Chapter 14

Challenges and opportunities related to the Spanish water-energy nexus

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ABSTRACT: Water-energy nexus outcomes are progressively going beyond the frontiers of academic institutions. The recent Bonn 2011 Conference gathered water, energy, and food perspectives and brought the issues to the policy arena. The private sector sees the water-energy nexus as a source of challenges but also identifies business opportunities for the near future. This chapter presents some striking outcomes of the consideration of the water-energy nexus for both public and private levels of action. The first of the two connections is the *energy for water*. We emphasize the energy needs of irrigated agriculture, a challenge for the coming decades (today, 67% of the withdrawn water in Spain) and the trade-offs between water conservation and energy demands of alternative supplies for the agricultural sector. The second connection is the *water for energy*. Around 8,500 million m^3 per annum of water are withdrawn per year in Spain to cool electricity generation plants. According to future electricity demand scenarios and the types of technology being installed, this volume could double, adding further pressure to already stressed Spanish basins. We conclude by highlighting the need to integrate both energy and water issues jointly in all decisions related to energy generation decisions and water use and conservation issues.

Keywords: water-energy nexus, energy scenarios, water demand, irrigation system modernization, Spain

1 UNDERSTANDING THE WATER-ENERGY NEXUS

Nexus has been the word used to emphasize the intimate connection between water, energy, and the recently added factor, food (Hoff, 2011). Water and energy still top the list of priority issues in sustainability assessments. The realization that they are closely linked and that both should not be treated independently is a source of complexity, but is the only way to make progress towards more sustainable water and energy management.

Within the water-energy nexus, we define the connection energy for water as the energy consumption in the integral water-use cycle. Numerous studies have already shown the existence of the energy consumption in the water use cycle in several countries and sectors (CEC, 2005; Pate *et al.*, 2007; Water Environment Federation, 2009;

Cabrera *et al.*, 2010). Hardy & Garrido (2010) and Hardy *et al.* (2012) have shown that the Spanish integral water-use cycle accounted for 6% of the electricity demand in 2008 (see Table 1). 64% of the 16,500 GWh consumed in the water use cycle was required for extraction and water treatment; of which, 25% was required to supply water for food production.

Table 1 does not include final usage of water, such as heating domestic water. It has been estimated (IDAE, 2010) that 21% of the primary energy bill (electricity, gas, and oil) of a household is allocated to heating domestic water. In addition, according to the same source, from the average household electricity bill of 4,000 kWh/year in Spain, 3% is necessary for domestic hot water. Annual electricity consumption for domestic hot water in the urban sector would be 2,260 GWh.

The *water for energy* connection accounts for the water required to procure the raw material to produce one unit of energy (the fuel) and the water used in the power plant cooling systems. Each energy generation technology has different energy needs. Based on data from Rio Carrillo & Frei (2009) and Linares & Sáenz de Miera (2009), fossil and renewable energies show significantly different volumes of water use (18,000 m^3/GWh *vs*. 29,000 m^3/GWh). Hardy *et al.* (2012) have shown that

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

Stages	*Water volume (hm^3)*	*Electricity*	
		Consumption (GWh)	*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
Municipalities 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
Wastewater Treatment	**2,842**	**2,530**	**15**
Wastewater collection	3,788	189	1.2
Wastewater treatment	2,842	1,454	9
Recycled water (treatment and distribution)	1,510	887	5.4
Total	**34,940**	**16,323**	**100**
Total Spain electricity use		**279,392**	
Percentage		**5.8%**	

Source: Hardy *et al.* (2012).

Note: The water volume column gives the volume of water for each stage of the water use cycle. "Total" is the total volume of extracted water in Spain. Not all the water extracted is distributed nor treated because of own extraction and treatment systems (agricultural sector, energy sector, and industrial sector).

depending on how we deal with a 153% increase in electricity demand for the year 2030 (following UNESA, 2007), there could be an impact in terms of required water withdrawal (see Section 3). According to the same authors, the energy sector withdrew 25% of the 35,000 hm^3 in Spain in 2008 (mainly for cooling purposes) [hm^3 = cubic hectometre = million $m^3 = 10^6\ m^3$]. Severe consequences on water availability should be expected according to some of the climate change scenarios.

The water-energy nexus has planning and economic implications for water management. Sustainability assessments have to integrate both resources and establish technical recommendations.

2 ENERGY FOR WATER

2.1 Energy use in irrigation communities

The Spanish irrigation system has experienced profound transformations in the last decade. Up until 2000, flood irrigation systems were common and did not involve major energy consumption (0.02–0.15 kWh/m^3). Since 2002, the modernization of the sector has led to the replacement of superficial irrigation systems by sprinkler and drip irrigation systems, which are much more energy intensive (0.28–0.68 kWh/m^3). Between 2002 and 2008 (Figure 1), while drip irrigation systems increased by 40%, electricity needs increased by 10% during the same period (MARM, 2008a; 2009), showing that, to some extent, water savings had been achieved at the expense of a higher energy consumption. At the same time, the price of electricity went up by 30–70% in 2007–2008 (Ederra & Murugarren, 2010; see Figure 2b). As we shall see below, modernization requires investment costs that might not justify the water savings considered, especially when there is an alternative source of water available like regenerated water or desalination. There is the risk that better irrigation technologies may end up increasing water consumption (Cots, 2011; Ward & Pulido, 2008).

