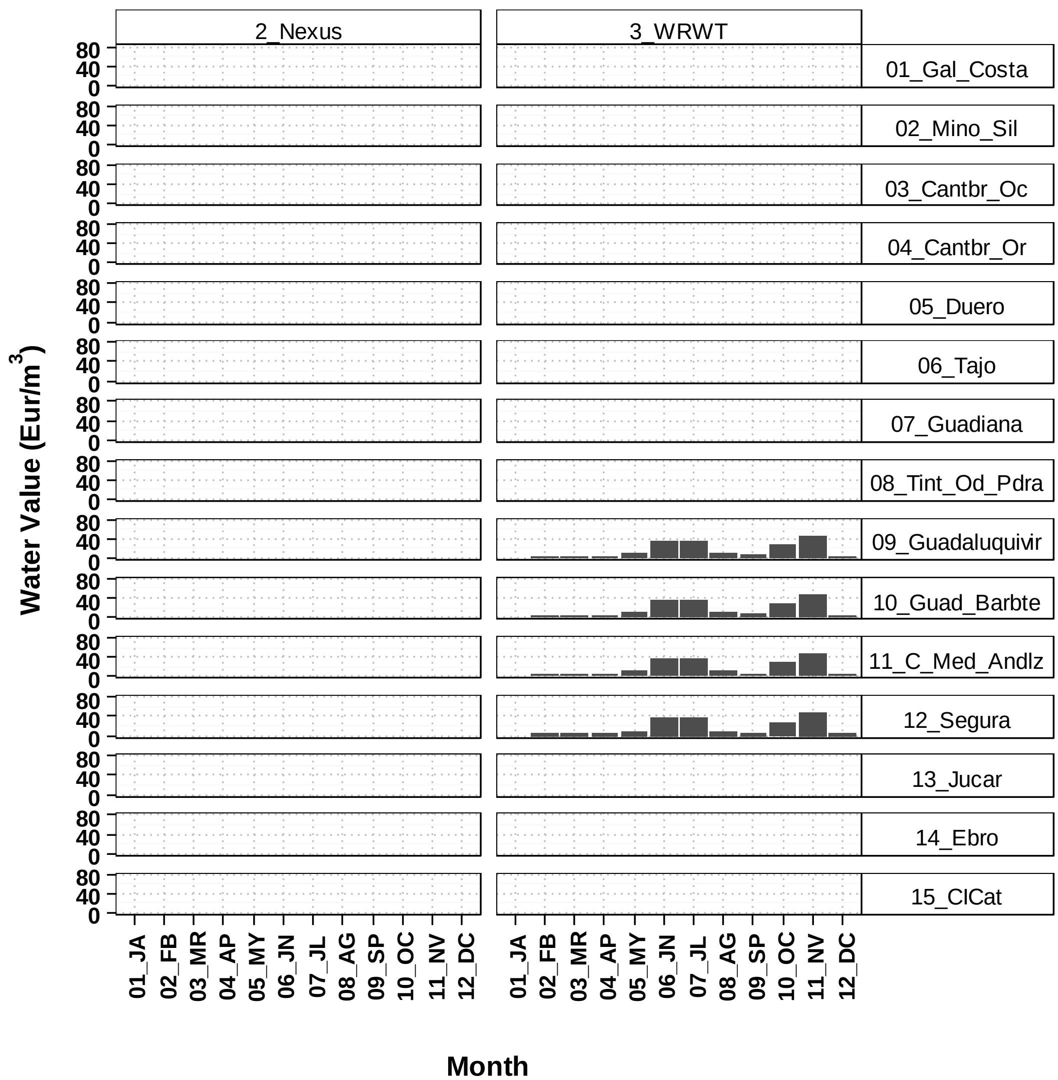

Figure 6: Water Values for scenarios “Nexus” & “WRWT”

4.2 Climate change scenarios, no adaptation

Economic impacts

The installed capacity decisions from scenario “WRWT” above were based on the assumption that the water situation in Spain will remain as it is today in 2050. Based on this the capacity is fixed in model “FXWT” and then compared to the climate change scenarios in which there are reduced water resources: “FXCCiWT” and “FXCCiiWT”. The following table shows a summary of some of the outputs from the three models. As seen in the chart the cost of system increases with a decrease in water resources. The increase in costs is primarily due to the increase in imports which replace the reduction in hydro resources in the system.

Table 5: Scenarios “FXWT”, “FXCCiWT” and “FXCCiiWT”

Output	6_FXWT	7_FXCCiWT	8_FXCCiiWT
Total system costs (Giga Eur)	249.6322	249.9059	250.569
Final Energy Activity Cost (GigaEurs)	169.7856	170.1048	170.4908
Total Energy Dependence (%)	75.2736	75.3916	75.741
Primary Energy Import Costs (GigaEurs)	13.0525	13.0544	13.2213

Active Capacity

Due to the reduction in hydro resources in each climate change scenario there is a reduction in the hydro-energy output. This is replaced by each scenario with regasification technology as shown in Figure 7 which consumes no water. Regasification technology as introduced in the model is assumed to use sea-water for heating the LNG gas.

