Evaluation of Spain's Water-Energy Nexus

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ABSTRACT *This paper explores the water-energy nexus of Spain and offers calculations for both the energy used in the water sector and the water required to run the energy sector. The article takes a prospective approach, offering evaluations of policy objectives for biofuels and expected renewable energy sources. Approximately 5.8% of total electricity demand in Spain is due to the water sector. Irrigated agriculture is one of the Spanish water sectors that show the largest growth in energy requirements. Searches for more efficient modes of farm water use, urban waste water treatment, and the use of desalinated water must henceforth include the energy component. Furthermore, biofuel production, to the levels targeted for 2020, would have an unbearable impact on the already stressed water resources in Spain. However, growing usage of renewable energy sources is not threatened by water scarcity, but legislative measures in water allocation and water markets will be required to meet the requirements of using these sources. Some of these measures, which are pushed by regional governments, are discussed in concluding sections.*

Introduction

The water-energy nexus has become a high-priority issue in sustainability assessments. The realization that the water sector is energy intensive and that innovative energy sources require stable water supplies has increased the interest in evaluating both sectors in a more integrative manner. Various studies have shown that the water use cycle is energy intensive (CEC, 2005; Pate *et al.*, 2007; Water Environment Federation, 2009; Cabrera *et al.*, 2010).

The two-way connection, water needed for energy generation and energy for the use of water distribution and treatment, has planning and economic implications for water management and for sustainable energy. Additional technical studies are needed for this connection to be understood in sufficient detail. This paper reviews the studies that have analyzed specific elements of the Spanish water sector involved in the nexus to present a clear balance of the country's water-energy relationship. It first focuses on the "energy for water" connection by breaking down the water use cycle into stages; the main stages are identified and their energy costs per unit of water volume (kWh/m^3) are evaluated. The paper then focuses on the other part of the nexus, "water for energy", offering evaluations of water needs in power plants per unit of electricity produced (m^3/GWh). The methodology used in most reports, including *California's Water–Energy Relationship*

(CEC, 2005), estimates a range of energy consumption for each stage of the water use cycle, using as many cases as possible, to offer a national estimate. This paper is based on that methodology for some elements, including the stages of the urban water cycle. For other elements, including biofuel production and irrigation technologies, new estimates are reported.

Understanding the Water-Energy Nexus

The expression "water-energy nexus" has been coined as such because of the bidirectional consequences of, among other factors, process efficiency, the amount of resources involved, leaks in the system, good or poor resource management, and the choice of technologies. On the one hand, the origin of the water allocation by water authorities dictates the energy associated with the process (pumping, water treatment or water distribution). For example, the energy cost of underground water pumping is higher than that of superficial water pumping, although during drought cycles, more groundwater is generally used (Hardy & Garrido, 2010; Iglesias *et al.*, 2009; Garrido *et al.*, 2006). On the other hand, according to Hardy and Garrido (2010), each sector that uses water has a specific level of energy consumption per unit of water used, and this level depends on the processes involved. The range is large; for example, the energy sector uses 0.06 kWh/m^3, urban users use 0.21 kWh/m^3, agriculture uses 0.34 kWh/m^3, and waste water treatment for recycling uses 0.56 kWh/m^3 (figures are representative of the whole sector they stand for).

Within the water-energy nexus, we define the "energy for water" connection as the processes that water passes through to reach quality level requirements before reaching final users or bodies of water (Figure 1). The required water quality can vary between final user types and countries or regions, but all of the stages presented in Figure 1 are required in some way.

We distinguish two paths within the water use cycle: integrated waste water treatment or no integrated waste water treatment. "Water for energy" is the second connection and accounts for the amount of water required to produce one unit of energy, both outside the plant to procure the raw material and inside the plant for cooling systems. Among various technologies, we find huge differences in the water usage requirements for generating energy from fossil fuels and renewable sources: in Spain, wind energy has almost no water withdrawal, whereas nuclear power can use up to 75,362 m^3/GWh (Rio Carrillo & Frei, 2009).

Energy for Water

As represented in Figure 1, one part of the relationship concerns the energy costs of the water use cycle, including the energy costs of water-pumping-related processes.

Comparative Results in Spain

In Table 1, a complete breakdown of Spain's water use cycle allows us to distinguish all stages and their related energy costs. Spain's total annual water withdrawal is 35,000 Mm^3 (millions of cubic metres), and its total water-related energy consumption is 16,500 GWh; the energy-related cost of every unit of water used in Spain is estimated at 0.45 kWh/m^3. The data shown in Table 1 account for the electricity used for water management in Spain.

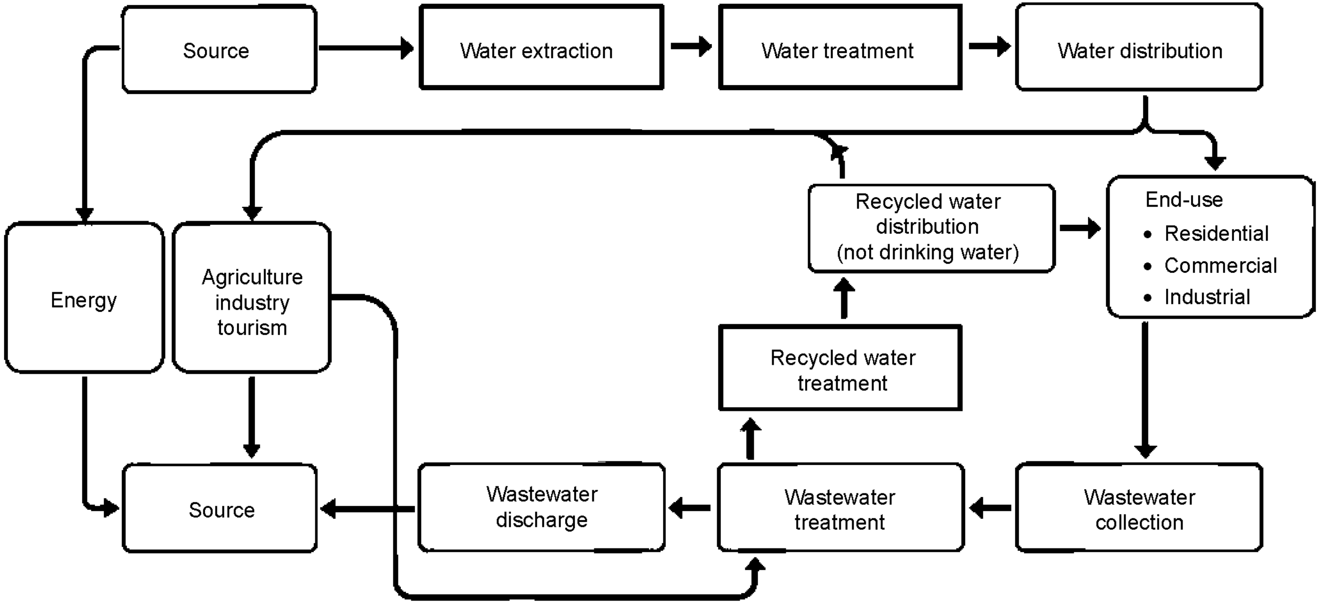

Figure 1. Spain's water use cycle.

Table 1. Water-related energy use in Spain in 2008.