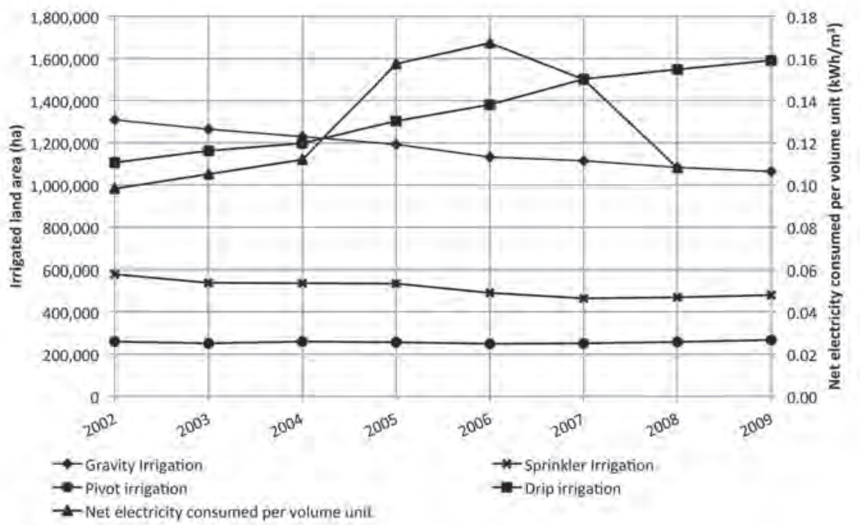

Figure 1 Evolution of Spanish irrigation systems. (Source: Hardy *et al.* (2012)).

Even if the evolution shows that improvements have been made in the use of energy, it is clear today that water savings come second because energy consumption has become the real issue. Abadía *et al*. (2010), and Carrillo-Cobo *et al*. (2010) show the importance of making energy audits in water users' associations because energy savings could be achieved through reorganization of irrigation periods and irrigation district management.

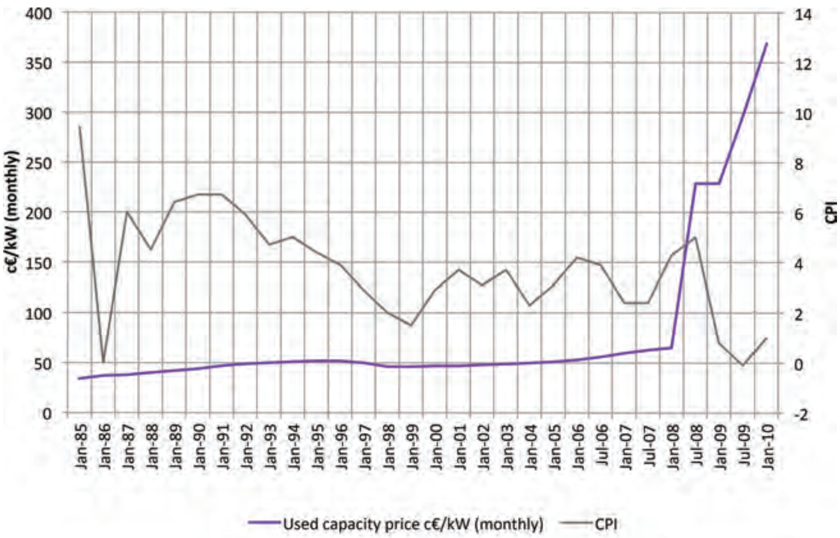

Figure 2a Evolution of contracted capacity price and the Consumer Price Index (CPI). (Source: Own elaboration with Ederra & Murugarren (2010)).

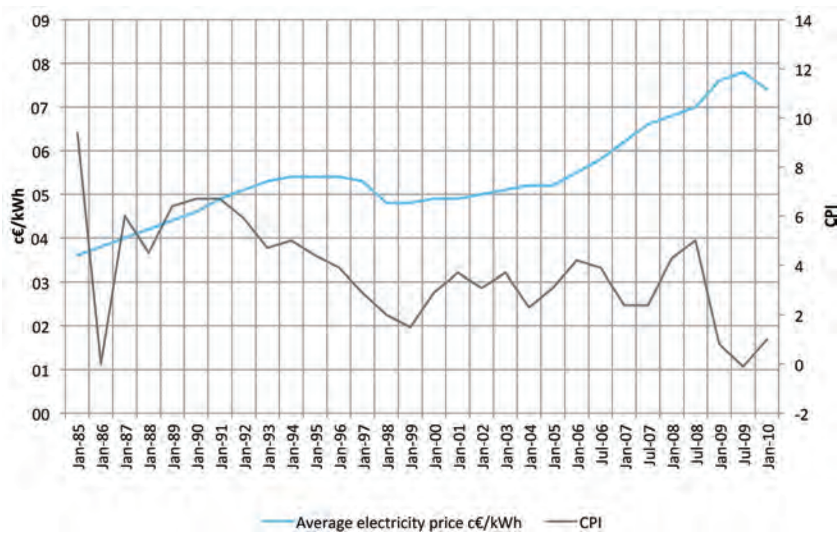

Figure 2b Evolution of the price of electricity consumed and the Consumer Price Index (CPI). (Source: Own elaboration with Ederra & Murugarren (2010)).