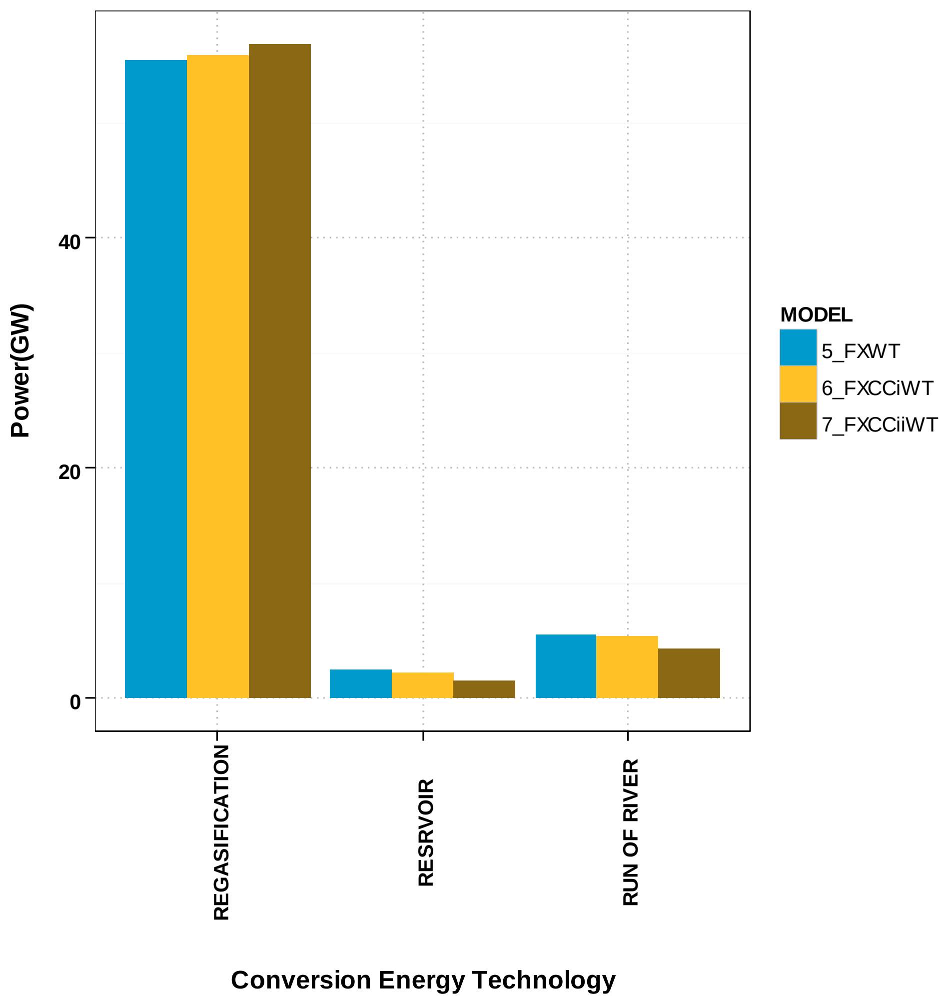

Figure 7: Total active capacity for scenarios “FXWT”, “FXCCiWT” & “FXCCiiWT”

Operation

As seen in Figure 8, the water efficient regasification technology is used in water scarce basins like Segura. The amount of regasification is also increased as the quantity of water available is reduced.