Stages	Water Volume (Mm^3)	Electricity Consumption (GWh)	Electricity Percentage (%)
Extraction and water treatment	34,940	10,418	64
Urban	4,343	5,457	33
from desalination	694	2,275	14
Agriculture	20,360	4,141	25
Energy	8,683	521	3
Industry	1,554	299	2
Distribution/water use	25,587	3,374	21
Residential	2,540	440	3
Commercial	833	144	0.9
Municipal and other	359	62	0.4
Industrial	286	49	0.3
Agricultural	20,360	2,469	15
Non-registered water	1,210	210	1.3
Waste water treatment	2,842	2,530	16
Waste water collection	3,788	189	1.2
Waste water treatment	2,842	1,454	9
Recycled water (treatment and distribution)	1,510	887	5.4
Total	34,940	16,323	
Total Spain electricity use		279,392	
Percentage		5.8%	

Note: The *water volume* column gives the volume of water involved in each stage of the water use cycle. *Total* is the total volume of extracted water in Spain. All the water extracted is not distributed nor treated because of own extraction and treatment system (as in energy or industrial sector).

Source: CEC, 2005; Bernat *et al.*, forthcoming; Corominas Massip, 2009; Cramwinckel, 2010; Guillamón Álvarez, 2007; GWID/ IDA, 2009; Eltawil *et al.*, 2008; EPRI, 2002b; Emasesa, 2005; Madrid City Council, 2010; MARM, 2010; Ródenas Cañada & Guillamón Álvarez, 2005; Sala, 2007; SEE, 2003a, 2003b.

This ignores the gas-oil energy component used by the agricultural sector because the last official data regarding this component are from 1995 (MARM, 2008). Also, water end-use is not included (e.g. domestic hot water, hot water for industrial processes, etc.). At this stage, all that is being attempted is to include water-related electricity consumption before the use of distributed water.

The most costly stages of the Spanish water use cycle are the extraction and water treatment stages, which account for 64% of the total water-related electricity demand. Irrigated agriculture in Spain underwent a rapid transformation between 2002 and 2009, and it now accounts for 40% of Spain's total water-related electricity demand. Although waste water treatment accounts for 16% of the water-related electricity demand, in 2008, 83% of the waste water volume from urban and industrial sectors was treated in waste water treatment plants (EuroStat, 2008b).

What exactly does 5.8% of Spain's total electricity use mean, and is this figure relevant? A similar study carried out in California (CEC, 2005) that applied the same methodology found that 19% of California's total electricity use is associated with the water sector. This high usage value is due to the fact that, unlike the present study, the Californian study counted hundreds of water processes from households (CEC, 2005). The urban sector accounts for 28,000 GWh in California, but it only accounts for 5,500 GWh in Spain. The water processes from households of urban water use could explain the difference in water-related energy consumption between California and Spain. Based on IDAE (2010), 21% of primary energy consumed in Spanish households is associated with domestic hot water, only 3% of total produced electricity (2,200 GWh per year).

Energy Intensity in Spain

Each stage in Spain's water use cycle has a specific energy intensity (i.e. the energy cost per unit of water necessary to carry out an industrial process). In Table 2, we show the energy intensity of all stages of the water use cycle.

Table 2 shows that water treatment has the largest range of energy intensity in the water use cycle: the reason is that water treatment depends entirely on the quality of the source water. In Spain, as in most countries suffering from hydrological stress, desalination has become an alternative water source. The salt concentration, which varies between almost pure water and brackish water or seawater, dictates the most appropriate technology in this case, and therefore, the energy consumption to meet quality standards will consequently vary. Owing to European efforts to collect the highest quantity of waste water and reach a higher waste water standard quality, the idea of constructing tertiary treatment plants has gained unprecedented interest. Plants that produce recycled water (but do not meet the quality standards for drinking water) have a supplementary energy cost that we estimate to be 0.13 kWh/m^3 in Spain, based on the data provided by Water Environment Federation (2009).

Agricultural Water and Energy Use Efficiency

Agriculture is a large consumer of water in Spain, using approximately 58% of the total water distributed (Hardy, 2010); in addition, it is a large consumer of energy. To replace gravity irrigation with pressurized irrigation systems (which require more energy) was, among other improvements, one of the main goals of the Shock Plan of Irrigation (BOE, 2006). Determining whether the achieved water savings makes up for the increase in energy usage is a complex investigation.

Table 2. Range of energy intensities by stage of the water use cycle.

	Energy intensity range (kWh/m^3)		
Stage	Min	Mean	Max
Water extraction and conveyance	0	0.21	2.10
Water treatment	0.11	0.57	4.67
Water distribution	0.12	0.21	0.22
Waste water treatment	0.41	0.53	0.61
Recycled water treatment and conveyance	0.32	0.59	0.85
Waste water discharge	0	0.05	0.11

Source: CEC, 2005; Bernat *et al.*, forthcoming; Corominas Massip, 2009; Cramwinckel, 2010; Guillamón Álvarez, 2007; GWID/ IDA, 2009; Eltawil *et al.*, 2008; EPRI, 2002b; Emasesa, 2005; Madrid City Council, 2010; MARM, 2010; Ródenas Cañada & Guillamón Álvarez, 2005; Sala, 2007; SEE, 2003a, 2003b.

Water and energy use in Spanish irrigation. During the past decade, important changes took place in Spanish irrigated agriculture. In addition to large-scale modernization projects, gravity irrigation systems have been replaced by drip irrigation systems (Figure 2). Although the last available data (from 1995) mention a 40% share of gas and oil use in irrigation systems (along with electricity), we believe that the share is now closer to 5–10%, as the vast majority of farms currently use electricity. We will not deal with primary energy in agriculture, only net electricity.

Electricity consumption did not decrease along with water needs, as shown in Figure 2. In fact, the area irrigated with drip irrigation systems increased by 40% between 2002 and 2008, replacing gravity irrigation systems (MARM, 2009). The net electricity consumed per volume unit, a valid indicator to compare irrigation systems as recommended by Abadia *et al.* (2010), increased by 10% during the same period. Many factors could explain these variations, but the modernization of irrigation systems most likely explains the increase. The decrease in electricity consumed per volume unit since 2006 could be due to changes in production, climatology, restriction in water use in the driest parts of Spain or increased production costs, such as that for electricity, or the fact that drip irrigation consumes less electricity than sprinkler irrigation—depending on the origin of the water (see Table 3). More research, however, is required to explain these variations.

Modernization of irrigation along with scarcity problems reduced the supplied water volume per hectare in farms by 5.10% from 2002 to 2007 (NIS, 2007), while in the same period, the irrigated area increased by 1.49% (MARM, 2009). As a result, water use in Spanish agriculture diminished from 5,158 m^3/ha in 2002 to 4,824 m^3/ha in 2007. Water use efficiency (water consumed/water used) in Spain increased year by year since 2002 and reached reasonably high values of 0.85 in 2007. Unless deficit irrigation is put into practice, it is difficult to run irrigation at efficiency ratios higher than 0.80. In Andalusia (with 900,000 hectares of irrigated land), García-Vila *et al.* (2008) optimized the land and water potential and compared those with the observed water application levels in an Andalusian water district. During 1991 and 2005, their evaluation of the ratio ARIS (annual relative irrigation supply, a ratio between annual volume of irrigation water flow and annual volume of crop irrigation demand) was always below 0.7. This is about 30% less than the crops demanded in theory. However, actual data about the use of deficit irrigation is largely missing.