2.2 Further energy savings in irrigation districts

In Spain, the relation between water consumed and water used is already close to 0.8 ± 0.27 according to Krinner *et al*. (1994) and 0.8 according to Corominas (2009). Without getting into deficit irrigation (i.e. to reduce the amount of water available for irrigation without reducing the yield, quality and production), it becomes very difficult to further increase the ratio. A method to assess modernization of irrigation systems *versus* using alternative sources of water (like regenerated water or desalination) has been described in Hardy & Garrido (2010) and is briefly presented in Box 1. It is important to notice that, although other solutions for modernization exist,

Box 1 Numerical model to assess modernization against the use of alternative sources of water

In a situation of water scarcity and water use efficiency (Y_1: water consumed/water used), we want to assess the best way of expanding the resource base. There are two possibilities: to modernize the irrigation system to save water at the expense of higher energy consumption or to get the water from an alternative source (like regenerated water or desalination). Equations 1 and 2 below show the situation in which the change is neutral.

$$E_2 \cdot \frac{Y_1}{Y_2} = E_1 + E_a \cdot \left(1 - \frac{Y_1}{Y_2}\right) \tag{1}$$

which is equivalent to

$$\frac{Y_2 - Y_1}{Y_1} = \frac{E_2 - E_1}{E_a + E_1} \cong \frac{E_2 - E_1}{E_a} \tag{2}$$

where E_1 and E_2 are the energy consumption for initial and modern irrigation systems. E_a is the energy consumption of the alternative water source. Both are in kWh/m^3.

The decision rule is based on the value of Y_2, which is the expected water use efficiency in a modernized irrigation system that justifies this option. If such efficiency is not realistic, then getting water from the alternative source might be the best option. The same analysis is carried out for the associated investment cost (see Equation 3).

$$\frac{Y_2 - Y_1}{Y_1} = \frac{C_2 - C_1}{C_a + C_1} \cong \frac{C_2 - C_1}{C_a} \tag{3}$$

where

$$C_{[€/m^3]} = \frac{C_{[€/ha]} \cdot d_{[year^{-1}]} \cdot Y}{ET_{[m^3/ha/year]}} \tag{4}$$

This decision tool can be used for instance to compare two irrigation techniques (drip irrigation and sprinkler), two alternative water sources (desalination and regenerated water) and all possible values for the evapotranspiration (ET: water loss by the plant or plant water needs, in m³/ha/year). Desalination requires $E_a = 2.70$ kWh/m³ and $C_a = 0.40$ €/m³ (Torres Corral, 2005) whereas regenerated water supposes $E_a = 0.60$ kWh/m³ and $C_a = 0.06$ €/m³ (Mujeriego, 2006). Damping factor (d) has been set to 0.12/year. C [€/ha] is the investment cost per hectare for the new irrigation system. The decision criterion requires the evaluation of two criteria (the energy needed and the cost performance) to assess the usefulness of modernization of irrigation systems instead of using alternative sources of water. The reference for acceptable water use efficiency is set to 0.80 (higher efficiencies would require deficient irrigation). In Tables 2 and 3, the value of Y_2 has been coloured so that green indicates that $Y_2 < 0.8$, yellow indicates that $0.8 < Y_2 < 1$ and red indicates that $Y_2 > 1$.

the analysis here focuses on what generally happened in Spain, i.e. the modernization of irrigation systems through pressurized systems of irrigation. Irrigation management can also produce water conservation even without making large investments (see Pérez Pastor, 2010).

Graphic results of the model presented in the Box 1 are shown below. Energy criteria of Table 2 (left hand side) shows that strong modernization (maximum energy increment) is worthwhile even with initial water use efficiencies Y_1 up to 0.75, but only when the alternative water source is desalination. Regenerated water has lower energy consumption per m³, therefore at a higher level of modernization the best option for high initial water use efficiencies is not modernization but – if available – regenerated water (Table 3). If irrigation techniques with higher energy consumption were used (sprinkler instead of drip irrigation), the expected water use efficiency Y_2 could be so high that modernization would not be justified; therefore, the best option might be to use alternative sources of water.

The investment cost (right-hand side of Tables 2 and 3) is a strong limiting factor and a final decision will be based on the combination of both energy criteria and investment cost. Investment cost is site-specific, i.e. the cost is determined by the importance of the installations required to modernize the irrigation system. Where modernization is justified from an energy point of view, we can see from Tables 2 and 3 that only irrigation areas with very low initial water use efficiencies (Y_1) would be worth modernizing, otherwise the best option is to rely on the alternative source of water (regenerated water or desalination).

In addition, we observe that crops need of water per hectare (ET) affect the minimum final water use efficiency (Y_2) that would justify modernization. If water use efficiency remains constant, as ET increases (i.e. plant water necessity increases), modernization becomes a better option over alternative sources of water. This is because as more water is needed for the whole irrigation system, the investment cost per m³ decreases (see Equation 4).

Modernization of irrigation systems entails an increase in energy demand. Consequently, the energy embodied in the food product will increase and so will the CO_2 footprint of the agricultural stage of the product. In Table 4 some examples of food products cultivated in Spain are given. We assume the modernization of an irrigated land from gravity irrigation to drip irrigation system and desalination as alternative source of water.

Table 2 Appreciation of the usefulness of modernizing irrigation systems. Irrigation system: drip irrigation; alternative water source: desalination; ET = 4,100 m³/ha/year.

