Exploring Spain's water security options in the face of uncertain climate and energy futures. An integrated water-energy analysis.

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Abstract

The WRI estimates that Spain will become a severely water stressed region by 2030 in all of its future scenarios considered. Getting water to the south-eastern basins will become a top political concern of critical importance. The issue is not a new one and several strategies have been proposed in the past, the most famous being the Ebro-River basin transfer program and the AGUA program each with supported by different governments. In addition to the need for physical water in the southern basins the situation is complicated further by the possibility of different energy pathways taken by Spain in meeting emission requirements and other EU regulations. This paper explores the different options for water security, while considering the impacts of climate change on temeprature, water availability and power plant cooling needs as well as the impacts of different energy strategies such as the penetration of nuclear, biofuels and other renewables into the energy mix. The water strategies considered include combinations of inter-basin transfers, desalination, groundwater pumping, rain-water harvesting, reuse as well as end user demand management in both the energy and water sectors. A fully integrated water-energy nexus model, SPATNEX, is used to analyze the coupled water-energy system. The model accounts for the complete life-cycle of both systems as is both spatially and temporally disaggregated. Optimal strategies for different scenarios are explored and a robust combination of the different options available are proposed to deal with a range of situations.

Keywords: Energy, water, nexus, integrated planning

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Preprint submitted to YSSP Final Report *July 1, 2016*

1. Introduction

It is clear that there is a need to address the increasing constraints in both water and energy systems, resulting from increased total demand due to population growth; increased per capita consumption due to economic changes; climate change impacts on demand and availability patterns; and increased resource consumption intensity due to technological advances [1]. Today, more than a third of the world's population lacks access to freshwater resources, with 1.2 billion people suffering from physical water stress while 1.6 billion lack access due to economic barriers [2, 3, 4]. More than a third of the world's population also lacks access to basic energy services [5], with 1.4 billion people lacking access to electricity and about 2.8 billion still cooking using solid fuels [6] leading to nearly 2 million annual deaths. [7].

The future is very uncertain with several possible socio-economic development pathways, simultaneously framing and shaped by several climate change scenarios [8]. Energy demand is expected to increase by about 40% from 2014 to 2040 [9]. At the same time water demand is predicted to increase by up to 55% by 2050 [10]. This will occur as a result of the increase in global population to about 9 billion [11] and the accompanying increases in food demand, economic growth and industrial activity. While demands are increasing, the amount of global water remains roughly constant at about 1.4 billion km^3 [4] with less than 1% being freshwater available for human uses. Accessible freshwater resources are becoming even more vulnerable due to increased pollution, uncontrolled groundwater depletion and climate change impacts on water availability patterns. According to the Intergovernmental Panel on Climate Change[12], the population at risk of increased water stress due to climate change can reach as high as 2 billion in 2040.

The problem is further complicated by the high interdependence of water and energy. Water is used in all phases of the energy cycle: in extraction and mining, directly in hydropower generation, for power plant cooling and to irrigate biofuel crops. At the same time, energy is needed in all phases of the water cycle: water extraction and pumping, desalination, purification and distribution to end users. In 2010 the world energy production was responsible for 15% of total global water withdrawals, of which about 10% (1.5% of the total water withdrawn) was consumed. The water withdrawal by the energy sector is predicted to increase by 20% in 2035, while water consumption is expected to increase by 85% as a result of higher efficiency plants with advanced cooling technologies as well as due to the possible expansion of biofuel crops [13]. The degree of interdependencies between the two systems can vary regionally based on the distribution of natural resources and existing state of infrastructure. For example, electricity consumption by the water sector varies from 5.8% in Spain (excluding end-water-use energy)[14] to about 9% in the Middle East and North African (MENA) countries [15], 12% in Ontario, Canada and 19% in California [16]. Similarly, the energy sector in the MENA regions consumes less than 0.5% of its freshwater resources, in Spain the energy sector withdraws 25% and consumes about 4%, while in the United States water use for energy accounts for about 40% of freshwater withdrawals and 4% of consumption [17].

The problem to address then, is tackling the issue of expected energy and water scarcity in the future, by improving existing management methodologies. The overall goal is to manage the supply of water and energy to multiple sectors competing for the two resources while meeting the multiple, sometimes conflicting objectives which may include adaptation strategies, costs, emissions, efficiency, international mitigation commitments and other policies.

This paper presents SPATNEX: a model which tracks the flows of energy and water from primary resources, through extraction, purification and conversion processes to final end users via different technology options. The model spatially and temporally synchronizes the water and energy systems in order to account for regional and seasonal variability in energy and water availability, infrastructure and demands. The main purpose of the model is to capture integrated opportunities to make both systems more efficient.

Section 2 reviews contemporary integrated water-energy modeling methodologies and summarizes the strengths and recommendations from these studies. Section 3 then discusses the methodology of the new SPATNEX model, with further details on equations and input parameters provided in supplementary materials Appendix ??. An example policy is examined in a case study for Spain as explained in Section 4. Results of the case study are discussed in Section 5 and show the capabilities of the model to identify, track and react to nexus issues such as water needs and constraints in energy systems and energy needs and constraints in water systems. Section 6 presents some possible future applications of the model and Section

7 discusses some of its limitations. The paper is concluded in Section 8 with a summary of the main results.

2. Literature Review

One of the earliest studies on integrating water into energy models, from 1979 [18], lays out some key pillars which still hold today. These include regional disaggregation of the energy system to watershed boundaries; synergies of cross-sector policies; flexibility in end-user demands and technologies; water quality; and consideration of stochasticity in contrast to deterministic solutions. Today, it is accepted that a system's performance cannot be optimized by optimizing the performance of its subsystems taken in isolation from one another [19].

Water and energy integrated planning has been practiced for some time in multi-purpose hydro electric reservoirs. Popular techniques for long term hydropower generation scheduling are stochastic dynamic programming (SDP) [20] and stochastic dual dynamic programming (SDDP) [21]. The non-linear relationship of hydropower potential with the net head poses several challenges and has been addressed using various modeling techniques, including power-flow relationships [22, 23], mixed-integer linear programming [24, 25], non-linear programming [26] and aggregated reservoir-energy coefficients [27]. While such multi-prupose reservoir studies [28, 27] are important, they only address a small part of the water-energy nexus without addressing other energy technologies or capturing the flows of water and energy resources during other parts of the resource lifecycles.