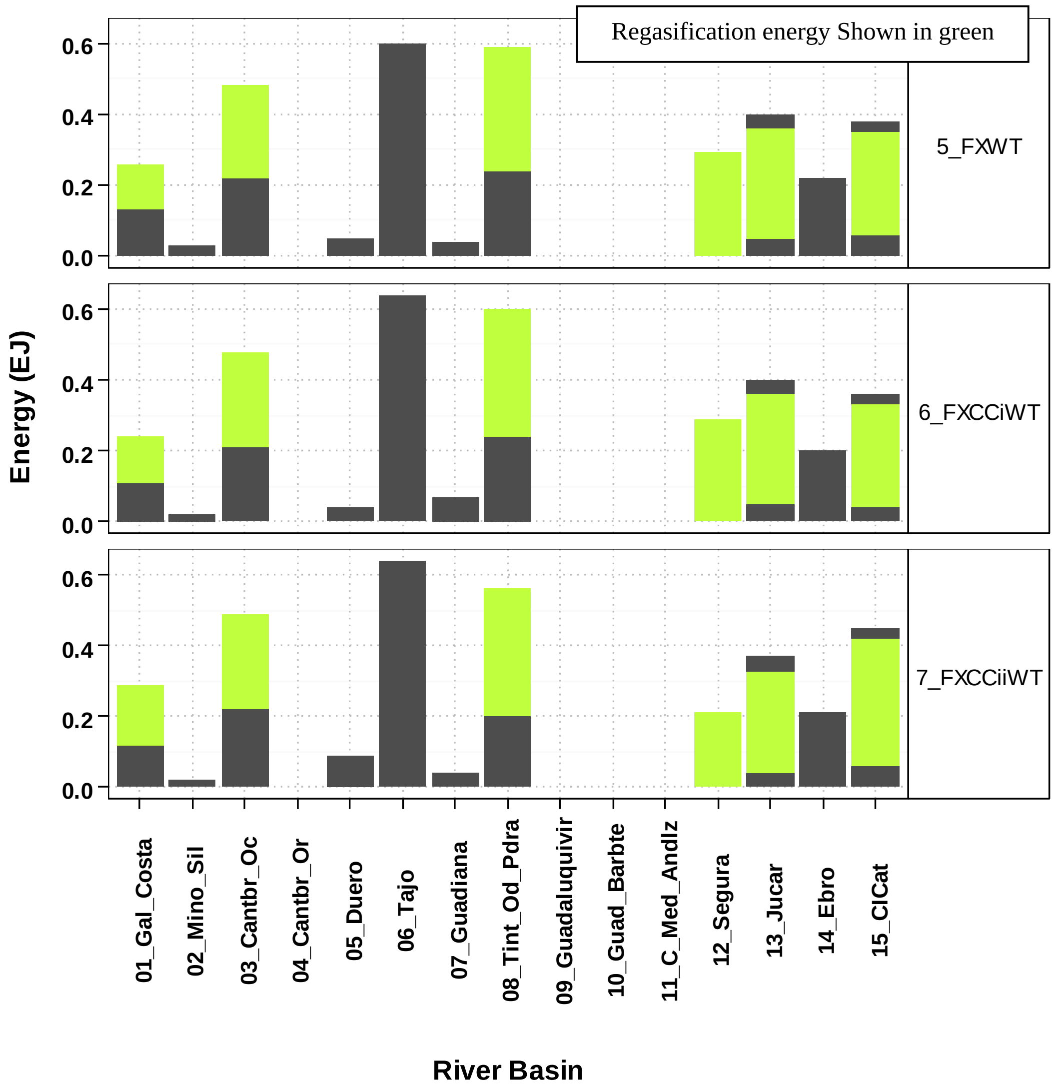

Figure 8: Comparison of Distributed Energy Output “FXWT”, “FXCCiWT” & “FXCCiiWT”

4.3 Effects of adaptation to climate change

Economic impacts

We now compare the impacts of planning for reduced water conditions as a result of climate change. The following summary Figure 8 shows some of the results of running these scenarios together. The CCi and CCii cases also reduce the final energy delivery costs and energy dependence.

Table 6: Comparison of “FXCCiWT”, “FXCCiiWT”, “CCiWT” & “CCiWT”

DATA	6_FXCCiWT	7_FXCCiiWT	8_CCiWT	9_CCiiWT
Final Energy Technology Costs (GEurs)	170.1048	170.4908	169.9847	169.7611
Dependence (%)	75.3916	75.741	74.8417	74.8388

Water Resources

Water resources and consumption is shown for the different scenarios in Figure 9. As seen in the figure the water consumed in each basin (besides from the four basins with no water available for energy) do not reach their limits. This means that the model is not constrained in these basins.