Y1 (Water consumed/Water used)	Increase in energy consumption E2-E1 (kWh/m³)									
	0.00	0.02	0.04	0.06	0.08	0.10	0.12	0.14	0.16	0.18
1.00	1.00	1.01	1.01	1.02	1.03	1.04	1.04	1.05	1.06	1.07
0.95	0.95	0.96	0.96	0.97	0.98	0.98	0.99	1.00	1.01	1.01
0.90	0.90	0.91	0.91	0.92	0.93	0.93	0.94	0.95	0.95	0.96
0.85	0.85	0.86	0.86	0.87	0.87	0.88	0.89	0.89	0.90	0.91
0.80	0.80	0.81	0.81	0.82	0.82	0.83	0.83	0.84	0.85	0.85
0.75	0.75	0.76	0.76	0.77	0.77	0.78	0.78	0.79	0.79	0.80
0.70	0.70	0.70	0.71	0.71	0.72	0.73	0.73	0.74	0.74	0.75
0.65	0.65	0.65	0.66	0.66	0.67	0.67	0.68	0.68	0.69	0.69
0.60	0.60	0.60	0.61	0.61	0.62	0.62	0.63	0.63	0.64	0.64
0.55	0.55	0.55	0.56	0.56	0.57	0.57	0.57	0.58	0.58	0.59
0.50	0.50	0.50	0.51	0.51	0.51	0.52	0.52	0.53	0.53	0.53
0.45	0.45	0.45	0.46	0.46	0.46	0.47	0.47	0.47	0.48	0.48
0.40	0.40	0.40	0.41	0.41	0.41	0.41	0.42	0.42	0.42	0.43
0.35	0.35	0.35	0.35	0.36	0.36	0.36	0.37	0.37	0.37	0.37
0.30	0.30	0.30	0.30	0.31	0.31	0.31	0.31	0.32	0.32	0.32
0.25	0.25	0.25	0.25	0.26	0.26	0.26	0.26	0.26	0.26	0.27
0.20	0.20	0.20	0.20	0.20	0.21	0.21	0.21	0.21	0.21	0.21
0.15	0.15	0.15	0.15	0.15	0.15	0.16	0.16	0.16	0.16	0.16
0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.11	0.11	0.11
0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05

Y1 (Water consumed/Water used)	Cost of water (€/m³)									
	0.03	0.06	0.08	0.11	0.13	0.16	0.19	0.21	0.24	0.27
	Investment cost (k€/ha)									
	1000	1900	2800	3700	4600	5500	6400	7300	8200	9100
1.00	1.00	1.06	1.12	1.18	1.25	1.31	1.37	1.43	1.49	1.55
0.95	0.95	1.01	1.07	1.12	1.18	1.24	1.30	1.36	1.42	1.47
0.90	0.90	0.96	1.01	1.07	1.12	1.18	1.23	1.29	1.34	1.40
0.85	0.85	0.90	0.95	1.01	1.06	1.11	1.16	1.22	1.27	1.32
0.80	0.80	0.85	0.90	0.95	1.00	1.05	1.09	1.14	1.19	1.24
0.75	0.75	0.80	0.84	0.89	0.93	0.98	1.03	1.07	1.12	1.16
0.70	0.70	0.74	0.79	0.83	0.87	0.91	0.96	1.00	1.04	1.09
0.65	0.65	0.69	0.73	0.77	0.81	0.85	0.89	0.93	0.97	1.01
0.60	0.60	0.64	0.67	0.71	0.75	0.78	0.82	0.86	0.89	0.93
0.55	0.55	0.58	0.62	0.65	0.69	0.72	0.75	0.79	0.82	0.85
0.50	0.50	0.53	0.56	0.59	0.62	0.65	0.68	0.71	0.75	0.78
0.45	0.45	0.48	0.51	0.53	0.56	0.59	0.62	0.64	0.67	0.70
0.40	0.40	0.42	0.45	0.47	0.50	0.52	0.55	0.57	0.60	0.62
0.35	0.35	0.37	0.39	0.41	0.44	0.46	0.48	0.50	0.52	0.54
0.30	0.30	0.32	0.34	0.36	0.37	0.39	0.41	0.43	0.45	0.47
0.25	0.25	0.27	0.28	0.30	0.31	0.33	0.34	0.36	0.37	0.39
0.20	0.20	0.21	0.22	0.24	0.25	0.26	0.27	0.29	0.30	0.31
0.15	0.15	0.16	0.17	0.18	0.19	0.20	0.21	0.21	0.22	0.23
0.10	0.10	0.11	0.11	0.12	0.12	0.13	0.14	0.14	0.15	0.16
0.05	0.05	0.05	0.06	0.06	0.06	0.07	0.07	0.07	0.07	0.08

Source: Own elaboration with Hardy & Garrido (2010).

Table 3 Appreciation of the usefulness of modernizing irrigation systems. Irrigation system: drip irrigation; alternative water source: regenerated water; ET = 4,100 m³/ha/year.

Y1 (Water consumed/Water used)	Increase in energy consumption E2-E1 (kWh/m³)									
	0.00	0.02	0.04	0.06	0.08	0.10	0.12	0.14	0.16	0.18
1.00	1.00	1.03	1.05	1.08	1.11	1.15	1.18	1.22	1.26	1.30
0.95	0.95	0.98	1.00	1.03	1.06	1.09	1.12	1.16	1.20	1.24
0.90	0.90	0.92	0.95	0.98	1.00	1.03	1.06	1.10	1.13	1.17
0.85	0.85	0.87	0.90	0.92	0.95	0.98	1.00	1.04	1.07	1.11
0.80	0.80	0.82	0.84	0.87	0.89	0.92	0.95	0.98	1.01	1.04
0.75	0.75	0.77	0.79	0.81	0.84	0.86	0.89	0.91	0.94	0.98
0.70	0.70	0.72	0.74	0.76	0.78	0.80	0.83	0.85	0.88	0.91
0.65	0.65	0.67	0.69	0.70	0.72	0.75	0.77	0.79	0.82	0.85
0.60	0.60	0.62	0.63	0.65	0.67	0.69	0.71	0.73	0.75	0.78
0.55	0.55	0.56	0.58	0.60	0.61	0.63	0.65	0.67	0.69	0.72
0.50	0.50	0.51	0.53	0.54	0.56	0.57	0.59	0.61	0.63	0.65
0.45	0.45	0.46	0.47	0.49	0.50	0.52	0.53	0.55	0.57	0.59
0.40	0.40	0.41	0.42	0.43	0.45	0.46	0.47	0.49	0.50	0.52
0.35	0.35	0.36	0.37	0.38	0.39	0.40	0.41	0.43	0.44	0.45
0.30	0.30	0.31	0.32	0.32	0.33	0.34	0.35	0.37	0.38	0.39
0.25	0.25	0.26	0.26	0.27	0.28	0.29	0.30	0.30	0.31	0.32
0.20	0.20	0.21	0.21	0.22	0.22	0.23	0.24	0.24	0.25	0.26
0.15	0.15	0.15	0.16	0.16	0.17	0.17	0.18	0.18	0.19	0.19
0.10	0.10	0.10	0.11	0.11	0.11	0.11	0.12	0.12	0.13	0.13
0.05	0.05	0.05	0.05	0.05	0.06	0.06	0.06	0.06	0.06	0.06