Irrigation system evaluations carried out in Spain (Krinner *et al.*, 1994; Spanish Irrigation Observatory, n.d.; Abadia *et al.*, 2010) have exhibited huge differences among farms. With those reported by Abadia *et al.*, we plotted average manometric elevation against the percentage of energy costs over crop economic productivity (see Figure 3). Each circle in the graph represents a water user association (WUA)—15 from Castille-La Mancha, 5 from Valencia, and 3 from Murcia. The horizontal axis represents the energy cost (€/m^3) over water productivity (in €/m^3, based on Garrido *et al.*, 2010); the vertical axis represents the average manometric elevation of the WUA, and the size of the circle represents proportional water use in m^3/ha among the 23 WUAs. While there is a marked correlation between the two ($R^2 = 0.61$), there are important differences around the fitted line. Furthermore, water applications are neither explained by the energy needs, nor by the proportion of energy costs over crop productivity.

Water used in drip irrigation systems consumes more energy than in sprinkler irrigation systems, possibly because of specific characteristics, such as the origin of the water (Table 3):

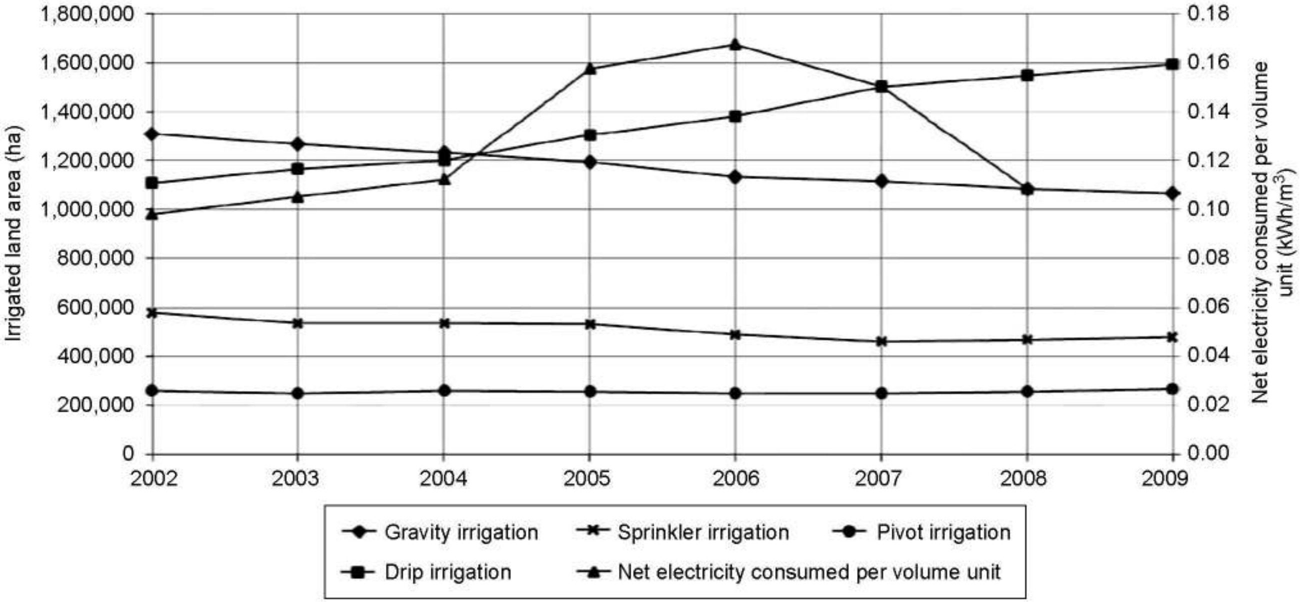

Figure 2. Evolution of Spanish irrigation systems. *Source*: MARM, 2009; MITYC, 2008; NIS, 2008.

Table 3. Energy consumption in Spanish irrigation by water source and irrigation system technique.

	Gravity irrigation	Sprinkler irrigation	Drip irrigation
Average water use (m^3/ha)	7,500	6,500	5,000
Unit energy consumption (kWh/m^3)			
Underground water	0.15	0.49	0.68
Superficial water	0.02	0.29	0.28
Interbasin diversion	1.20	1.44	1.38
Desalination	3.70	3.94	3.88
Water reuse	0.25	0.49	0.43

Source: own elaboration with data of Corominas Massip, 2009.

water coming from underground aquifers or desalination plants will ultimately require more energy than surface water.

Water savings and energy increase. Traditional Spanish coastal irrigation systems have been progressively replaced by drip irrigation systems. One reason for this change is to achieve water savings to meet or guarantee demand from other farms. Another reason is that agriculture was seen as a wasteful water user, especially during dry periods, preventing other uses of water aside from irrigation.

To assess the advantage in terms of energy of modernization of one irrigation system, we suppose the energy unit consumption H_d of desalination (or other water source) and H_1 and H_2 for initial and modern methods, respectively, as $H_2 > H_1$. We also suppose that both methods are crop-equivalent but have different efficiencies or yields in water use, R_{a1} and R_{a2}, respectively, and that $R_{a2} > R_{a1}$. Therefore, for each cubic metre supplied to the first method, R_{a1} is what the crop actually uses (because of the yield definition of useful volume over supplied volume). To fulfil these requirements, the second method should supply R_{a1}/R_{a2}, and the unit water savings with the modern method would be $1 - R_{a1}/R_{a2}$.

The energy consumption required to desalinate the unit of water saved, $H_d(1 - R_{a1}/R_{a2})$, added to its actual consumption, H_1, must be compared to the new method, H_2R_{a1}/R_{a2}. Therefore, the situation in which the change is neutral is defined by the expression

$$H_2\frac{R_{a1}}{R_{a2}} = H_1 + H_d\left(1 - \frac{R_{a1}}{R_{a2}}\right) \tag{1}$$

which is equivalent to

$$\frac{R_{a2} - R_{a1}}{R_{a1}} = \frac{H_2 - H_1}{H_d + H_1} \cong \frac{H_2 - H_1}{H_d} \tag{2}$$

Equation 2 allows the evaluation of the efficiency increase that would produce the change. Considering a new installation of $H_d = 2.7\,\text{kWh/m}^3$, each increment of energy $H_2 - H_1$ by units of $0.27\,\text{kWh/m}^3$ would become, after modernization, equal to a 10% yield increase.

If we adopt values for $H_2 - H_1$ (where H_2 is the energy cost of drip irrigation system and H_1 the energy cost of gravity irrigation system) for each possible origin of water (see Table 3), that is, $0.18\,\text{kWh/m}^3$ (basin diversion, desalination, and water reuse), $0.26\,\text{kWh/m}^3$ (superficial water), and $0.56\,\text{kWh/m}^3$ (underground water), the increase in yield that justifies modernization would be 7%, 10%, and 20%, respectively.

