Freshwater for Cooling Needs: A Long-Run Approach to the Nuclear Water Footprint in Spain

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Abstract

From the invention of the steam engine to the present, water has represented a significant input to the energy system, although this has been mostly ignored in the literature. In Spain, the most arid country in Europe, studies about water footprint typically just consider domestic, agricultural and industrial water uses, but water requirements for the electricity sector are omitted despite our dependence on thermal power. It has been demonstrated that for each available cooling technology, nuclear needs and consumption of water tend to be larger per MWh generated. We calculate a first approximation to the Spanish nuclear water footprint from 1969 to 2015. Our results show that while water consumed by Spanish nuclear power plants are around 3 m^3per capita/year, water withdrawals per capita/year are around 70 m^3. Moreover, our analysis allows extracting conclusions focusing on a River Basins approach. What is the water impact of our nuclear power plants? Will water limit our energy future? These are some of the issues at stake.

JEL Code: N540; Q49; Q25
Keywords: Energy, Water Footprint, Cooling Technology, Nuclear, Spain.

1. Introduction.

From the invention of the steam engine to the present, water has represented a significant input to the energy system, although this has been mostly ignored in the literature. The production of electrical power results in one of the largest uses of water worldwide. When accounting total volumes of water in the energy sector we differentiate within water withdrawals (the total amount of water removed from a source) and water consumption (the amount lost to evaporation that is not returned to the source). For example, it is estimated that in 2005 in the US about 41 percent of freshwater withdrawals were dedicated to electric production from thermoelectric plants, mainly for cooling (Kenny et al., 2009). Likewise, in the year 2010, France withdrawn 22 $\mathrm{km}^3$of water for cooling purposes and 20 km^3 in the case of Germany

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(EUROSTAT, 2014). Moreover, about 80 percent of the world´s electricity is generated in thermal power plants (IEA, 2013). In other words, 80 per cent of the world's electricity generation would cease to exist in absence of water; if we add the percentage corresponding to hydropower, the number will be close to 95 per cent. Thus, we must start thinking of water as the most needed natural resource for electricity generation.

Energy and water are valuable resources that support human wellbeing (Brundtland et al., 1987). Consequently, the mutual vulnerability of water and energy is considered one of the most important concerns of the future and, for this reason, it remains a challenge in achieving the Millennium Development Goals (MDGs). In this context, great amounts of water are needed in power generation, mainly for cooling processes, and the water sector needs energy to extract, treat and transport water. Several trends point to rising demands on energy and water because of the growth of population and expansion of economies. Therefore, ensuring the provision of water and energy in the future is essential to guarantee the sustainable development of many countries. In addition, climate change is causing the continued deterioration of global water sources. To this aim, several organizations and institutions have developed proposals to address the challenges of energy resources planning and water. Among these we can find the UN-Water Inter-agency, the World Water Forums, and the Thirsty-Energy Initiative launched by the World Bank. The UN-Water Interagency coordinates the work of the United Nations on freshwater and sanitation, including surface water and groundwater resources, the interface between freshwater and seawater and water-related disasters.[1] Similarly, the World Energy Council and the World Water Council through the World Water Forums spotlight the importance of water on the political agenda.[2] Finally, the Thirsty- Energy Initiative from the World Bank introduces a wide variety of regulations and management actions in order to help governments to ensure water and energy for future generations.[3] In other words, '*Thirsty Energy quantifies trade-offs and identifies synergies between water and energy resource management*' (Rodriguez et al., 2013).