Y1 (Water consumed/Water used)	Cost of water (€/m³)									
	0.03	0.06	0.08	0.11	0.13	0.16	0.19	0.21	0.24	0.27
	Investment cost (k€/ha)									
	1000	1900	2800	3700	4600	5500	6400	7300	8200	9100
1.00	1.00	1.30	1.59	1.89	2.18	2.48	2.77	3.07	3.36	3.66
0.95	0.95	1.23	1.51	1.79	2.07	2.35	2.63	2.91	3.19	3.47
0.90	0.90	1.17	1.43	1.70	1.96	2.23	2.49	2.76	3.02	3.29
0.85	0.85	1.10	1.35	1.60	1.85	2.10	2.35	2.61	2.86	3.11
0.80	0.80	1.04	1.27	1.51	1.74	1.98	2.22	2.45	2.69	2.92
0.75	0.75	0.97	1.19	1.41	1.64	1.86	2.08	2.30	2.52	2.74
0.70	0.70	0.91	1.11	1.32	1.53	1.73	1.94	2.15	2.35	2.56
0.65	0.65	0.84	1.03	1.23	1.42	1.61	1.80	1.99	2.18	2.38
0.60	0.60	0.78	0.95	1.13	1.31	1.49	1.66	1.84	2.02	2.19
0.55	0.55	0.71	0.87	1.04	1.20	1.36	1.52	1.69	1.85	2.01
0.50	0.50	0.65	0.80	0.94	1.09	1.24	1.39	1.53	1.68	1.83
0.45	0.45	0.58	0.72	0.85	0.98	1.11	1.25	1.38	1.51	1.65
0.40	0.40	0.52	0.64	0.75	0.87	0.99	1.11	1.23	1.34	1.46
0.35	0.35	0.45	0.56	0.66	0.76	0.87	0.97	1.07	1.18	1.28
0.30	0.30	0.39	0.48	0.57	0.65	0.74	0.83	0.92	1.01	1.10
0.25	0.25	0.32	0.40	0.47	0.55	0.62	0.69	0.77	0.84	0.91
0.20	0.20	0.26	0.32	0.38	0.44	0.50	0.55	0.61	0.67	0.73
0.15	0.15	0.19	0.24	0.28	0.33	0.37	0.42	0.46	0.50	0.55
0.10	0.10	0.13	0.16	0.19	0.22	0.25	0.28	0.31	0.34	0.37
0.05	0.05	0.06	0.08	0.09	0.11	0.12	0.14	0.15	0.17	0.18

Source: Own elaboration with Hardy & Garrido (2010).

As we can observe from Table 4, modernization of irrigation systems certainly has to undergo an in-depth analysis to be justified from both technical and economical points of view. That way, from the energy standpoint, improvements in irrigated areas in Spain would be optimally made: either modernization or alternative source of water. The use of energy would be more efficient and sustainability of agriculture could be improved.

Table 4 Estimation of energy increase and increase in CO_2 footprint for some products grown in Spain.

Product – Agricultural system	*Energy increase (kWh/tonne)*	*CO_2 footprint increase (g CO_2/tonne)*	*Percentage of agricultural CO_2 footprint (%)*
Wine – Organic	51.9	12,814	5.4
Wine – Conventional	51.9	12,814	14.4
Tomato cherry	18.3	4,509	4.0
Olive Oil – Organic	86.0	21,246	2.3
Olive Oil – Conventional	86.0	21,246	4.3
Apple	33.5	8,273	23.6

Source: Hardy & Garrido (2010), Junta de Andalucía (2010), AQUAVIR (2005), EPEA (2009), MARM (2008b) and MITYC (2011).

2.3 Economic considerations of energy use in irrigated agriculture

The price of electricity for farmers has been increasing since July 2008, since Spain's electricity sector entered the free market, especially because of the contracted capacity. Ederra & Murugarren (2010) estimate that between 2005 and 2009, the electricity bill increased by 82%. Figure 2a shows how the contracted capacity price skyrocketed since January 2008 (increased by 470%). Figure 2b shows that the price of electricity consumed also increased from January 2008 (augmented 9%).

A possibility proposed by the National Federation of Irrigation Communities of Spain (FENACORE) is to turn water users associations (WUA) into green electricity producers (solar photovoltaic, solar thermoelectric, wind or hydropower) and hence generate their own electricity. The irrigation period in Spain usually begins in March and ends in October. The electricity that they would produce should be enough to supply their own needs during the irrigation period and could represent an extra income during the rest of the year. WUAs are demanding their status as energy generators to be granted (currently not possible due to legal barriers). In the meanwhile, WUAs are finding ways either to save energy or money, for example developing collective agreements with private companies to negotiate better electricity supply contracts.