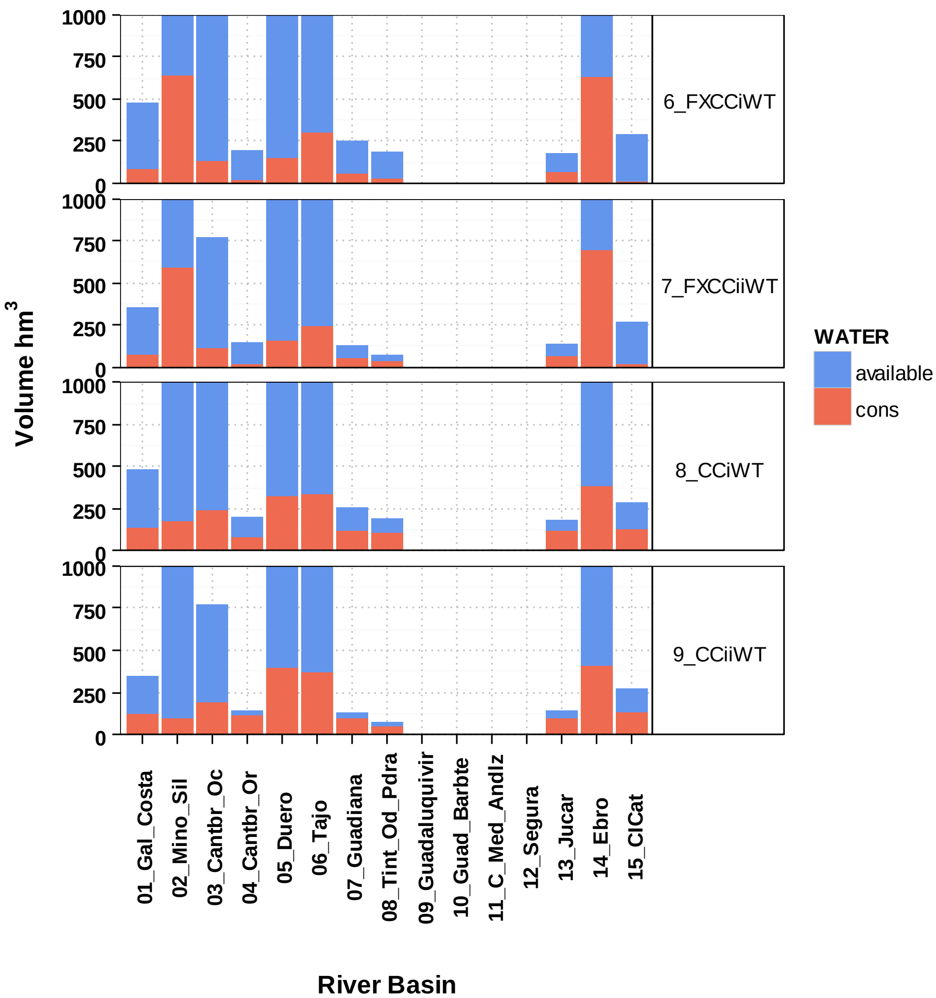

Figure 9: Water available and consumed for “FXCCiWT”, “FXCCiiWT”, “CCiWT” & “CCiWT”

Operation

The scenarios in which investments are allowed, pick slightly different technologies when given a choice. This is shown in Figure 10 where the investment scenarios have more wind and biogas as compared to the fixed models.

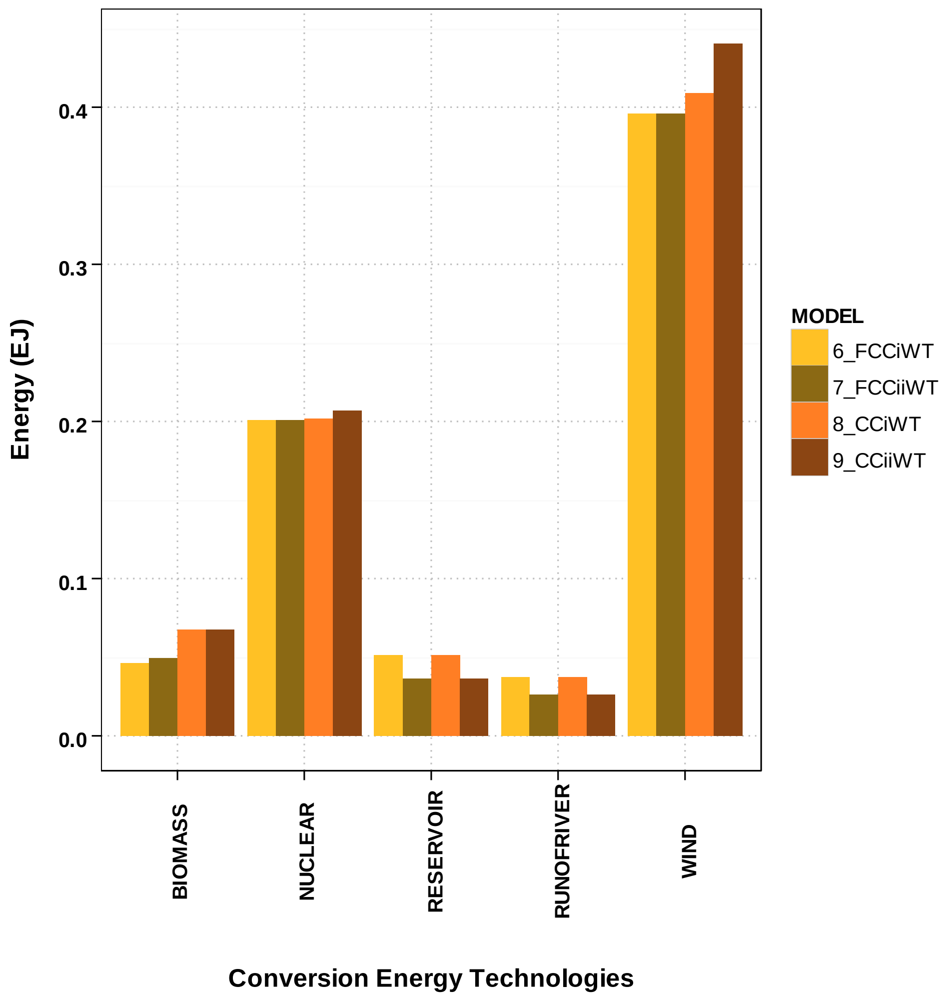

Figure 10: Energy Production for “FXCCiWT”, “FXCCiiWT”, “CCiWT” & “CCiWT”

Water Values

Finally we see that because of the different choice of energy production and investment the different scenarios result in different water shadow prices for the constrained basins depending on the time period. Again, water values in water-constrained basins are significantly higher than water prices for other uses.