Water for thermoelectric power is used in generating electricity with steam-driven turbine generators and to cool the power-producing equipment. The water constraint has already impacted the energy sector in many parts of the world. Some examples are the U.S, France, India, China or Brazil (Rodriguez et al., 2013). Among the available thermoelectric technologies, it has been demonstrated that nuclear power requires the largest amounts of water of the sector. In other words, for each available cooling technology, nuclear withdrawals and consumption of water tend to be larger per MWh generated (IEA, 2012).[4] The use of nuclear energy is one of the heated debates in many societies although nuclear energy meets more than 20% of electricity in OECD countries

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[1] For more information about UN-Water, see (http://www.unwater.org)

[2] For more information, see (http://www.worldwaterforum5.org)

[3] For more information about Thirsty Energy Initiative, see (http://www.worldbank.org/en/topic/sustainabledevelopment/brief/water-energy-nexus)

[4] Friends of the Earth Association (Australia) in its Anti-Nuclear & Clean Energy Campaign about nuclear power and water consumption states that '*a megawatt-hour (MWh) of electricity from coal uses 20 to 270 litres of water at the coal mining stage and an additional 1,200 to 2,000 litres when the energy in the coal is converted to electricity, totaling 1,220 to 2,270 litres of water consumed per MWh. In comparison, nuclear energy uses 170 to 570 litres of water per MWh during the mining of uranium and production of the reactor fuel and an additional 2,700 litres per MWh as the energy from nuclear fission is converted to electricity, for a total of 2,870 to 3,270 litres of water consumed per MWh'*. [www.foe.org.au/anti-nuclearJanuary 2013]

(Zohuri, 2016). But the discussions concentrate on other aspects of nuclear power (over all, radiation risks and spent fuel management) rather than on the freshwater requirements for nuclear generation.

In an international context, Spain, the most arid country in Europe, appears among the top ten producers of nuclear energy in the world (IAEA, 2015). Therefore, acquiring the knowledge of the Spanish position in this area is essential to provide the necessary judgment tools for the optimal decision-making processes by public authorities, and both public and private business community. As the literature review below reveals, in Spain, unlike other countries, the water problem within energy sector has not yet been considered.

This paper pioneers a first approximation to the water requirements of the Spanish nuclear power plants from 1969 to 2015. In other words, our aim is to calculate the consumptive use of water (i.e. the amount of water evaporated, transpired, or incorporated in energy production) by Spanish nuclear power plants, and the amounts of water withdrawals required for running nuclear power plants. Even if large portions of the water required return to the rivers, yet the opportunity cost exists for such water volumes. Our results show that water withdrawn from rivers by Spanish nuclear power plants is around 70 m^3 per capita in 2014. Likewise, water consumed (i.e. evaporated) by Spanish nuclear power plants is equivalent to around 3 m^3 per capita for the same year. The results also allow the comparison between sectors (for example, water for agricultural or urban uses) allowing us to scale the figures and appreciate the importance of this analysis. This study contributes to a better understanding of the necessary freshwater resources to produce nuclear electricity in Spain and raise awareness about the importance of this issue in a country where the water-energy nexus is not a priority on the political agenda. What is the water impact of our nuclear power plants? Will water limit our energy future? Should water be considered when planning the electricity mix in the future? These are some of the issues at stake.

The rest of the paper is structured as follows: Section 2 presents the background and the literature review; Section 3 explains the methodology and data used; Section 4 discusses the results and main conclusions. Finally, Section 5 reviews the potential uncertainties and limitations of the analysis presented.

2. Background & Literature Review.

The problem of the interdependence between water and energy is gaining importance because of their demand increases in the future. Accordingly, there are several international studies on the relationship between energy production and water (Malik, 2002; Kahrl and Roland-Holst, 2008; Perrone et al., 2011; Siddiqi and Anadon, 2011; Spang et al., 2014; Jägerskog et al., 2014). The expanding literature on the water-energy nexus developed different approaches to the issue. Rodríguez et al., (2013) analyze the issue by looking at the general water requirements for power generation, and introducing improvement proposals. Delgado et al. (2015) introduce the same problem, but from a more technical perspective. These authors add some explanations related to cooling systems, steam cycle processes, heat balance, and the efficiency in thermal power plants. For its part, the International Energy Agency (2012) provides data about global water withdrawals for power generation and water requirements in the energy sector, and analyses possible future scenarios leaving over the air a question: Is energy becoming a thirstier resource? Likewise, Morrison et al. (2009) highlight the intensifying conflict between energy use and water availability and suggest some guidelines that companies should take to evaluate and address water risks. Siddiqi and Anadon (2011) analyze water intensity throughout the different segments of the energy value chain (i.e. fuel extraction, refining, electricity generation) and calculate the energy intensity of the water value chain. Finally, WWAP (2014) produced a very extensive report about the linkages between freshwater and energy. In the first stage the report introduces the status, trends and challenges related to the water-energy nexus. After that, different central themes and regional areas are analyzed, keeping space at the end for new guidelines and good practices.