Technology investments and improvements are crucial long term decisions which need to be addressed taking into account future constraints. Realizing this, several models have been developed to improve energy and water planning taking into account nexus issues. The most common approach has been to take an existing energy model and introduce water consumption parameters for power plant cooling and primary energy resource extraction. A number of different studies have looked at these parameters in detail and are synthesized in a few review papers [29, 30]. Several of these models [31, 32, 33, 34] capture the water consumption by the energy system, but do not limit or link these to actual physical water constraints. These limitations prevent capturing the regional impacts of water scarcity, climate change or water competition with other sectors.

Some methodologies and models also track water use in the energy sector [35, 36, 37, 38]. A few studies look at the broader links in water, energy and other economic sectors using methodologies like the open source Global Change Assessment Model (GCAM) [29, 39], input-output analysis [40, 41] and lifecycle analysis [42, 1].

Realizing the importance of being able to react to water scarcity problems, models were expanded so as to include actual water availability constraints. This led to the development of a few water-responsive energy models [43, 44]. Some soft-linked iterative models have also been created which look for convergence by analyzing energy decisions and the corresponding impacts on water and other systems (SATIM [45], CLEWS [46, 47], PRIMA [48]).

The next step in completing the water energy nexus links was to include a representation of the water system and the corresponding energy consumption. This has been addressed to some degree in a few studies [49, 50, 51, 52] however several issues still remain, such as: improving the hydrological modeling; allowing for optimization of water infrastructure and end-user technolgies; cross-basin water transfers; and finer temporal and spatial synchronization of water and energy systems.

In summary, there have been several attempts to integrate water and energy models, however, developments are still ongoing and many challenges remain to be addressed. There is a tendency to focus exclusively on energy models with water systems being under-represented and physical water resources often ignored. Recent developments [43, 50, 51] show that this trend is changing. It is important to spatially and temporally synchronize the water and energy systems at various lifecycle stages. Reservoir levels need to be linked to future hydro-energy potentials and water quality and temperature impacts on power plant cooling requirements also need to be better represented. The SPATNEX model, presented in this paper, addresses some of these issues by developing a fully coupled spatially and temporally synchronized water-energy model capable of simultaneously optimizing both water and energy systems to improve efficiency in both investment and operation decisions.

3. Methodology

The framework of the SPATNEX model is shown in Figure 1. The model is programmed in GAMS (General Algebraic Modeling System [53]) and is a partial equilibirum linear optimization model. The model can be thought of as consisting of two modules, the energy module and the water module which are inter-connected via various links. Multi-purpose reservoirs provide water for multiple sectors as well as generate electricity. Water consumers govern the amount of water processed in the water system, which has a corresponding energy consumption becoming a variable input for the energy module. In turn, the total energy consumption governs how much energy is processed in the energy system and the corresponding water consumption becomes a variable input for the water model. Throughout the lifecycle of both systems, costs, losses, emissions, water consumption and energy consumption are tracked and can be combined into a global weighted objective function depending on the needs of the planners.

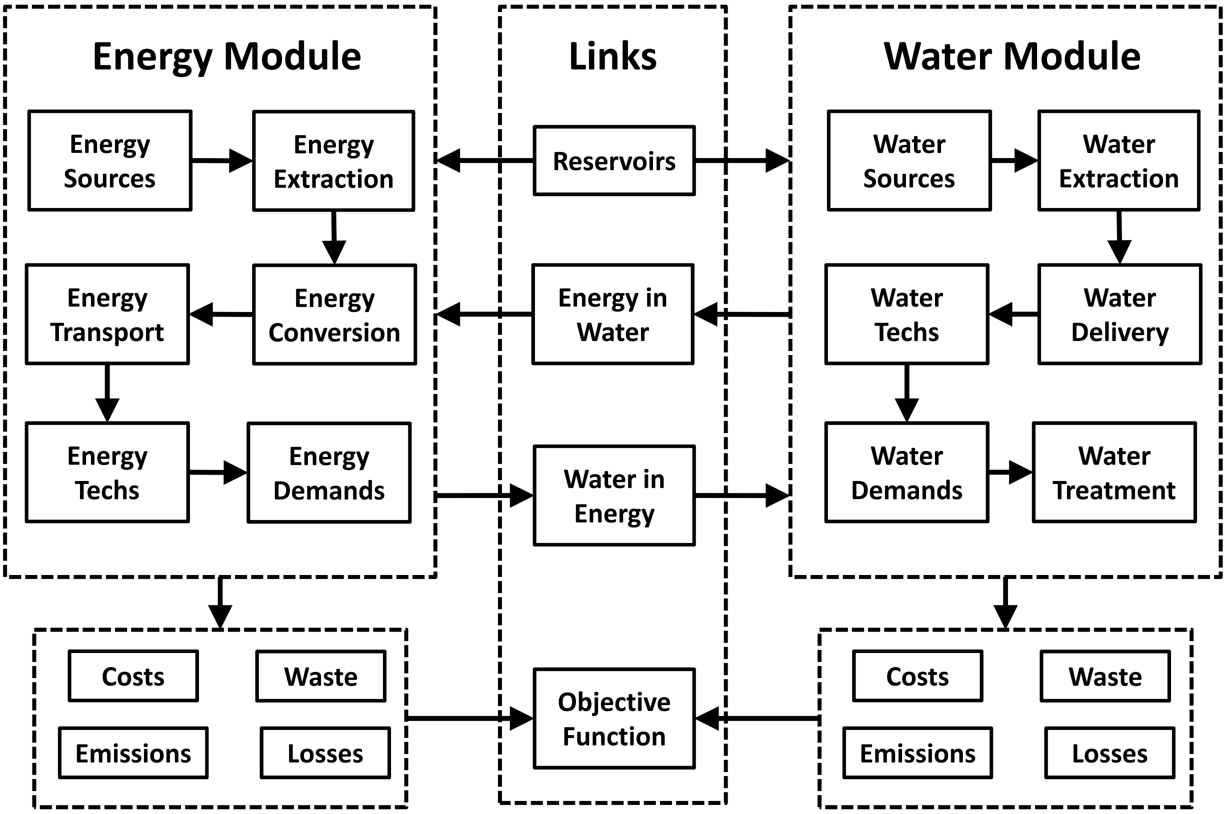

Figure 1: SPATNEX Conceptual Model

The original energy module, called MASTER_SO, has been developed at the Instituto de Investigación Tecnológica of the University of Comillas in Madrid. A brief description of the MASTER_SO model is provided here and a detailed description can be found in Fernández, 2014 [54]. MASTER_SO is designed to satisfy a given demand for energy services for a chosen year, by optimizing the energy production, subject to emissions constraints while minimizing the total cost. It considers the entire lifecycle of the energy production from primary fuel extraction to the final user. The model considers a single node energy sector i.e. a system with well-connected transportation and distribution networks for oil, gas and electricity. The model is divided into twelve months, each of which is further divided into working and non-working days. Each day has sub-categories corresponding to five load levels.