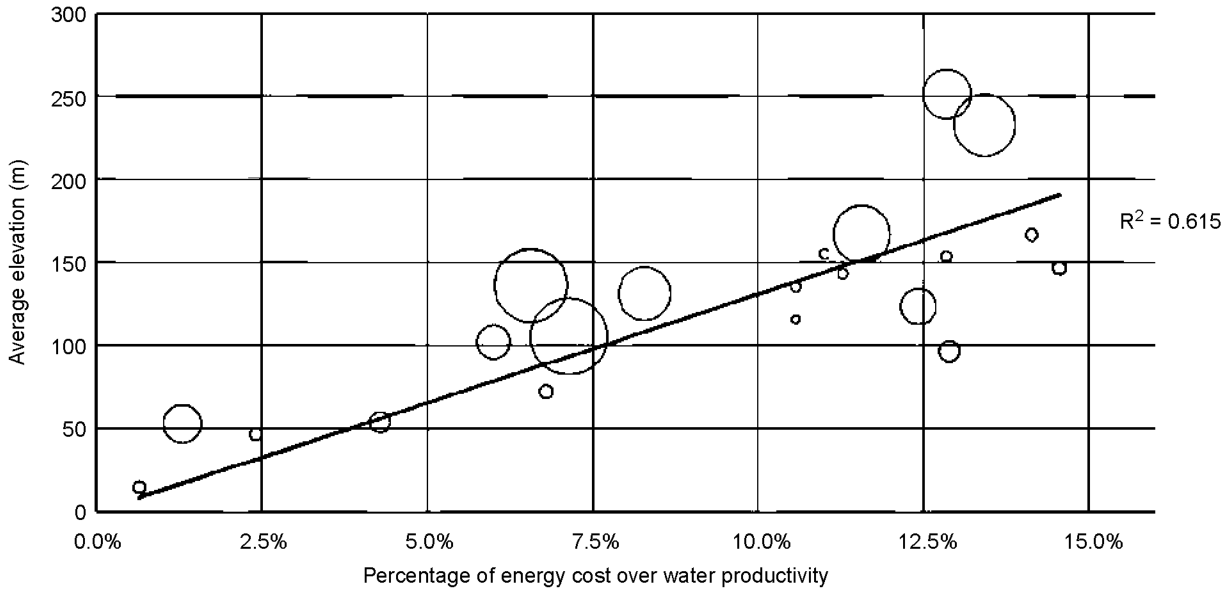

Figure 3. Average elevation and proportion of energy cost over average water productivity in 23 water user associations of Castille-La Mancha, Valencia and Murcia. *Note*: Size of circles represents proportionally water use in terms of m^3/ha. *Source*: Own elaboration with Abadía *et al.*, 2010; Garrido *et al.*, 2010.

Table 4. Final yield R_{a2} of equalization as a function of the energy increase and previous yield R_{a1}.

$H_2 - H_1$ (kWh/m^3)	0.14	0.27	0.54	0.82	1.4	2.1	2.7
$(H_2 - H_1)/H_d$	0.05	0.10	0.20	0.30	0.50	0.75	1
R_{a1}				R_{a2}			
0.40	0.42	0.44	0.48	0.52	0.60	0.70	0.80
0.50	0.53	0.55	0.60	0.65	0.75	0.88	1.00
0.60	0.63	0.66	0.72	0.78	0.90		
0.65	0.68	0.72	0.78	0.85			
0.70	0.74	0.77	0.84	0.91			
0.75	0.79	0.83	0.90				
0.80	0.84	0.88	0.96				

Note: Alternative entry with $H_2 - H_1$ values supposes $H_d = 2.7$ kWh/m^3.

Compared to seawater desalination, modernization of irrigation systems might be an efficient alternative, especially if the original crop yield is low because of poor soil. Even adequate crop yields of 0.75 for gravity irrigation systems should, however, move to 0.80 and 0.88, respectively, for sprinkler and drip irrigation systems. These values may be considered reasonable in sprinkler and drip irrigation projects, respectively. With different values for $H_2 - H_1$, more results are found in Table 4. For instance, starting on a situation where the energy cost of supplied water is 1.4 kWh/m^3 and initial yield R_{a1} is 0.50, modernization of the actual irrigation system would be justified if the final yield R_{a2} is 0.75 or higher, that is, a 50% yield increase. In situations where alternative water sources requiring less energy (such as water reuse or river basin transfers) exist, irrigation modernization might not be the best solution.

Water for Energy

The inverse connection to which to which this article been referring is the amount of water that energy-producing plants require to complete their industrial processes successfully. First, every electricity-producing technology requires a different amount of water, according to the specific raw material that is being used, such as coal, oil, gas, uranium, and biomass production (Gleick, 1994). Second, the plant cooling systems require different amounts of water depending on the technology used.

Results for Spain

The energy sector accounts for only 3.2% of the total water-related energy usage, but in terms of extracted volumes, it reaches 25% of the total water withdrawn. The energy sector is a good example to illustrate that even if one unilateral connection does not seem to have major importance, we must consider the reciprocal relationship to be sure that no connection exists. The results for Spain (Figure 4) include water withdrawal and consumption for the extraction and refining stages, as well as biomass production; hydropower is not included because it does not refer to water extraction.

Excluding hydropower (water withdrawal = 24,400 Mm^3, water consumption = 1,250 Mm^3, according to Hardy & Garrido, 2010), nuclear power accounts for 50% of Spain's water withdrawals by the energy sector, whereas solar thermal only accounts for 0.03%

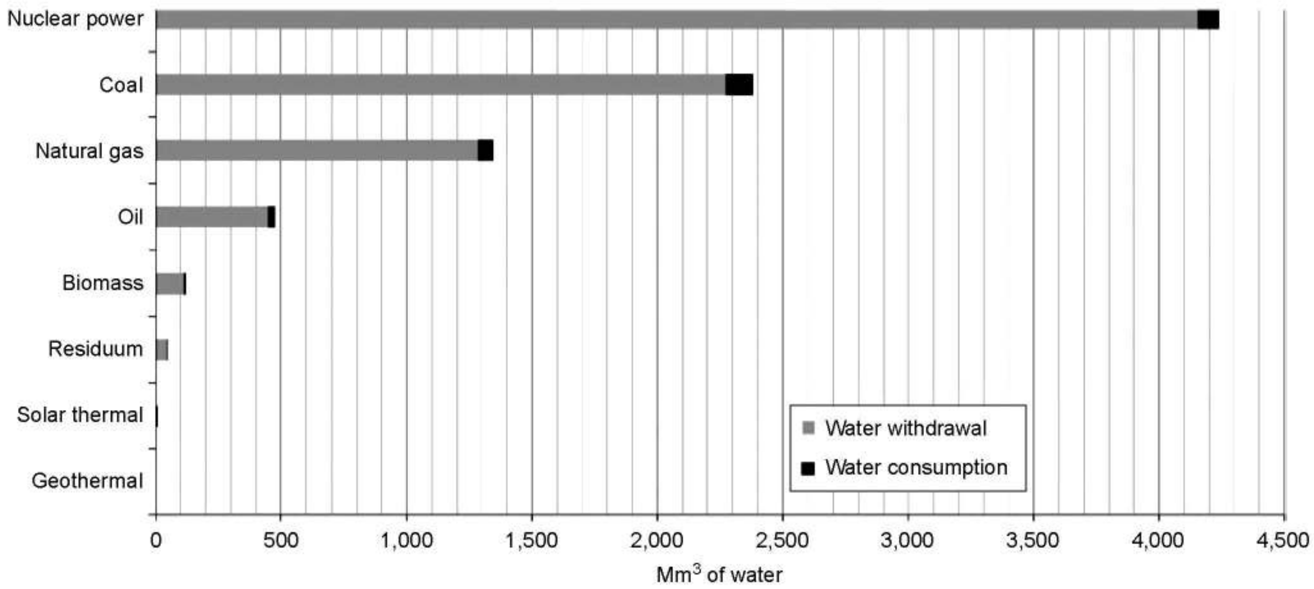

Figure 4. Yearly water withdrawals and water consumption by technology (except hydropower) in Spain, 2007. *Source*: Rio Carrillo & Frei, 2009; Linares & Sáenz de Miera, 2009.