More to our point of interest, some articles and technical reports describe the water requirements of power production by cooling technology and several methodologies to calculate water footprint and asses the impacts of water uses. For example, Jeswani and Azapagic (2011) is a good example showing that. In this case, authors analyze some methodological developments which propose methods for inventory modelling and impact assessment for water use in life cycle assessment. Alternatively, Dodder (2014) provides a systems-level perspective regarding different power technologies and Meldrum et al. (2013) and Macknick et al. (2012) introduce a review and harmonization of water withdrawal and water consumption factors found in the literature. Moreover, Delgado Martín (2012) in her doctoral thesis analyses the water use in power plants from a technological perspective through a model based on the heat balance of the power plant. Feeley et al. (2008) also analyses water availability in a power generation context for the development of a program to reduce the water withdrawals and consumptions in the future. In contrast, Spang et al. (2014) explore the geographic distribution of water use by national energy portfolios. They define and calculate an indicator to compare the water consumption of energy production for over 150 countries for year 2008 . For their part, Flörke et al. (2011) assess future changes in freshwater needs on electric sector in Europe thought the combination of two approaches: a scenario approach and a modelling approach. In fact, there exists an expanding literature of technical reports on the water required for electricity production: Torcellini et al. (2003), IAEA (2012), EPRI (2000), Averyt et al. (2011), and Kohli and Frenken (2011).

Other strain of the literature concentrates on the potential water quality and ecosystem impacts by the energy sector. For instance, water withdrawn for cooling but not consumed returns to the environment at a higher temperature affecting to surface water and aquatic ecosystems (Gunter et al., 2001). Likewise, when water withdrawn enters the system can trap fish and other aquatic wildlife. And when power plants tap groundwater for cooling, they can deplete aquifers critical for meeting many different needs. A related vast body of literature focuses on the ecological footprint of water used in different human activities. For example, Wackernagel and Rees (1997) are the first to suggest a sustainable development index to evaluate human impact on ecosystems in terms of land and water areas. Another source that talks about water resources and human impacts on them is Kenny et al. (2009) that, specifically, achieve an estimation of water uses in the Unites States differentiating within different activities (i.e. public and domestic supply, irrigation, livestock, aquaculture, industrial uses, mining, and thermoelectric power). Moreover, these authors show the evolution of water trends in the U.S. from 1950 to 2005.

Hoekstra and Hung (2002) introduced the concept of water footprint as an indicator of freshwater uses that considers, in addition to the direct water use by consumers or producers, the indirect water uses made by the same processes. Most of international literature about water footprint analysis differentiate three water footprints: green (evaporated, transpired or incorporated by plants), blue (evaporated, incorporated into product or withdrawn from a body of water) and grey water (the amount of fresh water required to restore polluted water to a specified standard).[5] In this context, Hoekstra (2008) analyzed the water footprint of food, taking into consideration the international trade in agricultural commodities. Also, Rost et al. (2008) quantify the global blue and green water consumptions in an agricultural context resulting from human effect. Another international study based on the agricultural sector and crops production is (Mekonnen and Hoekstra, 2011).