The existing MASTER_SO model has been modified by including water consumption and water withdrawal parameters for each energy production process. The parameters used were chosen from an analysis of several studies [29, 30, 55, 56, 36, 14]. Range of value is high. Explain different scales of energy and water systems and how disaggregation is needed.

update this part A spatially and temporally compatible water module has been developed to complement the energy module. The water module is a process based conceptual model which tracks the flows of water from various sources to the final end user. The infrastructure and processes to extract, treat, purify and deliver water to users are modeled as part of the hydrological cycle conserving mass balance for each water basin considered as shown in Equation 3.1, where S is the freshwater storage, P is precipiation, O is desalinated ocean water, I is interbasin transfers, E is evaporation, T is transpiration and Q is the runoff. For each time period t, net freshwater storage S (groundwater aquifers, surface water lakes, reservoirs and harvested rainwater) in each basin can change when rainwater less evapo-transpiration is surplus or additional water is added to the system from ocean water desalination or inter-basin transfers. Water used by different sectors is either consumed as E or T or it is returned to the system as runoff Q. A more detailed description of the model with equations and constraints is provided in **??**.

$$dS/dt = P(t) + O(t) + I(t) - E(t) - T(t) - Q(t) \tag{3.1}$$

Explain inputs needed, resource availability, demands, climate change impacts, time period chosen and hydro electric relationship

4. Case Study

4.1. Why Spain

Why Spain

4.2. Bioful Policy

Introduce Biofuels Policy

4.3. Model Inputs for Spain

Model Inputs for Spain

The single node energy model was divided into the fifteen river basins shown in Figure 2 and Table 1. The existing energy capacity is divided amongst the different basins based on various sources and data bases. Nuclear power plants, oil refineries and regasification power plants are distributed according to their individual geographic locations.Thermal power plants are distributed using the online database of the Technical University of Delft [57]. Cogeneration, photovoltaics, solar thermal, wind, and mini-hydro power plants are distributed using data from the Comisión Nacional de Energía [58].

Table 1: River Basins in Spain

Basin	Label	Area (km2)	Coast (km)	Rivers (km)
Galicia Costa	Gal_Costa	13217	2120	2875
Mino Sil	Mino_Sil	17592	0	4473
Cantabrico Occidental	Cantbr_Oc	17436	807	3839
Cantabrico Oriental	Cantbr_Or	5807	266	1282
Duero	Duero	78860	0	13539
Tajo	Tajo	55764	0	10130
Guadiana	Guadiana	55389	34	8046
Tinto Odiel Piedras	Tint_Od_Pdra	4751	214	871
Guadaluquivir	Guadaluquivir	57228	73	9701
Guadalete Barbate	Guad_Barbte	5928	280	1195
Mediterraneas Andaluza	C_Med_Andlz	17948	652	2145

Table 1: River Basins in Spain

Basin	Label	Area (km2)	Coast (km)	Rivers (km)
Segura	Segura	18897	395	1469
Jucar	Jucar	42958	588	5386
Ebro	Ebro	85567	148	12495
Catalunya	CICat	16494	795	2786

The existing water resources in each basin have been analyzed based on historical data and reports from the Spanish Ministry of Environment [59, 60]. Changes in the availability of these resources were analyzed for different climate change scenarios. These scenarios were based on the predictions for water resources made by the Centro de Estudios y Experimentacion de Obras Publicas (CEDEX) [61].

It was also important to correlate the changes in water resources with the corresponding hydroelectricity potential in each basin. In order to model this correlation all the reservoirs in each basin have been aggregated into a single representative reservoir. The aggregated changes in historical reservoir levels and the run-off values for each basin were then correlated with the historical hydro-electricty production potential taken from the Spanish System Operator, Red Electrica [62].

The year 2050 has been chosen as the year to simulate, since this allows 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 technologies, costs, and emission levels are consistent with the Energy Roadmap 2050 of the European Commission.

4.4. Strategy

Strategy - BAU vs.Unlinked vs. Linked model (energy choice, water choices)

5. Results

First a buisness as usual (BAU) scenario is run for 2050 with no policy constraints and no links between the energy and water modules. This is then compared to a scenario in which there is a policy constraint requiring 10% of final energy to be produce from local biofuels, however still using the model in an unlinked mode (Unlinked). The impacts of introducing biofuels, on the system are discussed in Section 5.1. Next the the model is run in a linked mode (scenario: Linked) and this is compared with the unlinked run. The impacts and benefits of the linked model over the unlinked model are discussed in Section 5.2.

5.1. BAU vs Unlinked

In Figure 3 and Table 2 we can see that final energy consumption by the transport sector decreases when the biofuels constraint is implemented. In Figure 4 and Table 3 we see that the decrease occurs as a result of oil being replaced by biofuels. This also has an impact on local production, with imported oil in the BAU scenario being replaced by locally produced biofuels explain this assumption. Overall energy demand in the transport sector decreases because the "Unlinked" scenario optimizes the system by choosing to supply a large part of public transport using more expensive but more energy efficient large biodiesel vans, instead of cheaper but more energy intensive medium sized gasoline vans. Increase in local biofuel production results in a corresponding increase in the water consumption as shown in Figure 5

Table 2: Final Energy Consumption by Sector

Sector	BAU(TWh)	Unlinked(TWh)	BAU(%)	Unlinked(%)
Transport	727.81	682.27	43.78	42.50
Residential	297.99	286.21	17.92	17.83
Industry	636.72	636.72	38.30	39.67

Figure 2: River Basins in Spain

Figure 3: Final Energy Consumption by Sector (TWh)