2.4 Long term perspectives for regenerated water

Successive national water and wastewater treatment plans (PNSD) were implemented in order to enforce the 91/271/CE Directive from the European Commission on urban wastewater treatment. The 1995–2005 PNSD ended up with 77% of the cities and villages in conformity with the 91/271/CE Directive, which aimed at getting wastewater treatment in all cities and villages of at least 2,000 inhabitants equivalent. In 2008, although 92% of the population is connected to a wastewater treatment system, only 51% are connected to a tertiary wastewater treatment system (EuroStat, 2008). Energy consumption for primary and secondary wastewater treatment in Spain is estimated to be 0.53 kWh/m^3 (Hardy & Garrido, 2010) and adding a tertiary treatment stage, a supplementary 0.13 kWh/m^3 (Water Environment Federation, 2009). Although the Spanish wastewater treatment system is well developed, with 83% of the wastewater generated from all the sources being treated (EuroStat, 2008), improvements still have to be made. Table 5 provides a complete breakdown of the wastewater treatment sector according to the most recent data (2008) where 17% of the wastewater generated in Spain is not treated at all. Regarding urban wastewater treatment system, almost all the population is connected to a primary treatment system (96%) but percentages for secondary and tertiary treatment are lower (respectively 37% and 51%). In addition, we give an estimation of the supplementary energy consumption for the full treatment (tertiary treatment) of the 650 hm^3 that are not treated.

Compared to the energy consumption of the total water use cycle of Spain (see Table 1), the extension of the wastewater treatment system to a 100% tertiary treatment system would increase the water-related electricity consumption by 3%.

2.5 Water-related greenhouse gas emissions

The water-related electricity consumption in the Spanish water use cycle was 16,500 GWh for 2008. The CO_2 emitted due to electricity generation is about 4.3 million tonnes of CO_2. Over a total of 406 million tonnes of CO_2 emitted in 2008 (EuroStat, 2008), the Spanish water use cycle accounts for 1% of total Spanish CO_2 emissions. This does not include CO_2 emissions from the energy required for final usages of water such as domestic hot water.

As shown earlier in this chapter, if 100% of the generated wastewater were to be treated and recycled, i.e. all the wastewater generated undergoes tertiary treatment, the related energy consumption would be close to 430 GWh/year. The question (still open) is whether the CO_2 emissions of the wastewater saved due to the treatment (air contamination avoided) compensate for the CO_2 emissions due to the production of energy necessary for their treatment. An integral wastewater treatment system in Spain would suppose 106,000 tonnes of supplementary CO_2 emitted due to electricity generation, or 0.03% of total Spanish CO_2 emissions.

In the UK, it has been estimated that nearly 6% of the greenhouse gas emissions relate to water use and 90% of the water-related greenhouse gas emissions result from

Table 5 Estimated energy consumption (GWh) for a 100% tertiary wastewater treatment.

	2006	*2008*
Wastewater generated by all sources	3,962	3,788
from industry sector	905	828
from urban sector	3,057	2,960
Treated discharges of wastewater treatment plants	85%	83%
Total wastewater not connected to urban wastewater collecting system	585	649
Energy consumption for primary, secondary and tertiary treatment (GWh)	**396**	**429**

Source: Own estimation with EuroStat (2008).

Note: All values are in hm^3 unless specified. The energy consumption (GWh) are calculated from standard energy consumption of a 190,000 L/day treatment plant (see Water Environment Federation, 2009).

water usage inside the house, i.e. final usage of water is amongst all the stages of the water use cycle the most greenhouse gas emissions intensive (Clarke *et al.*, 2009).

Although no study has been carried out for Spain yet, Cabrera *et al.* (2010) showed that the interest in carrying out energy audits in water networks relies not only in making energy savings, but also in making CO_2 credit savings. According to MITYC (2011), Spanish electricity production in 2009 emitted 0.306 kg CO_2/kWh, but the evolution of the Spanish technology mix toward a cleaner production system brought this figure to 0.247 kg CO_2/kWh in 2010.

3 WATER NEEDS FOR FUTURE ENERGY GENERATION

Energy demand is expected to increase in the next 20 years in Spain like in the rest of the world. Scenarios for future electricity generation propose different demands and different technology mixes (IIT, 2005; UNESA, 2007; PwC, 2010). The water-energy nexus is relevant in determining the best technology mix. Rio Carrillo & Frei (2009) have shown for Spain that renewable energy systems are less water-intensive (in terms of withdrawn water) than fossil fuel energy systems (18,000 m^3/GWh *vs.* 29,000 m^3/GWh). Nuclear energy is the most water-intensive technology with 75,362 m^3/GWh. Geographic location is also important when planning a new power plant. For example, thermo solar power plants usually are constructed in arid regions where the access to water will be a limiting factor and demands have to be managed properly.

The energy sector is a water withdrawal sector, not a primary water consumptive sector. In Spain, it needs around 8,600 hm^3/year (around 25% of the water extracted annually in Spain). If electricity demand were going to increase, it would be prudent to include the water needs comparing the different proposed scenarios and their respective technology mix. Figure 3 presents seven scenarios with technology mix from two different institutions (UNESA, 2007; PwC, 2010) for electricity production in the year

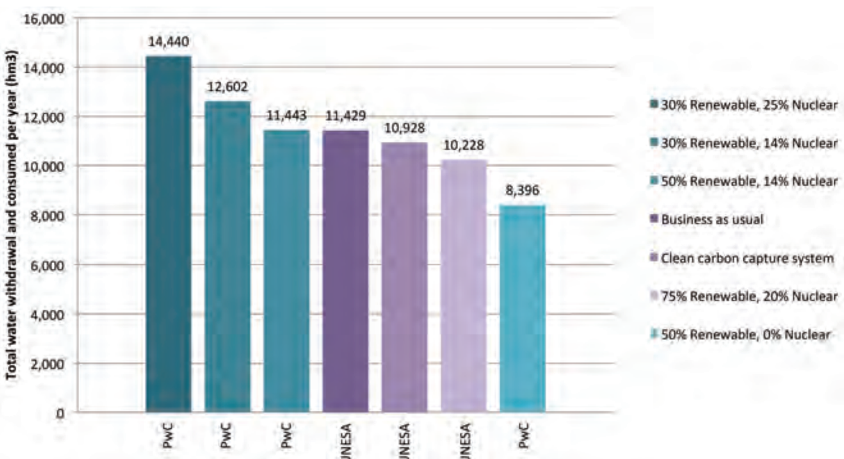

Figure 3 Water withdrawal and consumption for 7 scenarios of electricity production for the year 2030 in Spain. (Source: Rio Carrillo & Frei (2009), Linares & Sáenz de Miera (2009), UNESA (2007) and PwC (2010)).