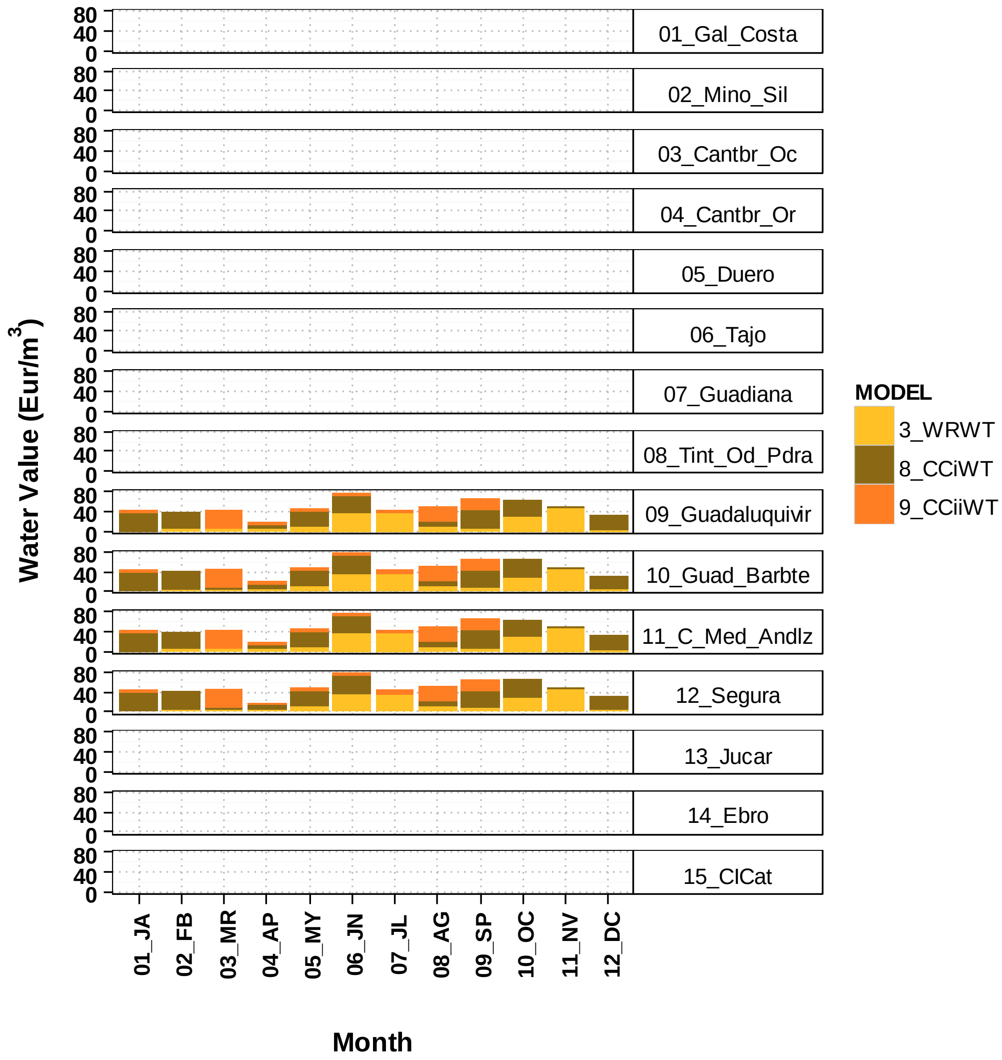

Figure 11: Water Shadow Prices for “FXCCiWT”, “FXCCiiWT”, “CCiWT” & “CCiWT”

5 Conclusions

The major conclusion of this study is that a lower availability of water has consequences on the energy sector in Spain: the cost of supplying energy increases, although not much. This change in costs results from the need to substitute energy generation technologies, now limited in their production, by others not constrained by water, or by energy-efficient demand technologies.

These costs can be determined in an absolute basis, or as opportunity costs, assessing the extent to which energy costs would be reduced if more water were available. In this regard, the shadow prices estimated for water show how the energy sector may in some cases (for particular basins and periods) be willing to pay water at a higher price than the current one in some uses (such as agriculture). That is, the water constraint for the energy sector could be solved, at least partially, if water could be traded.

The second relevant conclusion is that the adaptation to climate-induced water scarcity is very important. In those scenarios where we allow the system to respond (by changing investments) to this reduced water availability, the cost increase is lower, as well as shadow prices.

The changes in the system come, on one hand, from shifting generation technologies to demand technologies. On the other hand, hydro production is also reduced, since runoff is also reduced. This also has consequences on the reliability of the electricity sector: absent fossil fuels (because of the decarbonisation requirements), hydro is the energy source responsible to provide backup for solar and wind energy. In fact, we see that in the most drastic climate change scenarios (with adaptation), there is an increase in the investment in pumping, precisely to provide this backup.