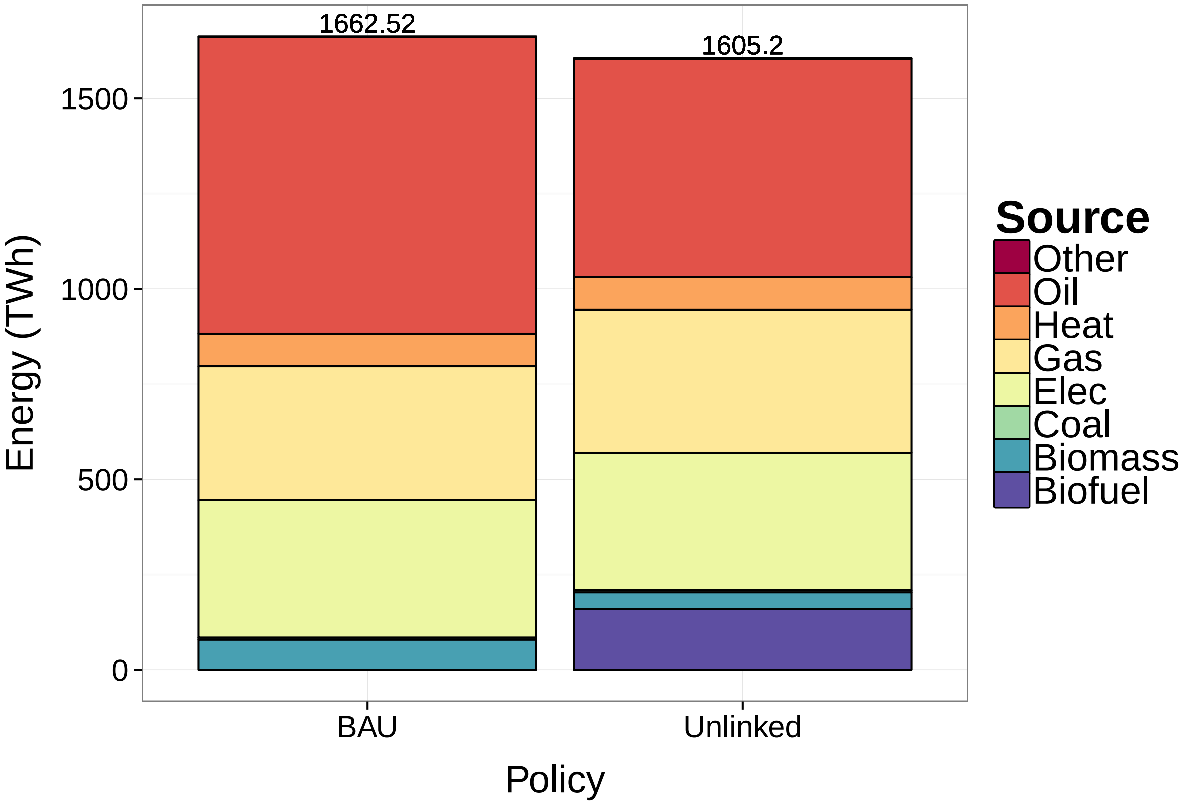

Figure 4: Final Energy Consumption by Source (TWh)

Table 3: Final Energy Consumption by Source (TWh)

Source	BAU(TWh)	Unlinked(TWh)	BAU(%)	Unlinked(%)
Other	1.31	1.31	0.08	0.08
Oil	779.11	573.37	46.86	35.72
Heat	85.26	85.26	5.13	5.31
Gas	351.39	375.50	21.14	23.39
Elec	360.47	360.80	21.68	22.48
Coal	5.44	5.44	0.33	0.34
Biomass	79.54	43.32	4.78	2.70
Biofuel	0.00	160.20	0.00	9.98

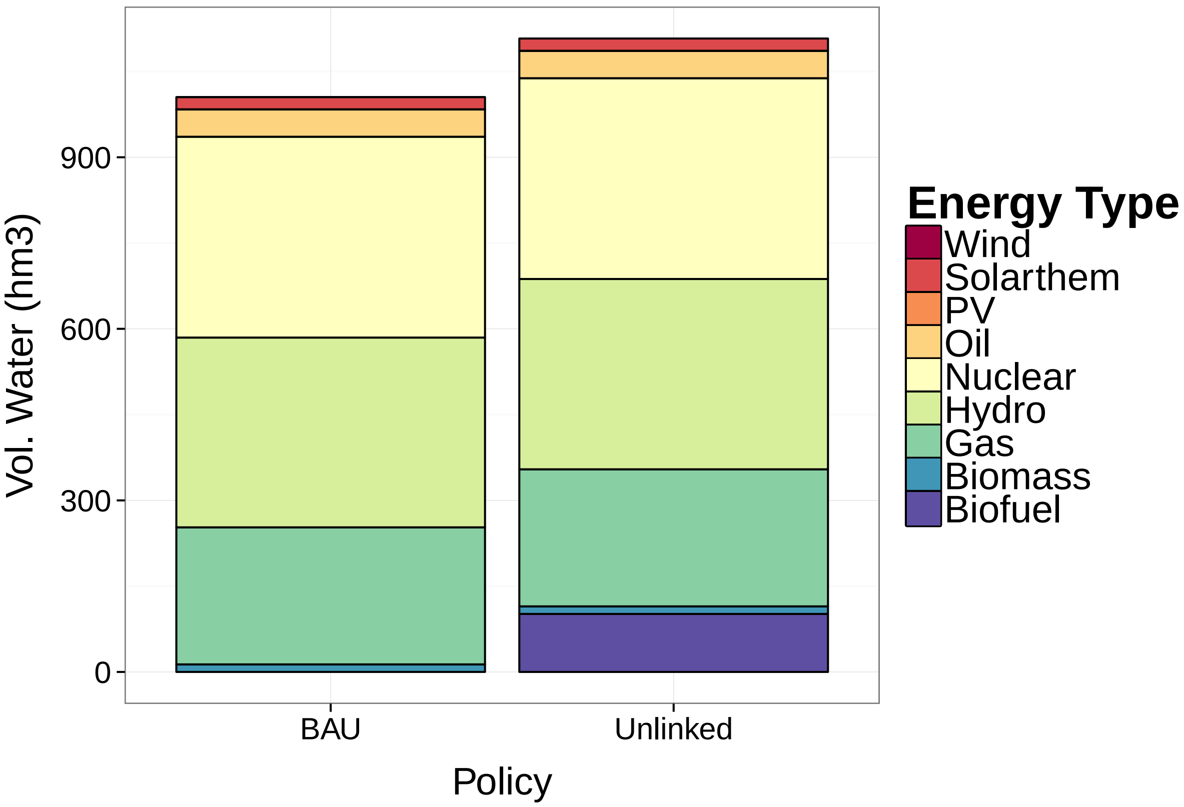

Figure 5: Water Consumption by Energy (hm3)

5.2. *Unlinked vs Linked*

Next the the model is run in a linked mode (Linked) and this is compared with the unlinked run. First we look at the energy consumption in the entire system as shown in Figure 6 and Table 4. We see here that the unlinked scenario is not able to account for the energy consumed by the water system. The linked scenario however, accounts for the energy consumed by the water system and this allows it to optimize the water system to be more energy efficient. The actual energy consumed by the unlinked scenario is higher than in the optimized linked scenario as shown in Figure 7 and Table 5, however, the unlinked model ignores this energy consumption. The ability of the linked scenario to react to energy efficiency and optimize the water system is shown in Figure 8 where we see how the linked scenario decreases desalination and groundwater pumping processes and improves its surface water management.