2030. Scenarios have been regrouped as a function of the percentage of renewable energy technologies and the percentage of nuclear energy used in the technology mix. UNESA and PricewaterhouseCoopers have evaluated the electricity demand for the year 2030 to 428,773 GWh and 461,580 GWh respectively. The results presented in Figure 3 are volumes of water used for the power plant cooling systems (the *business as usual* scenario refers to the Spanish technology mix in 2007).

This suggests that water savings are higher when more renewable energy systems and less nuclear energy are present in the technology mix. Interestingly, we also observe that the reduction in total water required is higher if less nuclear plants are used than if more renewable energy technologies are used. Therefore and according to these scenarios, all else remaining the same, the larger savings in water for the electricity generation are made by taking nuclear technology out of the electricity production system, and to a lesser extent by introducing renewable energy technologies.

4 CONCLUSIONS

In Spain, two of the main conclusions after analysing the main aspects of the water-energy nexus are the importance of the irrigation sector and future energy generation. Spain has developed an intensive process of modernization of irrigated areas since 2002, with the aim of saving water (see Chapter 19). However, an undesirable consequence has been the increase in energy consumption. Hence, we developed a tool to appreciate the usefulness of modernizing irrigation systems that considers all the available options to face a situation of water scarcity before getting into the process of modernization. We find that from the water-energy perspective, unless there is a low initial water-use efficiency (around 50%), modernization of irrigation systems might not be the best option. It would be better instead to consider alternative sources of water such as desalination or regenerated water. Investment costs are always a limiting factor to modernization. As a water savings generation strategy, modernization generally performs worse than using desalinated water and much worse than using regenerated water.

Apart from becoming an alternative source of water, regenerated water production is an important challenge in the European Union. Considering the water-energy nexus, it would be an option to lower our dependency on resources, with the added advantage of providing an economical use for raw material like wastewater, which has no significant usage now. To extend wastewater treatment systems to include tertiary treatment all over Spain would account for 3% of the water-related electricity consumption (i.e. 0.2% of the Spanish electricity demand).

Spain still lacks a comprehensive analysis of final usages of water (in terms of both water and energy). However, it is estimated that the water use cycle (without considering final usage), could account for 1% of the total CO_2 emissions of Spain. If final usage (such as water heating) were taken into account, we surmise that the energy consumed per m^3 will grow, and hence, the CO_2 footprint would go above the said 1%.

One important conclusion in terms of energy planning from the study is that electricity consumption is likely to increase in the future, therefore several scenarios of technology mix and electricity demands exist. By relating the production of electricity to water needs, we show that more water is saved if nuclear power is removed than if more renewable energy systems are built.

REFERENCES

Abadía, R.; Rocamora, M.C.; Córcoles, J.I.; Ruiz-Canales, A.; Martínez-Romero, A.; Moreno, M.A. (2010). Comparative analysis of energy efficiency in water users associations. *Spanish Journal of Agricultural Research*, 8(2): 134–142.

AQUAVIR (2005). Superficie de los Cultivos de Regadío y sus Necesidades de Riego, en la Demarcación de la Confederación Hidrográfica del Guadalquivir [Irrigated Agriculture Area and Water Needs in the Guadalquivir River Basin District]. Final report.

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): 669–677.

Carrillo-Cobo, M.T.; Rodríguez-Díaz, J.A. & Camacho-Poyato, E. (2010). The role of energy audits in irrigated areas. The case of *Fuente Palmera* irrigation district (Spain). *Spanish Journal of Agricultural Research*, 8(S2): S152–S161.

CEC (California Energy Commission) (2005). California's Water-Energy Relationship. Final Staff Report. California Energy Commission, State of California, USA.

Clarke, A.; Grant, N. & Thornton, J. (2009). *Quantifying the energy and carbon effects of water saving*. Environment Agency, Energy Saving Trust, UK.

Corominas, J. (2009). Agua y energía en el riego, en la época de la sostenibilidad [Water and Energy in Irrigated Agriculture in Sustainable Times]. *Ingeniería del Agua*, 17(3): 221–233.

Cots, Ll. (2011). *Desarrollo y calibración de un modelo de simulación de recursos hídricos aplicado a la cuenca del río Corb dentro de la zona regable de los canales de Urgell* (*Lleida*) [Design and Calibration of a Water Resources Simulation Model Applied to Corb River Basin Located Within the Irrigation District of Urgell Canals (Lleida)]. Barragán, J. (dir.), PhD Thesis, Escola Tècnica Superior d'Enginyeria Agrària, Universitat de Lleida, Spain.

Ederra, I. & Murugarren, N. (2010). *La nueva tarifa eléctrica, la escalada de precios del agua de riego* [The New Electricity Tariff, the Escalation in Water Prices for Irrigation]. Navarra Agraria. March–April 2010, pp. 45–50. Available from: [http://www.riegosdenavarra.com/publica/TarifasElectricas2010 NavarraAgraria.pdf].