We should also remind that the year chosen for the simulation is 2050 in which, according to the Energy Roadmap of the European Commission, generation technologies must be either renewables or nuclear for the electricity system to be carbon-free. In this regard, climate change scenarios do not introduce significant changes to the reference scenario.

We should also highlight as a conclusion of the study the relevance of using a geographically-disaggregated model. As may be seen in the results, the changes in water availability also mean a change in the distribution of the generation technologies. Again, adaptation scenarios result in larger changes, at lower costs.

Results also show that the basins in the Southeast are very limited in their availability of water, and therefore the model does not allow for electricity generation in these areas. This may have relevant consequences on the way electricity demand is served in them.

Considering the large uncertainties associated to a simulation for 2050, we consider the approximations of the modeling exercise quite modest, and that they do not have a large influence on the robustness of the conclusions offered. Anyway, we recommend interpreting the results not in absolute terms, but in relative ones, comparing scenarios against each other. In this regard, the bottom-up formulation offers some security in that the impacts simulated are realistic. Improvements in the model should not change significantly the direction and magnitude of the results.

References

[1] P. H. Gleick and M. Palaniappan"Peak water limits to freshwater withdrawal and use," *(PNAS) Proceedings of the National Academy of Sciences of the United States of America*, vol. 107, no. 25, pp. 11155-11162, June 2010.

[2] UNESCO, "The United Nations World Water Development Report 4," World Water Assessment Programme (WWAP), United Nations Educational, Scientific and Cultural Organization (UNESCO), Paris, France, ISBN 978-92-3-104235-5, 2012. [Online]. Available: http://unesdoc.unesco.org/images/0021/002156/215644e.pdf

[3] P. H. Gleick, *The World's Water 2008-2009: The Biennial Report on Freshwater Resources*. Washington, DC, USA: Island press, 2009.

[4] United Nations Development Programme (UNDP), "Human Development Report 2006 - Beyond Scarcity: Power, poverty and the global water crisis," United Nations Development Programme (UNDP), New York, USA, Report, 2006.

[5] IEA, "Water for Energy: Is Water Becoming a Thirstier Resource," in *World Energy Outlook 2012*, 1st ed.: Organization for Economic Cooperation and Development (OECD), 2012, ch. 17, pp. 501-528.

[6] H. Hoff, "Understanding the Nexus. background Paper for the Bonn2011 Conference: The Water, Energy and Food Security Nexus," Stockholm Environment Institute, Stockholm, Sweden, 2011.

[7] UNEP. (2012, January). A Glass Half Empty: Regions at Risk Due to Groundwater Depletion. Global Environmental Alert Services (GEAS), United Nations Environmental Program (UNEP), [Web Article]. [Online]. Available: http://na.unep.net/geas/getUNEPPageWithArticleIDScript.php?article_id=76 [Accessed: 14 January 2014]

[8] D. Glassman, M. Wucker, T. Isaacman, and C. Champilou, "The Water-Energy Nexus: Adding Water to the Energy Agenda," World Policy Institute, New York, NY, March 2011.

[9] WEC, "Water for Energy," World Energy Council (WEC), London, United Kingdom, ISBN: [978-0-946121-10-6], 2010. [Online]. Available: http://www.worldenergy.org/documents/water_energy_1.pdf

[10] E. Grubert, F. C. Beach, and M. E. Webber"Can switching fuels save water? A life cycle quantification of freshwater consumption for Texas coal- and natural gas-fired electricity," *Environmental Research Letters*, vol. 7, no. 4, December 2012.

[11] B. K. Sovacool and K. E. Sovacool"Identifying future electricty-water tradeoffs in the United States," *Energy Policy*, vol. 37, no. 7, pp. 2763-2773, July 2009, doi: 10.1016/j.enpol.2009.03.012.

[12] R. Pate, M. Hightower, C. Cameron, and W. Einfeld, "Overview of Energy-Water Interdependencies and the Emerging Energy Demands on Water Resources," Sandia National Laboratories, New Mexico, NM, SAND 2007-1349C, March 2007.

[13] I. Herath, M. Deurer, D. Home, R. Singh, and B. Clothier"The water footprint of hydroelectricity: A methodological comparison from a case study in New Zealand," *Journal of Cleaner Production*, vol. 19, no. 14, pp. 1582-1589, September 2011.

[14] L. Hardy and A. Garrido, "Análisis y Evaluación de las Relaciones Entre el Agua y la Energía en España," Centro de Estudios e Investigación para la Gestión de Riesgos Agrarios y Medioambientales, Universidad Politécnica de Madrid, Madrid, Papeles de Agua Virtual - Número 6, ISBN: 978-84-96655-78-2, September 2010.