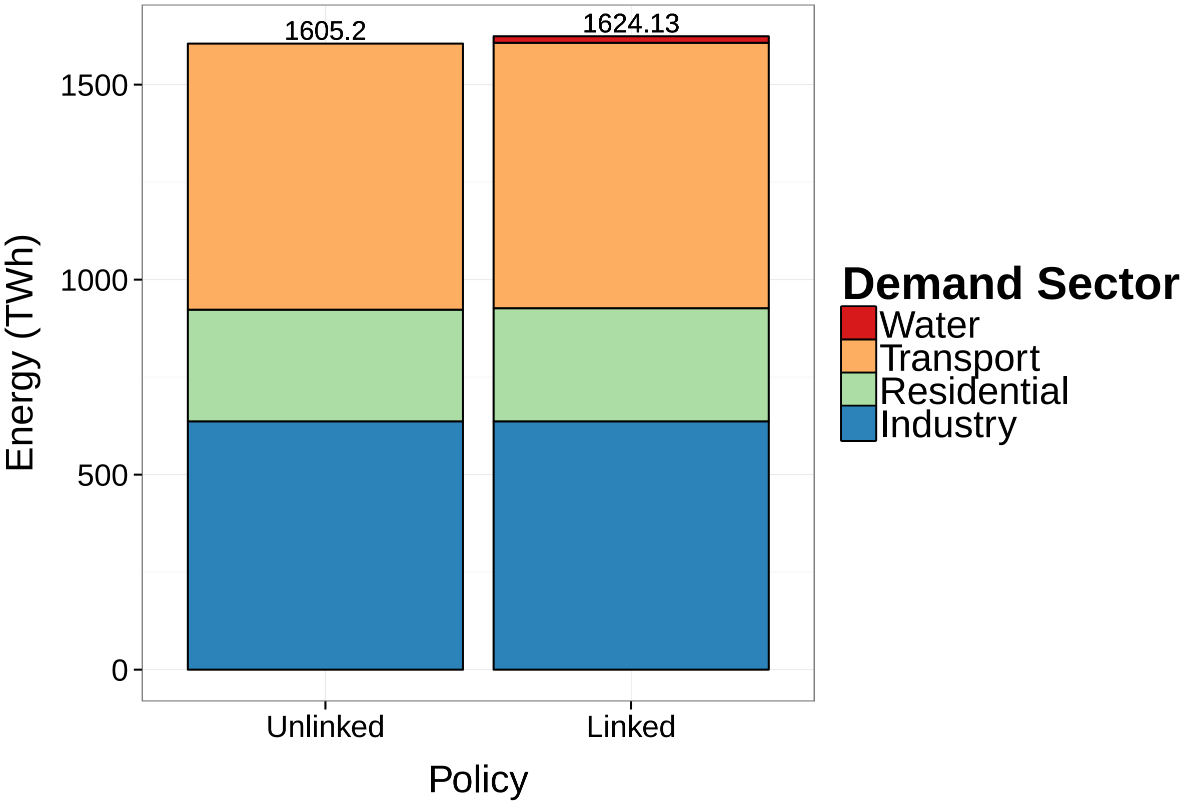

Figure 6: Final Energy Consumption by Sector (TWh)

Table 4: Final Energy Consumption by Sector (TWh)

Sector	Unlinked(TWh)	Linked(TWh)	Unlinked(%)	Linked(%)
Water	0.00	16.85	0.00	1.04
Transport	682.27	680.45	42.50	41.90
Residential	286.21	290.13	17.83	17.86
Industry	636.72	636.70	39.67	39.20

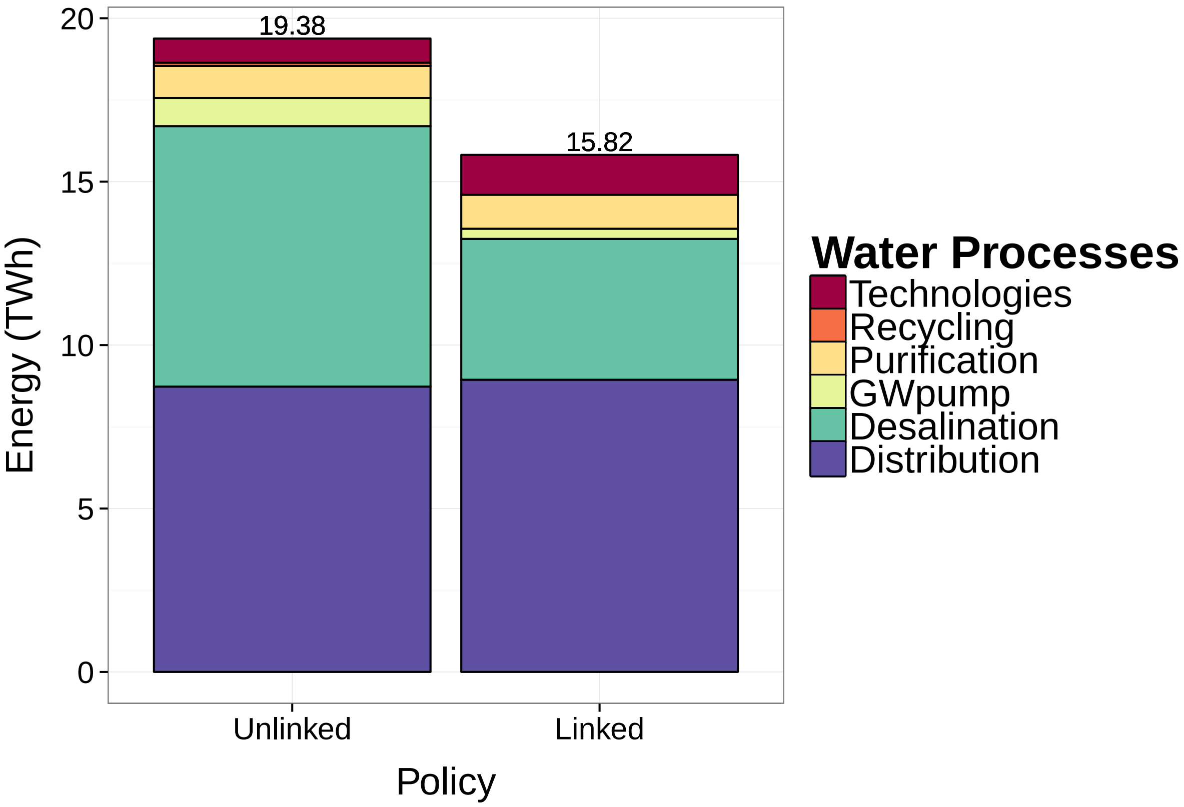

Figure 7: Energy used by Water Processes (TWh)