Most of the studies about water usage in Spain relate to the concept of water footprint. They consider domestic, agricultural and industrial water uses, but the water requirements for the energy sector tend to go unnoticed. Aldaya et al. (2010) present the estimation and analysis of the water footprint in Spain, from a hydrological, economic and ecological perspective providing a multidisciplinary framework for optimizing water policy decisions and contributing to the implementation of the EU Water Framework Directive (2000/60/EC). Cazcarro et al. (2013) analyze the evolution of water consumptions of the Spanish regions and perform a structural decomposition about how determinants of economic growth influence water consumption. Their numbers show that the Spanish economy has evolved towards a more water-intensive society since 1980. Cazcarro et al. (2014) estimate the water footprint within the tourism sector through an input-output analysis differentiating between direct domestic water and embodied water. They conclude that water footprint of national tourism is 3,248,000 hm^3. Cazcarro et al. (2015a) combine input-output analyses and GIS localized information to estimate the grey virtual water interregional flows and footprints in Spain. By their part, Cazcarro, et al. (2015b) analyze the changes in 50 years in the water footprint in Spain. These authors analyze the blue and green water footprint of crop production at the provincial level and from a long-term perspective. Historical and spatial dimensions allow them to evaluate the environmental and economic impacts associated to the Spanish economic growth. Duarte et al. (2002) analyze the behavior of the economic sectors in Spain as water consumers, identifying the importance of the agriculture and food sectors as the main water consumers in the country. In a step forward, Duarte et al. (2014) analyzed the water footprint of the Spanish agricultural sector for the period 1860-2010. In this case, the authors applied a decomposition analysis. Another important study about water footprint in the

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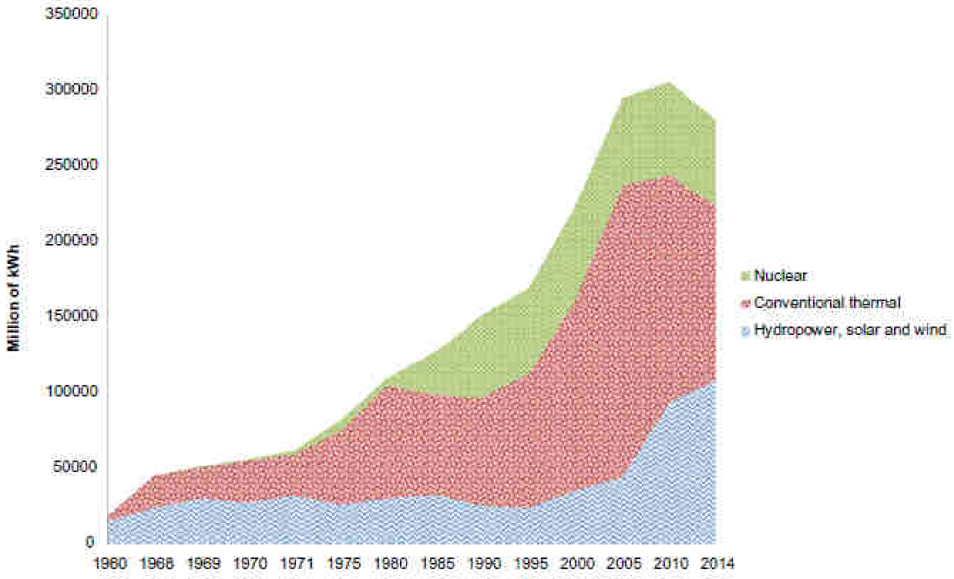
[5] Water footprint network, What is a water footprint?
http://waterfootprint.org/en/water-footprint/what-is-water-footprint/

agricultural sector in Spain is (Rodriguez Casado et al., 2008). There exists also studies at the regional level. Velazquez (2006) and Tello and Ostos (2012) calculated the water footprint of the thirsty region of Andalusia and Barcelona city, respectively. Likewise, Aldaya and Llamas (2008) calculate the water footprint for the Guadiana river basin and Vanham and Bidoglio (2014) quantify the water footprint of consumption and production of Milan.