(solar thermal accounts for 0.41% of the 93,729 MW installed capacity in Spain in 2009 [Protermo Solar, 2010; REE, 2010]). There are concerns about the impact of solar thermal power plants on the water sector because Spain's use of renewable energy sources accelerated in response to subsidies for this type of power production. As estimated in Table 5, solar thermal power plants are, among renewable technologies, one of the best in terms of water requirements, after wind power and photovoltaic cells. The 2,422 MW total installed capacity planned (Protermo Solar, 2010) would account for only 17.5 Mm^3, or 0.2% of the water involved in the energy sector.

Determinant Factors

In terms of water withdrawal and consumption, nuclear technology has the largest needs per unit of energy produced (excluding the amount of water used by hydropower plants). Even if renewable energy technologies have generally lower water needs (King *et al.*, 2008; Gleick, 1994) than fossil energies (18,000 m^3/GWh vs. 29,000 m^3/GWh in Spain), some renewable technologies have high water needs (see biomass results in Table 5).

Three different power plant cooling systems exist (EPRI, 2002a; Torcellini, 2002; King *et al.*, 2008; CATF-WRA, 2003); the differences among them are in the ways in which a portion of the water used can be saved. The open-loop or once-through cooling system is the simplest system: water is pumped, used for cooling, and returned to the river. This system involves a large water withdrawal owing to the short contact time between vapour and cool-off water; it also increases the river evaporation rate, leading to more water being consumed by evaporation. Water reductions can be achieved by allowing longer contact periods between cold and hot flows. The closed-loop cooling system includes a cooling

Table 5. Spain's water-related energy-producing technologies and water needs.

Technology	Technology process[1]	Unit water needs (m^3/GWh)	Total water volume (Mm^3)
Coal	W.W.	31,047	2,207
	W.C.	1,552	113
Oil	W.W.	24,322	450
	W.C.	1,216	22.5
Gas	W.W.	13,675	1,283
	W.C.	684	64
Nuclear power	W.W.	75,362	4,153
	W.C.	1,569	86
Hydropower	W.W.	791,676	24,389
	W.C.	20,000	1,257
Biomass	W.W.	31,047	113
	W.C.	1,552	5.6
Residuum	W.W.	31,047	46
	W.C.	800	1.2
Solar Thermal	W.W.	3,090	0.02
	W.C.	3,090	0.02
Geothermal	W.W.	7,400	0
	W.C.	5,180	0

Source: Rio Carrilo & Frei, 2009; Linares & Sáenz de Miera, 2009; EuroStat, 2008a.

[1] W.W. = water withdrawal; W.C. = water consumption

tower or cooling pond that cools down the cool-off water by evaporation: pumped water offsets the water lost by evaporation. In this system, water withdrawal is reduced, but more water is consumed because the exchange is based on evaporation. The dry cooling system is similar to the wet cooling system, except that the heat transfer medium is air, which is cooled down by a large pipe system with many fins to increase the exchange surface. The use of a fan increases the evaporation rate. It drastically reduces water use and gives more flexibility to power plant location (Wolfe *et al.*, 2009). The higher investment costs and possible reduction in performance during the hottest days prevent its widespread use (Wolfe *et al.*, 2009).

Water Footprint for Biofuels in Spain

The reason there is such enthusiastic interest in biofuels relates to both energy security and a reduction in greenhouse gas emissions. In Spain, approximately 39% of the total energy consumption is intended for the transport sector (IDAE, 2007). Biofuels are therefore seen as an outstanding opportunity to act against global warming. European countries embarked on rapid development of the biofuel industry to meet the recommendation of the Directive 2003/30/EC (EC, 2003), which states that 10% of vehicle fuel consumed inside the EU should be biofuel. However, it has been widely accepted that first-generation biofuels might not be a panacea, according to *An Energy Policy for Europe* (COM(2007)1 final), where the present energy policies within the EU have been declared unsustainable. Second-generation biofuels made from ligno-cellulosic crops from herbaceous or woody-type plants could be selected for Spanish industrial biofuel production (Fernández, 2007) and would ensure that biofuels are sustainable both within and outside the EU (EEA, 2006).

This paper focuses on the consequences of the increase in water usage and additional land area required if first-generation biofuels were used to accomplish the "Pack 20 20 by 2020" recommendation in Spain. To carry out the estimations, the following assumptions were made: (1) crops for ethanol production are wheat, corn, and barley; crops for biodiesel production are rape, soy, and sunflower; (2) 30% of the ethanol-based biomass production is national; 48% of the biodiesel-based biomass is national; (3) biofuel conversion factors have been estimated for each crop; and finally, estimated for each crop were (4) the average production yields and (5) the amount of green water (precipitation), blue water (artificially diverted from sources and used for irrigation), and grey water (technical processes) required. We assume a 2009 ethanol-biodiesel ratio of 1:0.72 (European Biomass Association, 2009). The final energy demand for the transport sector in Spain to accomplish the "Pack 20 20 by 2020" recommendation that 10% should be biofuel would be 4.75 million TOE (tons of oil equivalent) for 2020.

The virtual water VW embodied in biofuel production is calculated by the following expression:

$$VW = \frac{(VW_g S_d) + (VW_g + VW_b) S_i}{P} \tag{3}$$

where VW_g is green water (water supplied to crops by precipitation), VW_b is blue water (water supplied to crops by irrigation systems), S_d is the agricultural dry land surface, S_i is the agricultural irrigated land surface, and P is the crop production.

The water footprint WF is therefore calculated by the expression:

$$WF = (VWY_b + PW)V_b \tag{4}$$

where Y_b is the biofuel yield (tonnes of crop required per cubic metre of biofuel), PW is the process water needed in the elaboration process of biofuel (from the crop reception in the factory to the fuel exit of the factory), and V_b is the volume of biofuel produced.

In the case described above for Spain, the amount of water required for agriculture would increase 10% for dry land agriculture (i.e. if biomass is grown on dry land) and 26% for irrigated land agriculture (i.e. if biomass is grown on irrigated land). Considering the problems that basin agencies have with the current amount of water required for agriculture (MARM, 2008; Garrido *et al.*, 2010), this increase in water usage is clearly a nonviable alternative for Spain, as the results in Table 6 show (data for grey water come from Mekonnen & Hoekstra (2011)). The supplementary land area required is also worrisome: supplementary dry land area would account for 11% of the total agricultural area, and supplementary irrigated land area would account for 5%. For a semi-arid country like Spain, and its generally low yields under rainfed regimes, such land conversions would severely impact agricultural production. With the same assumptions, our estimations for 2008 led to the conclusion that biofuels did not affect water use or land occupation (average results are 3% of blue water or 3% of green water, and 2% of dry land agriculture or 4% of irrigated land agriculture).