Table 5: Energy used by Water Processes (TWh)

Water_Process	Unlinked(TWh)	Linked(TWh)	Unlinked(%)	Linked(%)
Technologies	0.74	1.22	3.82	7.71
Recycling	0.10	0.00	0.52	0.00
Purification	0.98	1.04	5.06	6.57
GWpump	0.86	0.31	4.44	1.96
Desalination	7.97	4.31	41.12	27.24
Distribution	8.73	8.94	45.05	56.51

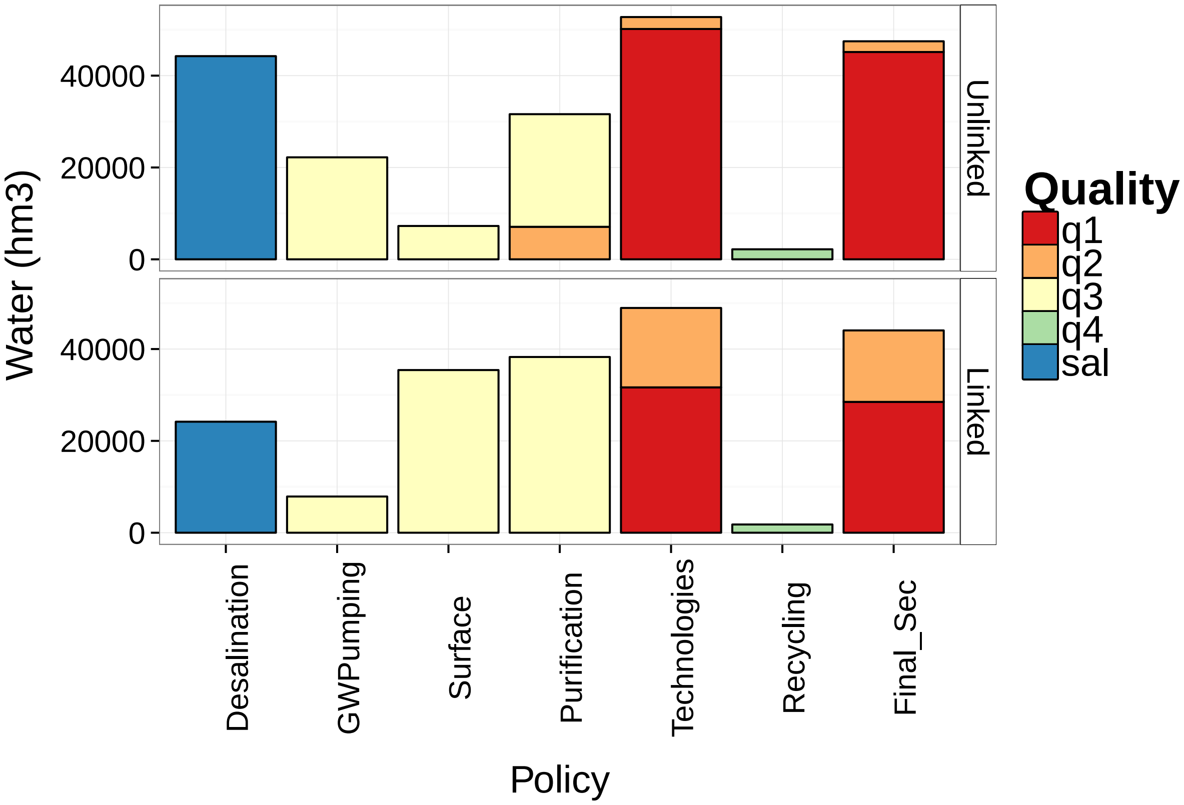

Figure 8: Flows through Water Processes (hm3)

Similariy we can see the water consumption by the different sectors for Spain shown in Figure 9 and Table 6. Again, we see that the unlinked scenario is not able to account for the water consumed by the energy system, while the linked scenario optimizes the energy system to be more water efficient. Water availability is a regional issue, and we see in Figure 10 how the linked scenario adjusts energy production to shift to the water rich basin of Mino-Sil, from the land-locked water scarce basin of Guadiana, which does not have access to ocean water. Table 7 also shows how the linked scenario makes the energy system more water conscious by reducing nuclear power production, which is replaced by hydropower. Finally we also see the ability of the SPATNEX model to optimize the processes temporally in Figure 11 where the linked model conserves surface water in the spring and increases surface water use during the summer months to replace desalination and ground water pumping when demand is higher.