EPEA (Asociación de Empresas con Productos Ecológicos de Andalucía) (2009). *Dinámica de desarrollo de la agricultura ecológica e innovación*, Loriol-sur-Drôme [Development Dynamic of Organic Agriculture and Innovation]. Available from: http://www.agencebio.org/upload/pagesEdito/fichiers/JMLuque090909.pdf [Accessed 3rd March 2011].

EuroStat (2008). Water Statistics – Annual data, EuroStat Database. Available from: http://epp.eurostat.ec.europa.eu/portal/page/portal/statistics/search_database [Accessed 3rd March 2011].

Hardy, L. & Garrido, A. (2010). *Análisis y evaluación de las relaciones entre el Agua y la Energía en España* [Analysis and Evaluation of Spain's Water–Energy Relationship]. Botín Foundation, Santander, Spain.

Hardy, L.; Garrido, A. & Juana, L. (2012). Evaluation of Spain's Water-Energy Nexus. *International Journal of Water Resources Development*, 28(1), Special Issue: Water Policy and Management in Spain. Taylor & Francis, Leiden, the Netherlands.

Hoff, H. (2011). *Understanding the Nexus*. Background Paper for the Bonn 2011 Conference: The Water, Energy and Food Security Nexus. Stockholm Environment Institute, Sweden.

IDAE (Instituto para la Diversificación y Ahorro de la Energía) (2010). *Guía Práctica de la Energía, Consumo Eficiente y* Responsible [Practical Guide to Energy, Efficiency and Responsible Consumption]. Madrid, Spain.

IIT (Instituto de Investigación Tecnológica) (2005). *Renovables 2050 – Un informe sobre el potencial de las energías renovables en la España peninsular* [Renewables 2050 – Report on Renewable Energies Potential for Peninsular Spain]. Greenpeace.

Junta de Andalucía (2010). *Inventario de regadíos y su evolución en la última década* [Irrigation Districts Inventory and Evolution from the Last Decade]. Department of Agriculture and Fishing, Committee of Andalucía, Seville, Spain.

Krinner, W.; García, A. & Estrada, F. (1994). Method for Estimation of Efficiency in Spanish Irrigation Systems. *Journal of Irrigation and Drainage Engineering*, ASCE, 120(5): 979–986.
Linares, P. & Sáenz de Miera, G. (2009). *Implications for water of the world energy scenarios*. Working paper of the Instituto de Investigación Tecnológica, Universidad Pontificia Comillas, Madrid, Spain.
MARM (Ministerio de Medio Ambiente, Rural y Marino) (2008a). *Encuesta sobre superficies y rendimientos de cultivos* [Crop Areas and Yields Survey] (ESYRCE). Available from: http://www.magrama.gob.es/ministerio/pags/Biblioteca/Revistas/pdf%5FESRC%2FESRC%5F2008%2Epdf [Accessed 4th March 2011].
MARM (Ministerio de Medio Ambiente, Rural y Marino) (2008b). Anuario de estadística agraria 2009 [Agricultural Statistics Yearbook 2009]. Available from: http://www.magrama.gob.es/es/estadistica/temas/estad-publicaciones/anuario-de-estadistica/default.aspx#para3 [Accessed 4th March 2011].
MARM (Ministerio de Medio Ambiente, Rural y Marino) (2009). *Encuesta sobre superficies y rendimientos de cultivos* [Crop Areas and Yields Survey] (ESYRCE). Available from: http://www.magrama.gob.es/ministerio/pags/Biblioteca/Revistas/pdf%5FESRC%2FESRC%5F2009%2Epdf [Accessed 4th March 2011].
MITYC (Ministerio de Industria, Turismo y Comercio) (2011). *Balance Energético 2010 [Energy Balance 2010]*. Press release. Madrid, Spain.
Mujeriego, R. (2006). *La reutilización planificada del agua* [Managed Water Reuse]. Sabadell Universitat. Available from: http://www.canagua.com/es/pdf/reutilizacion.pdf [Accessed 4th July 2011].
Pate, R.; Hightower, M.; Cameron, C. & Einfeld, W. (2007). *Overview of Energy-Water interdependencies and the emerging energy demands on water resources*. Sandia National Laboratories, Albuquerque, New Mexico, USA.
Pérez Pastor, A. (2010) (Coord). Special issue (S2). Solutions to the water deficit in agriculture. *Spanish Journal of Agricultural Research* 8(S2), S3
PwC (PricewaterhouseCoopers) (2010). *El modelo eléctrico español en 2030, Escenarios y alternativas* [The Spanish Electricity Model in 2030, Scenarios and Alternatives]. PricewaterhouseCoopers.
Rio Carrillo, A.M. & Frei, C. (2009). Water: A key resource in energy production. *Energy Policy*, 37: 4303–4312, DOI: 10.1016/j.enpol.2009.05.074.
Torres Corral, M. (2005). Desalación y planificación hidrológica hoy [Desalination and Water Management today]. *Ingeniería y Territorio*, 72. Colegio de Ingenieros de Caminos, Canales y Puertos, Barcelona, Spain.
UNESA (2007). *Prospectiva de Generación Eléctrica 2030* [Prospective of Electricity Generation in 2030]. Madrid, Spain.
Ward, F.A. & Pulido, M. (2008). Water conservation in irrigation can increase water use. *Proceedings of the National Academy of Sciences of the USA* (PNAS), 105(47): 18215–18220.
Water Environment Federation (2009). *Energy Conservation in Water and Wastewater Facilities. Manual of practice No. 32*. WEF Press, Virginia, USA.