[15] L. Hardy and A. Garrido, "Challenges and Opportunities related to the Spanish Water-Energy Nexus," in *Water, Agriculture and the Environment in Spain: can we square the circle?*, Lucia De Stefano and M. Ramón LLamas, Eds. Leiden, The Netherlands: CRC Press, 2012, ch. 14, pp. 177-189.

[16] L. Hardy, A. Garrido, and L. Juana"Evaluation of Spain´s Water'Energy Nexus," *International Journal of Water Resources Development*, vol. 28, no. 1, pp. 151-170, 2012.

[17] A. M.R. Carrillo and C. Frei"Water: A key resource in energy production," *Energy Policy*, vol. 37, no. 11, pp. 4303-4312, November 2009, doi:10.1016/j.enpol.2009.05.074.

[18] USDOE, "Energy Demands on Water Resources: Report to Congress on the Interdependency of Energy and Water," United States Department of Energy (USDOE), 2006. [Online]. Available: http://www.sandia.gov/energy-water/docs/121-RptToCongress-EWwEIAcomments-FINAL.pdf

[19] E. Mielke, L. D. Anadon, and V. Narayanamurti, "Water Consumption of Energy Resource Extraction, Processing, and Conversion," Belfast Center for Science and International Affairs, Harvard Kennedy School, Cambridge, MA, Discussion Paper #2010-15, October 2010. [Online]. Available:

http://belfercenter.ksg.harvard.edu/files/ETIP-DP-2010-15-final-4.pdf

[20] J. Macknick, R. Newmark, G. Heath, and K. Hallett, "A Review of Operational Water Consumption and Withdrawal Factors for Electricity Generating Technologies," National Renewable Energy Laboratory (NREL), Technical Report, NREL/TP-6A20-50900, March 2011. [Online]. Available: http://www.nrel.gov/docs/fy11osti/50900.pdf

[21] H. Poole, T. Younos, and R. Hill, "Water Dependency of Energy Production and Power Generation Systems," Virginia Polytechnic Institute and State University, Blacksburg, USA, VWRRC Special Report No. SR46-2009, July 2009.

[22] EPRI, "Comparison of Alternate Cooling Technologies for California Power Plants: Economic, Environmental, and Other Tradeoffs," Electric Power Research Institute, Palo Alto, CA, 500-02-079F, February 2002. [Online]. Available: http://www.energy.ca.gov/reports/2002-07-09_500-02-079F.PDF

[23] P. Linares and G. Sáenz de Miera, "Implications for Water of the World Energy Scenarios," Economics for Energy, Working Paper, 2172/8437, January 2010.

[24] D. M. Marsh, "The Water-Energy Nexus: A Comprehensive Analysis in the Context of New South Wales," Faculty of Engineering and Information Technology, University of Technology, Sydney, Sydney, Australia, PhD Thesis, 2008.

[25] P. H. Gleick"Water and Energy," *Annual Review of Energy and Environment*, vol. 19, pp. 267-299, 1994.

[26] Electric Power Research Institute, "Water & Sustainability (Volume 3): U.S. Water Consumption for Power Production—The Next Half Century," EPRI (Electric Power Research Institute), Palo Alto, USA, Topical Report, 1006786, March 2002.

[27] M. Wu, M. Mintz, M. Wang, and S. Arora, "Consumptive Water Use in the Production of Bioethanol and Petroleum Gasoline ," Center for Transportation Research - Energy Systems Division, Argonne National Laboratory, USA, Report, 2008.

[28] E. Antipova, A. Zyryanov, D. McKinney, and A. Savitsky"Optimization of Syr Darya Water and Energy Uses," *Water International*, vol. 27, no. 4, pp. 504–516, December

2002.

[29] SEI, "Integrating the WEAP and LEAP systems to support planning and analysis at the water-energy nexus," Stockholm Environment Institute (SEI), Somerville, MA, USA, 2012.

[30] M. Welsch, S. Hermann, and M. Howells, "Why CLEWS matter: A Focus on the Energy System of Mauritius," KTH Royal Institute of Technology, Stockholm, Sweden, Presentation, 2013.

[31] V. Bhatt, K. Crosson, W. Horak, and A. Reisman, "The Energy-Water Nexus (EWN): a New York City Pilot Study," Brookhaven National Laboratory, University of Dayton, USA, Presentation, 2009.

[32] V. Bhatt, P. Friley, and S. Politis, "Energy-Water Nexus Policy Modeling (ETSAP Workshop at IEA)," Brookhaven National Laboratory, Paris, France, Presentation, June 2013.

[33] D. J. Rodriguez, "Quantifying the tradeoffs of the Water-Energy Nexus," The World Bank, Stockholm, Sweden, Presentation, 2013.

[34] S. Bouckaert, S. Selosse, A. Dubreuil, E. Assoumou, and N. Maizi"Analyzing water supply in future energy systems using the TIMES Integrated Assessment Model (TIAM-FR)," *SYSTEMICS, CYBERNETICS AND INFORMATICS*, vol. 10, no. 1, 2012.