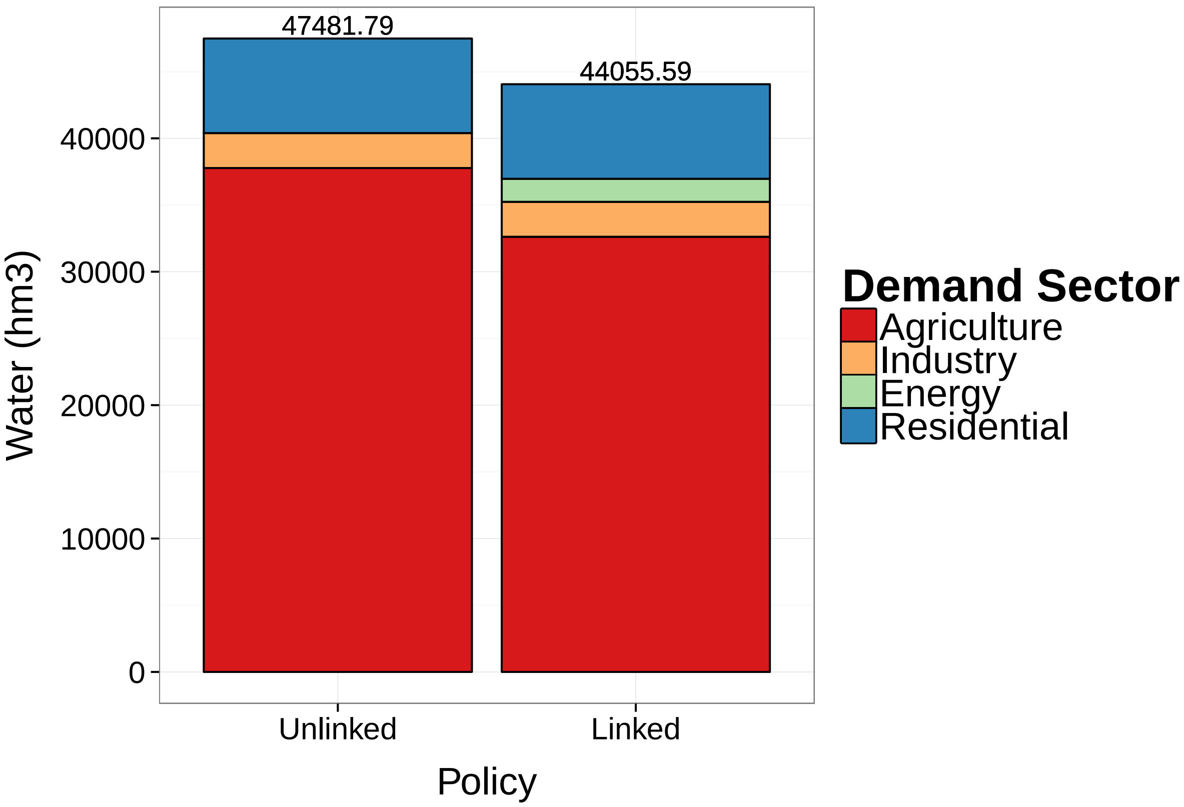

Figure 9: Water Flow to Final Sectors (hm3)

Table 6: Water Flow to Final Sectors (hm3)

Sector	Unlinked(hm3)	Linked(hm3)	Unlinked(%)	Linked(%)
Agriculture	37773.70	32620.15	79.55	74.04
Industry	2619.65	2619.61	5.52	5.95
Energy	0.00	1727.39	0.00	3.92
Residential	7088.44	7088.44	14.93	16.09

Table 7: Electricty Production (TWh)

Source	Unlinked(TWh)	Linked(TWh)	Unlinked(%)	Linked(%)
Wind	47.21	47.21	12.55	12.23
Solarthem	6.15	6.15	1.63	1.59
PV	8.37	8.37	2.22	2.17
Nuclear	184.73	169.17	49.10	43.83
Hydro	33.86	60.09	9.00	15.57
Gas	83.24	83.24	22.12	21.57
Biomass	12.67	11.76	3.37	3.05

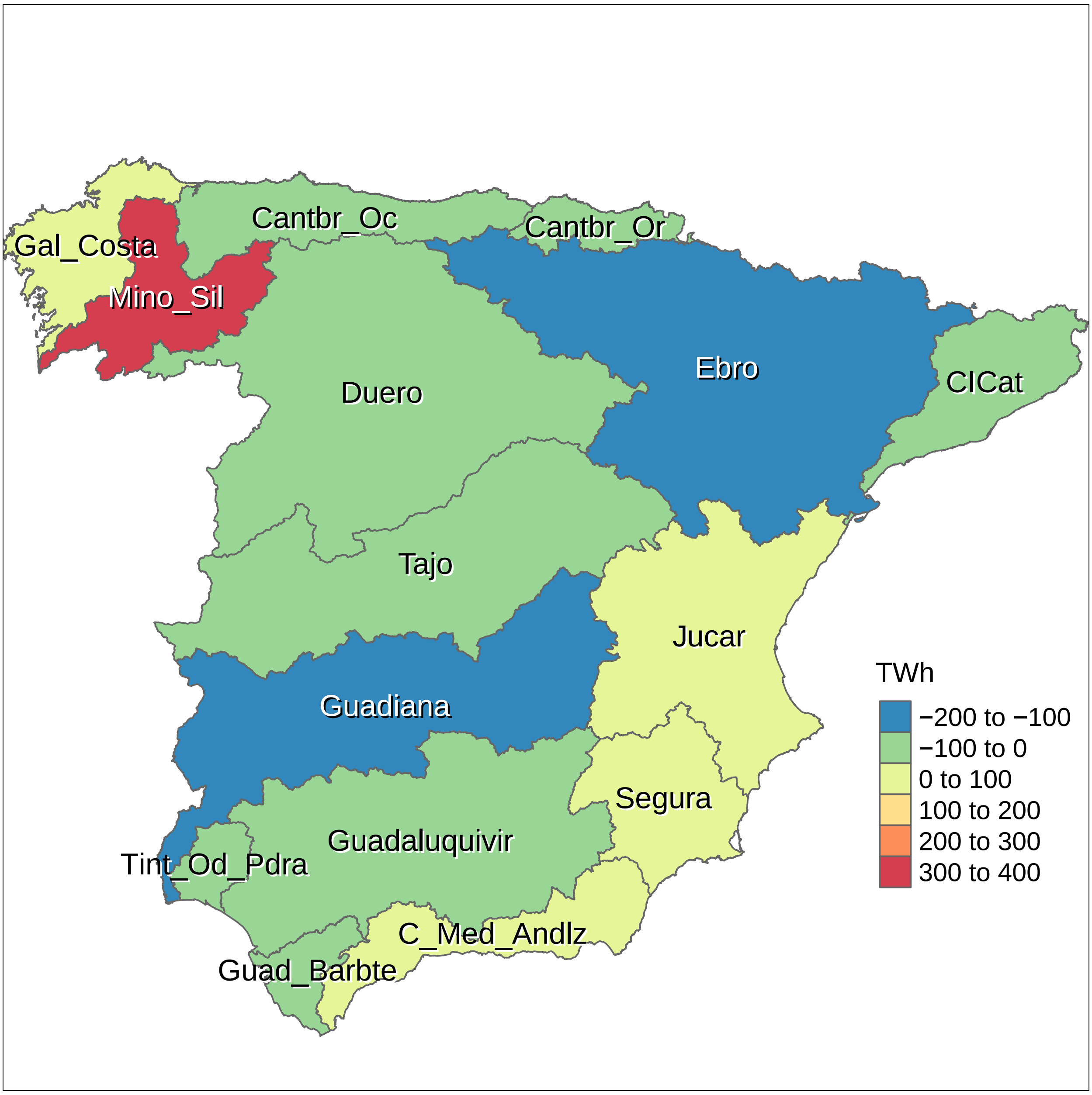

Figure 10: Energy Production Difference between Linked and Unlinked Scenarios (TWh)