Projected Bilateral Consequences

Predicted electricity demand in Spain around 2030 involves scenarios supposing a maximum use of renewable energies with a very optimistic energy efficiency plan (IIT, 2005), whereas other, more cautious, scenarios present a range of possible electricity demand in the coming years (IDEAS, 2008; UNESA, 2007). The water-energy nexus is relevant in the choice of the technologies to be used. Consider the example of UNESA (2007) for the year 2030: installed power would reach 131,438 MW in the “business-as-usual” scenario and the clean carbon capture system scenario, but with maximum use of renewable energies, the installed power would reach 152,698 MW. This change means a shift from carbon-based power plants to renewable energy power plants. As shown in Table 5, renewable energy technologies require less water per unit of electricity produced than fossil fuel energies. Figure 5 compares three scenarios (“business-as-usual”, clean carbon capture system and high penetration of renewable). If a high penetration of renewable energy systems scenario was chosen, a higher installed capacity would be necessary, but it would avoid a considerable increase in water needs for electricity production.

Desalination technologies could also be part of the solution to the water-energy issue. Anderson *et al.* (2010) proposed a new technology, called capacitive deionization. The energy liberated by the chemical process of desalination itself is stored in a capacitor and directly used in a parallel unit. The process is repeated so that the system generates the energy required to produce fresh water. Initial pilot plants showed an energy consumption of 0.6 kWh/m^3 (Welgemoed & Schutte, 2005).

Policy Dimensions

Increases in water demand for new energy plants have added further pressure to many over-allocated Spanish basins. Granting new concessions is almost impossible without cancelling

Table 6. Global results of possible biofuels production in Spain in 2020.

	Water needs				
	Green water (Mm^3)	Percentage of actual uses	Blue water (Mm^3)	Percentage of actual uses	Grey water (Mm^3)
25th percentile	2,189	26.73%	6,200	30.45%	–
Average	2,543	31.06%	6,282	30.85%	1,434
75th percentile	2,548	31.12%	6,432	31.59%	–

	Required land area			
	Dry land agriculture (ha)	Percentage of actual uses	Irrigated land agriculture (ha)	Percentage of actual uses
25th percentile	4,899,829	35.75%	1,903,163	51.58%
Average	3,112,590	22.71%	1,558,598	42.25%
75th percentile	2,401,530	17.52%	1,320,241	35.78%

Note: For each parameter, we give the 25th percentile, the average, and the 75th percentile.

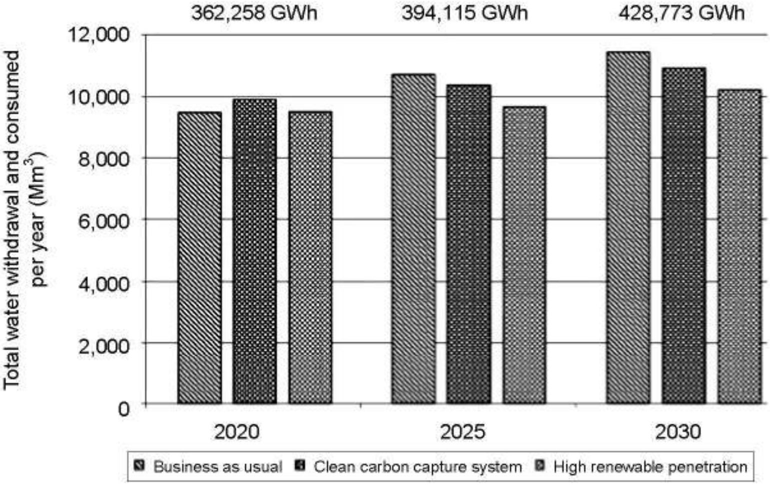

Figure 5. Water withdrawal and consumption for electricity production for the years 2020, 2025 and 2030 in Spain. Note: Predicted electricity demand is indicated as in UNESA (2007). *Source*: UNESA, 2007; Rio Carrilo & Frei, 2009; Linares & Sáenz de Miera, 2009.

existing concessions. Water trading is not an easy route for obtaining new concessions. Spain amended its 1985 Water Law in 1999 to permit water rights holders to exchange their water rights. However, the priority allocation rules that were established by the 1985 law remain in force. This means that as water becomes scarcer as a result of drought, priority rules apply to distribute the available resources among the sectors. As a general rule, the Water Law sets a priority criterion that places urban users at the top of a list of eight categories, on which farmers come second and industries third (including energy producers).

A distorting regulatory provision is the ban on rights holders from leasing their water rights to lower-ranking holders. By drafting market regulation without abolishing the priority system, legislators believed that they would protect urban consumers from speculative market behaviour and increase their supply security levels. The 1999 amendment to the law was meant to facilitate exchanges of rights among rights holders by adding several new articles to regulate transactions. However, it left the main features of the 1985 water rights definition unchanged (Ariño & Sastre, 2009). As the best locations for solar thermal plants are in the most arid and climate change–stressed basins (Guadalquivir, Guadiana, Tagus, Ebro, Júcar, Segura), new users must use resources that were previously used by others. However, in accordance with market regulation, only rights holders can purchase water rights. Thus, promoters of a new plant without water rights cannot purchase water rights from previous rights holders.

Interestingly, the recent Andalusian Water Law of 2010 (BOE, 2010) relaxed these rigid rules. First, it removed the priority criterion, with the exceptions of urban users and low-consumption industrial/commercial users linked to urban networks, which were granted priorities one and two. Other productive users are given equal priority unless explicitly stated in the water plans. Second, it allows a non-holder of water rights to acquire water rights in the market and become a legal water user. These two provisions are supported in the law's preamble: "Andalusian waters are overallocated, so that new strategic users, including renewable energy plants, can have available water resources at the expense of previous ones."

Another crucial dimension of the water-energy nexus in Spain is the increasing cost of energy for irrigators (Ederra & Murugarren, 2010) and the recent estimates of the CO_2 footprint of exported fruits and vegetables. As irrigator communities are large water rights holders, a number of them are installing renewable electricity plants to feed their own energy demands and sell the extra capacity which comes with the feed-in premium for renewable sources to the market (Sallán Villegas, 2010). With regard to the CO_2 footprint, talks are being held with farmers' organizations to help growers become massive users of renewable energy or purchasers of certified green electricity, so that their products' footprints can be reduced. These two clear market signals for farmers will provide an incentive for creative energy use in irrigated agricultural production.

The Spanish irrigation system has experienced profound transformations in the last decade. Energy consumption dropped between 2006 and 2008 to the level of 2004, but the price for energy increased by 30–70%. Modernization appears to be more appealing than desalination from an energy point of view. However, modernization requires investment costs that do not seem to be justified by the predicted water savings. There is a risk, moreover, that better irrigation technologies will increase water consumption and decrease returns.

Spanish biofuel production did not affect the water needs for agriculture in 2008, but in the event that the European Union accomplishes the Directive 2003/30/EC goal with first-generation biofuels, we can expect water needs to reach 4,400 Mm^3 per year and the corresponding land area required to reach 2.3 Mha. These estimates clearly cause concerns about first-generation biofuels continuing to receive state aid to accomplish EU objectives, whereas other immature technologies, such as microalgae (Chisti, 2008; Haag, 2007), present many advantages in terms of water use, required land area and impact on food crops but currently lack profitability. In Spain, first-generation biofuel should be considered obsolete because of its land and water demands.