[35] CNA Analysis & Solutions, "A Clash of Competing Necessities: Water Adequacy and Electric Reliability in China, India, France, and Texas," CNA Corporation, Arlington, USA, IRM-2014-U-007191, July 2014.

[36] S. M. Cohen, J. Macknick, K. Averyt, and J. Meldrum, "Modeling Climate-Water Impacts on Electricity Sector Capacity Expansion," National Renewable Energy Laboratory (NREL), USA, Preprint of Conference Paper, NREL/CP-6A20-61435, May 2014.

[37] M. D. Bartos and M. V. Chester"The Conservation Nexus: Valuing Interdependent Water and Energy Savings in Arizona," *Environmental Science & Technology*, vol. 48, no. 4, pp. 2139-2149, January 2014.

[38] M. Bartos and M. Chester. (2014, January). Supporting Information for: The Conservation Nexus: Valuing Interdependent Water and Energy Savings in Arizona. [PDF].

[Online]. Available: http://pubs.acs.org/doi/suppl/10.1021/es4033343

[39] S. Pereira-Cardenal et al."Assessing climate change impacts on the Iberian power system using a coupled water-power model," *Climate Change*, vol. 364, no. 126, p. 351, August 2014.

[40] A. Bhattacharya and B. K. Mitra, "Water-Energy-Climate Nexus: An assessment of long term energy scenario in South and Southeast Asia," Institute for Global environmental Strategies (IGES) - Internation institute for Applied Systems Analysis (IIASA), Hayama, Japan, Presentation, 2013.

[41] Á. López-Peña, P. Linares, and I. Pérez'Arriaga, "MASTER.SO: a Model for the Analysis of Sustainable Energy Roadmaps. Static Optimisation version," Escuela Técnica Superior de Ingeniería, Instituto de Investigación Tecnológico (IIT) Universidad Pontificia Comillas, Madrid, Working Paper, IIT-11-157A, February 2013.

[42] TU Delft. Enipedia. [Online Database]. [Online]. Available: http://enipedia.tudelft.nl/wiki/Spain/Powerplants

[43] CNE, "Régimen especial de producción de Energía Eléctrica en España," Comisión Nacional de Energía, Spain, Informe mensual de ventas de energía del régimen especial, 2013.

[44] CEDEX, "Estudio de Los Impactos Del Cambio Climático en los Recursos Hídricos y las Masas de Agua, Effecto del Cambio Climático en los Recursos Hídricos Disponibles en los Sistemas de Explotación," Centro de Estudios Hidrográficos, Centro de Estudios y Experimentación de Obras Públicas (CEDEX), CEDEX: 43-308-5-001, December 2012.

[45] B. Woods. (2006, April). A World Without Water. True Vision, London. UK. [Documentary]. [Online]. Available: http://truevisiontv.com/films/details/80/a-world-without-water

[46] J. H. Hoover, "The Arizona Water-Energy Nexus: Electricty for Water and Wastewater Services," Department of Geography and Regional Development, University of Arizona, USA, 2009.

[47] K. Averyt et al."Water use for electricity in the United States: an analysis of reported and calculated water use information for 2008," *Environmental Research Letters*, vol.

8, no. 1, 2013.

[48] Pacific Institute. Water Conflict Chronology List. [Web Page]. [Online]. Available: http://www.worldwater.org/conflict/list/ [Accessed: 14 January 2014]

[49] USGS. Groundwater Depletion. United States Geological Survey (USGS), [Web Page]. [Online]. Available: http://ga.water.usgs.gov/edu/gwdepletion.html [Accessed: 14 January 2014]

[50] National Geographic. 8 Mighty Rivers Run Dry From Overuse. National Geographic, [Web Page]. [Online]. Available: http://environment.nationalgeographic.com/environment/photos/rivers-run-dry/ [Accessed: 14 January 2014]

[51] MNN. 7 Lakes and rivers that are drying up. Mother Nature Network (MMN), [Web Page]. [Online]. Available: http://www.mnn.com/earth-matters/wilderness-resources/photos/7-lakes-and-rivers-that-are-drying-up/aral-sea [Accessed: 14 January 2014]

[52] A. Brooke, D. Kendrick, A. Meeraus, R. Raman, and R. Rosenthal, "GAMS A User's Guide," GAMS Development Corporation, Washington DC, USA, December 1998.

[53] KTH (Royal Institute of Technology). (2013) Overview of on-going CLEW Initiatives. [Online]. Available: http://www.clews.info/documents/CLEW_Examples.pdf

[54] M. Welsch et al."Adding value with CLEWS – Modelling the energy system and its interdependencies for Mauritius," *Applied Energy*, vol. 113, pp. 1434-1445, January 2014.

[55] K. Averyt et al., "Freshwater use by U.S. Power Plants: Electricity's thirst for a precious resource," Union of Concerned Scientists, Cambridge, MA, USA, A report of the Energy and Water in a Warming World initiative, November 2011.