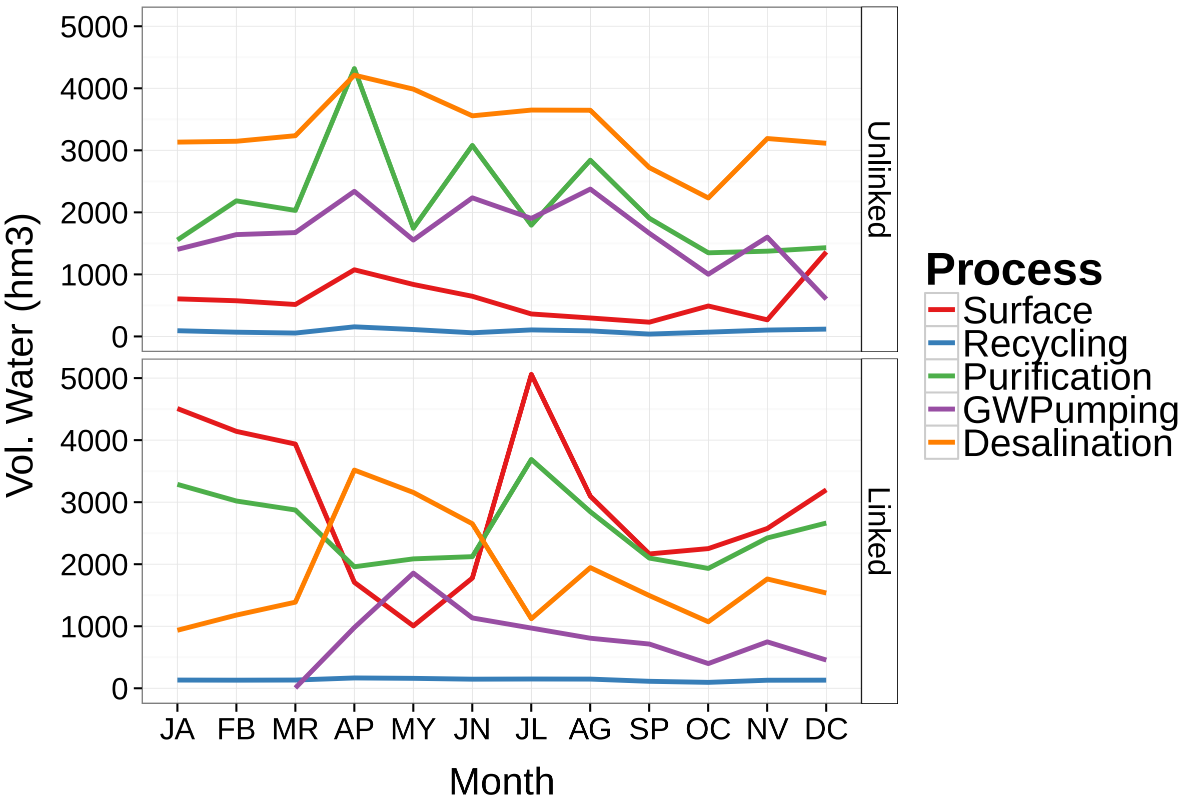

Figure 11: Water Processes by Month (hm3)

6. Future Applications

The SPATNEX model will be suitable for several future policy and scenario analyses particularly influenced by and influencing water and energy nexus issues. These include energy system decisions such as nuclear technology de-regulation; converting to new power plant water cooling methods; integration of biofuels, wind and other renewables; increases in electric vehicle fleets; load-shifting and demand side management. At the same time several investment and policy decisions in the water sector will be suitable for a SPATNEX analysis including drip irrigation technology subsidies; agriculture crop and land-use decisions; desalination integration and large scale inter-basin transfer plans such as the famous Ebro River Water Transfer Plan [63]. The SPATNEX model is also designed to incorporate the impacts of different climate change scenarios on availability of and demand for resources.

7. Limitations and Future Developments

The model simplifies the hydro-energy potential relationship between water available in the regional reservoirs and electricity production by considering an aggregated reservoir for each river basin. This assumption leads to the loss of some of the details regarding reservoir topology and the non-linear effects of net-head levels with power production, however given the scale of the model such details would become excessive. The model is able to provide a general guide to reservoir usage and management in conjunction with other water sources.

While the model is able to optimize its energy and water system operation and outputs, resource uses in other sectors are still an exogenous input. In particular agricultural practices and landuse decisions can be developed into responsive, optimizable food and agriculture modules. This would expand the model into a water-energy-landuse nexus model which would then be better suited to address the issues of food security and environmental degredation in addition to water and energy.

8. Conclusions

It is clear that water and energy are key interdependent resources shared across sectors and regions. The issues of water and energy shortage with increasing demands are predicted to escalate in the next few decades and to avoid serious consequences action is needed now. Traditional methods of managing water and energy systems independently can lead to management decisions which are wasteful and expensive. For optimal allocation of the resources and to maximize co-benefits it is essential to consider water and energy as one interdependent system. A popular approach to addressing the water-energy nexus has been to take an already existing energy system and modify it to account for water consumption. This has led to several energy models with water use parameters which calculate the amount of water needed by the energy system for the period analyzed. However, few models exist in which physical water availability is treated as a constraint to power production. Even fewer models include a representation of the water infrastructure system and corresponding energy use in the water abstraction, treatment and distribution phases. The addition of energy use by the water system and the physical constraints of water availability are essential in capturing feedback implications and realistic inter-sector dependencies of water-energy nexus systems.

In order to address these issues a spatially and temporally synchronized, partial-equilibirum linear optimization, water-energy nexus model (SPATNEX) was developed. An example case study looked at the integration of biofuels in the energy mix in Spain. The results showed that linking the water and energy systems allows capturing feedback loops which in turn permit operation and investment decision optimization simultaneously in both sectors. Choices of water processes can be modified both temporally and by water technology to reduce energy demands and energy operation and investments can be shifted both regionally and by technology to reduce water consumption. Without linking the two systems water consumption by future power plants would be ignored leading to inefficient and in some cases infeasible investments decisions such as biofuel expansion in water-scarce basins. Similarily, without feedback loops, energy in-efficient water processing systems will intensify the energy and corresponding regional water demands.

It is clear that integrated, holistic management approaches will be the key to sustain the kinds of lifestyle patterns and population increases that are predicted in the face of diminishing natural resources and climate change.

Acknowledgements

This work was funded by the European Commission as part of the Erasmus Mundus Joint Doctorate in Sustainable Energy Technologies and Strategies (SETS). The authors would also like to acknowledge the support of the Fundación Canal, Spain. The work was also supported by the Inistitute of Applied System Analysis (IIASA) Young Scientist Summer Program (YSSP).

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