Conclusions

Although it does not cover every detail, this paper introduces the relevance of Spain's water-energy nexus to give a national overview of the bilateral consequences that affect end users, hydrological planning, applied aspects of water management, and entire sectors, such as irrigation, manufacturing and mining industries, and, last but not least, energy. For those reasons, it appears that the water-energy nexus must be managed as a complex issue and that energy efficiency becomes especially important with regard to water use and water management.

This paper focused on two approaches: the energy related to the water use cycle in Spain, with special consideration of irrigation, and the water-related energy sector, with a question about first-generation biofuels as a sustainable solution for vehicle fuel replacement in Spain. Any analyst must confront the difficulties of working with isolated data and providing national estimates, as studies on the topic are still lacking. The work presented here is sufficiently relevant to realize the closeness of the relationship between water and energy, but it must be considered as the first of many sector-specific studies.

Another relevant observation is the difficulty of investigating the water-energy nexus while the problem has not yet been considered as a nexus. Most studies to date have only covered partial aspects of the nexus; only analyses such as those dealing with the concept of exergy (which is used to quantify the energy cost linked to the use of a water body) could lead to more complete comprehension of the problem. The complete water use cycle (from water supply to final water use) required, in the present estimate, approximately 5.8% of the total electricity usage of Spain in 2008. The energy sector accounts for 25% of Spain's water use cycle (without considering the amount of water used by hydropower plants); however, 96% of that volume is water that returns to where it has been pumped immediately after use.

The main recommendation of this study is that energy audits be carried out in each of the aforementioned stages (extraction, treatment, distribution of water, collection, treatment, and recycling of waste water). It is well known that facilities are designed with optimization criteria that are executed with cost criteria and operated with technical coefficients far below those the project designer had planned. Maintenance is frequently neglected, which leads to an increased gap between optimal and actual facility performance. The increasing price of energy jeopardizes the economic profitability of facility owners, but finding a facility's weak points requires specific evaluations. Benchmarking studies and pilot plant construction are thought to be fundamental tools for increasing energy efficiency and reducing energy-related water usage in energy facilities.

References

Abadia, R., Rocamora, M. C., Corcoles, J. I., Ruiz-Canales, A., Martinez-Romero, A. & Moreno, M. A. (2010) Comparative analysis of energy efficiency in water users associations, *Spanish Journal of Agricultural Research*, 8(2), pp. 134–142.

Anderson, M. A., Cudero, A. L. & Palma, J. (2010) Capacitive deionization as an electrochemical means of saving energy and delivering clean water. Comparison to present desalination practices: Will it compete? *Electrochimica Acta,* No. 55, pp. 3845–3856.

Ariño, G. & Sastre, M. (2009) Water sector regulation and liberalization, in: A. Garrido & M. R. Llamas (Eds) *Water Policy in Spain*, pp. 95–106 (Leiden: Taylor & Francis).

Bernat, X., Gibert, O. & Campos, C. (forthcoming) General trends on costs for desalination of sea water, in: L. Martinez Cortina, A. Garrido & E. Lopez-Gunn (Eds) *Re-thinking Water and Food Security: 4th Marcelino Botin Foundation Water Workshop* (Leiden: Taylor & Francis).

BOE (Official State Gazette) (2006) Royal Decree 287/2006, of 10 March, on the Emergency Plan for the Modernization of Irrigation 2006–2008 that regulates the urgent improvement works of irrigation systems, in order to save water to avoid the damage caused by droughts, BOE No. 60, 11 March 2006. (In Spanish).

BOE (Official State Gazette) (2010) Law 9/2010, of 30 July, on Andalucia's waters, BOE No. 208, 27 August 2010. (In Spanish).

Cabrera, E., Pardo, M. A., Cobacho, R. & Cabrera, E. Jr. (2010) Energy audit of water networks, *Journal of Water Resources Planning and Management,* 136(6), pp. 669–677.

CATF-WRA (Clean Air Task Force and Western Resource Advocates) (2003) *The Last Straw: Water Use by Power Plants in the Arid West* (Energy Foundation and Hewlett Foundation).

CEC (California Energy Commission) (2005) *California's Water–Energy Relationship, Final Staff Report* (Sacramento: CEC).

Chisti, Y. (2008) Biodiesel from microalgae beats bioetanol, *Trends in Biotechnology*, 26(3), pp. 126–131.

Corominas Massip, J. (2009) Agua y energía en el riego, en la época de la sostenibilidad, Comunicaciones de los invitados especiales, paper presented at *Jornadas de Ingeniería del Agua*, Madrid.

COM (2007) 1 Final, Communication from the Commission to the European Council and the European Parliament, An Energy Policy for Europe, {SEC (2007) 12}. Available at http://register.consilium.europa.eu/pdf/en/07/st05/st05282.en07.pdf

Cramwinckel, J. F. (2010) Water and energy nexus – role of technology, in: L. Martinez Cortina, A. Garrido & E. Lopez-Gunn (Eds) *Re-thinking Water and Food Security: 4th Marcelino Botin Foundation Water Workshop* (Leiden: Taylor & Francis).

EC (European Community) (2003) Directive 2003/30/EC of the European Parliament and of the Council of 8 May 2003, on the promotion of the use of biofuels or other renewable fuels for transport. (Official Journal of the European Communities L 123 of 17.5.2003).

Ederra, I. & Murugarren, N. (2010) La nueva tarifa eléctrica, la escalada de precios del agua de riego, Navarra Agraria, March–April 2010, pp. 45–50. Available at http://www.riegosdenavarra.com/publica/TarifasElectricas2010NavarraAgraria.pdf

EEA (European Environment Agency) (2006) *How much bioenergy can Europe produce without harming the environment?* EEA Report No. 7 (Copenhagen: EEA).

Eltawil, M. A., Zhengming, Z. & Yuan, L. (2008) Renewable energy powered desalination systems: technologies and economics – state of the art, paper presented at *Twelfth International Water Technology Conference, IWTC12 2008*, Alexandria, Egypt.

Emasesa (Empresa Municipal de Abastecimiento y Saneamiento de Aguas de Sevilla) (2005) *Sostenibilidad y gestión 2005* (Seville: Emasesa).

EPRI (Electric Power Research Institute) (2002a) *Water & Sustainability (Vol. 3): U.S. Water Consumption for Power Production – The Next Half Century,* technical report (Palo Alto, CA: EPRI).

EPRI (Electric Power Research Institute) (2002b) *Water & Sustainability (Vol. 4): U.S. Electricity Consumption for Water Supply & Treatment - The Next Half Century,* technical report (Palo Alto, CA: EPRI).

European Biomass Association (2009) *European Biomass Statistics 2009: A statistical report on the contribution of biomass to the energy system in the EU 27* (Brussels: Aebiom).

EuroStat (2008a) Energy Statistics – Supply, transformation, consumption – Electricity – Annual data, *EuroStat Database*, accessed March 2011.

EuroStat (2008b) Water Statistics – Annual data, *EuroStat Database*, accessed March 2011.

Fernández, J. (2007) Presente y futuro de los biocarburantes en la UE, *Vida Rural,* Dossier Agroenergética, No. 257, pp. 25–29.

García-Vila, M., Lorite, I. J., Soriando, M. A. & Fereres, E. (2008) Management trends and responses to water scarcity in an irrigation scheme of Southern Spain, *Agricultural Water Management*, 95(4), pp. 458–468.

Garrido, A., Llamas, M. R., Varela-Ortega, C., Novo, P., Rodríguez-Casado, R. & Aldaya, M. M. (2010) *Water Footprint and Virtual Water Trade in Spain* (New York: Springer).

Garrido, A., Martinez-Santos, P. & Llamas, M. R. (2006) Groundwater irrigation and its implications for water policy in semiarid countries: the Spanish experience, *Hydrogeology Journal*, 14, pp. 340–349.

Gleick, P. H. (1994) Water and energy, *Annual Review of Energy and the Environment,* No. 19, pp. 267–299.

Guillamón Álvarez, J. (2007) Trasvase y desalación, las cifras y las cuentas, Boletín No. 3, *V Congreso Nacional de Ingeniería Civil,* Sevilla.

GWID/IDA (Global Water Intelligence DesalData, International Desalination Association) (2009) *Country Profile: Spain*, accessed on October 2009.

Haag, A. L. (2007) Algae bloom again, *Nature*, 447, pp. 520–521.

Hardy, L. & Garrido, A. (2010) *Análisis y evaluación de las relaciones entre el Agua y la Energía en España* (Santander, Spain: Fundación Marcelino Botín).

IDEAS (2008) *Un Nuevo Modelo Energético Para España – Recomendaciones Para un Futuro Sostenible* (Madrid: Fundación Ideas). Available at http://www.fundacionideas.es/sites/default/files/Informe_Modelo_Energetico_1.pdf

Iglesias, A., Cancelliere, A., Cubillo, F., Garrote, L. & Wilhite, D. (Eds) (2009) *Coping with Drought Risk in Agriculture and Water Supply Systems* (Dordrecht: Springer).

IDAE (Instituto para la Diversificación y Ahorro de la Energía) (2007) *Biocarburantes en el transporte* (Madrid: Ministerio de Industria, Turismo y Comercio).

IDAE (Instituto para la Diversificación y Ahorro de la Energía) (2010) *Guía Práctica de la Energía: Consumo Eficiente y Responsable* (Madrid: IDAE).

IIT (Instituto de Investigación Tecnológica) (2005) *Renovables 2050 – Un informe sobre el potencial de las energías renovables en la España peninsular* (Madrid: Greenpeace).

King, C. W., Holman, A. S. & Webber, M. E. (2008) Thirst for energy, *Nature Geoscience*, 1, pp. 283–286.

Krinner, W., García, A. & Estrada, F. (1994) Method for estimation efficiency in Spanish irrigation systems, *Journal of Irrigation and Drainage Engineering*, ASCE 120(5), pp. 979–986.

Linares, P. & Sáenz de Miera, G. (2009) *Implications for water of the world energy scenarios*, working paper, Instituto de Investigación Tecnológica (Universidad Pontificia Comillas), Madrid.

Madrid City Council (2010) Data of the complete sanitation system of Madrid, 2002–2009 (Wastewater Treatment Department).

MARM (Ministerio de Medio Ambiente, Rural y Marino) (2008) *Plan Nacional de Regadío – Horizonte 2008.* (Madrid: MARM).

MARM (Ministerio de Medio Ambiente, Rural y Marino) (2009) *Encuesta sobre superficies y rendimientos de cultivos (ESYRCE)* (Madrid: MARM).

MARM (Ministerio de Medio Ambiente, Rural y Marino) (2010) *Perfil Ambiental de España 2009, Informe basado en indicadores* (Madrid: MARM).

Mekonnen, M. M. & Hoekstra, A. Y. (2011) The green, blue and grey water footprint of crops and derived crop products, *Hydrology and Earth System Sciences*, 15(5), pp. 1577–1600.

MITYC (Ministerio de Industrias, Turismo y Comercio) (2008) Estadística de la industria eléctrica, 2002–2008. Available at http://www.mityc.es/energia/balances/Publicaciones/ElectricasAnuales/Paginas/ElectricasAnuales.aspx

NIS (National Institute of Statistics) (2008) *Encuesta sobre el suministro y saneamiento del agua, 2008* (Madrid: Instituto Nacional de Estadística).

Pate, R., Hightower, M., Cameron, C. & Einfeld, W. (2007) *Overview of Energy–Water Interdependencies and the Emerging Energy Demands on Water Resources* (Albuquerque, NM: Sandia National Laboratories).

Protermo Solar (2010) *Localización de las plantas termosolares en España* (Seville, Spain: Available at: http://www.protermosolar.com/boletines/boletin24.html#mapa Protermo Solar).

REE (Red Eléctrica de España) (2010) *El sistema eléctrico español 2009* (Madrid: REE).

Rio Carrillo, A. M. & Frei, C. (2009) Water: a key resource in energy production, *Energy Policy*, 37, pp. 4303–4312, DOI: 10.1016/j.enpol.2009.05.074.

Ródenas Cañada, M. A. & Guillamón Álvarez, J. (2005) Transvases y desalación – Tiza y pizarra, *Ingeniería y Territorio* No. 72, Colegio de Ingenieros de Caminos, Canales y Puertos, Barcelona.

Sala, L. (2007) Balances energéticos del ciclo del agua y experiencias de reutilización planificada en municipios de la Costa Brava, Consorcio de la Costa Brava, Seminario Internacional *Agua, Energía y Cambio Climático*, Valencia, 29–31 October.

Sallán Villegas, J. M. (2010) Coste energético y energías renovables: soluciones y oportunidades para las comunidades de Regantes, in: A. Embid (Dir) (Ed.) *Agua y Energía*, pp. 421–452 (Zaragoza: Thomson Reuters).

SEE (Secretaria de Estado de Energía) (2003a) *Estrategia de ahorro y eficiencia energética en España 2004–2012 – Sector Servicios Públicos* (Madrid: Secretaria de Estado de Energía, Desarrollo Rural y de la Pequeña y Mediana Empresa, Ministerio de Economía).

SEE (Secretaria de Estado de Energía) (2003b) *Estrategia de ahorro y eficiencia energética en España 2004–2012 – Sector Agricultura y Pesca* (Madrid: Secretaria de Estado de Energía, Desarrollo Rural y de la Pequeña y Mediana Empresa, Ministerio de Economía).

Spanish Irrigation Observatory (n.d.) Availabe at: http://www.marm.es/es/agua/temas/observatorio-del-regadio-espanol/default.aspx

Torcellini, P., Long, N. & Judkoff, R. (2003) *Consumptive Water Use for U.S. Power Production* (Washington, DC: National Renewable Energy Laboratory).

UNESA (2007) *Prospectiva de Generación Eléctrica 2030* (Madrid: UNESA).

WEF (Water Environment Federation) (2009) *Energy Conservation in Water and Wastewater Facilities*, Manual of practice No. 32 (Virginia: WEF Press).

Welgemoed, T. J. & Schutte, C. F. (2005) Capacitive deionization technology: an alternative desalination solution, *Desalination*, 183, pp. 327–340.

Wolfe, J. R., Goldstein, R. A., Maulbetsch, J. S. & McGowin, C. R. (2009) An electric power industry perspective on water use efficiency, *Journal of Contemporary Water Research & Education*, 143, pp. 30–34.