Despite the above-mentioned efforts, there exist a gap in the literature in the case of issue of water needs of the energy sector in Spain. To understand the water requirements the electricity sector, we must introduce the evolution of the electric generation in Spain in the long run. Until the 1960s, hydroelectricity remained the major contributor to Spanish electricity generation. The economic miracle of the 1960s and early 1970s required more energy input. In the case of electricity, it translated into more thermal plants (coal and fuel-oil) and the beginning of nuclear generation with the opening of the first generation of nuclear power plants: Zorita, Garoña and Vandellós I opened in 1968, 1971 and 1972 respectively. Over the 1970s Spain become the major nuclear client of the US, the world´s largest reactor exporter (De la Torre and Rubio-Varas, 2016). The utilities projected over 22,000 MW of nuclear installed capacity in the frenzy of atomic optimism, of which only 7000MW got eventually connected to the grid, given the declaration of a nuclear moratorium in 1984. From the 1980s to the present, nuclear electricity contributed with an average 23.9% of the electric generation in Spain. With the turn of the century wind and solar power, and biomass join to the electricity mix. The figure below shows the complete drawing. Fig.1 shows the evolution of the Spanish power generation by technology.

Figure 1. Evolution of Spanish Power Generation by technology (1960-2015)



Note: Solar and wind power are included coupled with hydropower from 2003. Conventional thermal includes coal, fuel-oil, gas and combined cycle plants.
Source: own elaboration from UNESA´s Annual Reports

3. Methodology & Data.

The information related to water resources for energy purposes is heterogeneous and, in most cases, limited within Spain. One of the reasons is that water competences on water issues are distributed between different administrative levels. The hydraulic public property belongs to the State. In addition, water issues affect the environment, fishing, agriculture, energy, health, sport and leisure, civil defence, etc., and every territorial entity (municipalities, provinces and regional governments) have some degree of competence in all these matters. In addition, river basins had their own management organization with the denomination Hydrographic Confederations. These are public entities attached for administrative purposes to a Ministry (today that of Environment and Rural and Marine Affairs) but in basins within a single region the water management corresponds to the region alone.[6] Furthermore, published statistical figures are not clearly disaggregated within different types of water (i.e. surface water and groundwater) or water uses (withdrawals vs. consumption).

The choice between a cooling system or another has a great impact on water requirements for a given type of thermal power generation. Spanish nuclear power plants tend to work with two cooling systems: once-through (open-loop) systems and cooling towers. On the one hand, once-through systems withdraw water passing it through a steam condenser and returning it to a nearby water location downstream (legal boundaries tend to apply to the temperature of the returning water). This cooling technology evaporates a small fraction of the water withdrawn. On the other hand, a cooling tower is a heat rejection mechanism, which extracts waste heat to the atmosphere though the cooling of a water stream to a lower temperature. There exist a trade-off between water withdrawn and water evaporated. Open-loop systems withdraw much more water than cooling towers, but cooling towers evaporate much more water than open-loop systems.

To produce a first approximation to the water needs of the Spanish nuclear power plants we have just considered those nuclear facilities operating with freshwater withdrawing water from rivers or lakes. Plants working with seawater or other coolants (such as gas) have been omitted in this study. In environmental terms, however, power plants working with seawater also entail potential consequences for the environment (for example, those related to the increase in the temperature of the water returned to the sea). Spain had 10 nuclear reactors commercially connected to the grid, of which only 7 remain operative as for 2016, contributing to about 20 per cent of the final electricity generation of the country on that year. They differ in cooling technology, with a wide range of water withdrawals and water consumption factors.

The nuclear power plants that we consider are Trillo I, Cofrentes, Almaraz I and II, Ascó I and II, Santa María de Garoña and José Cabrera (Zorita, as known). We have excluded from our analysis Vandellós units I and II which use gas and sea water for cooling, respectively. In Table 1 we have categorized Spanish nuclear power plants by type of

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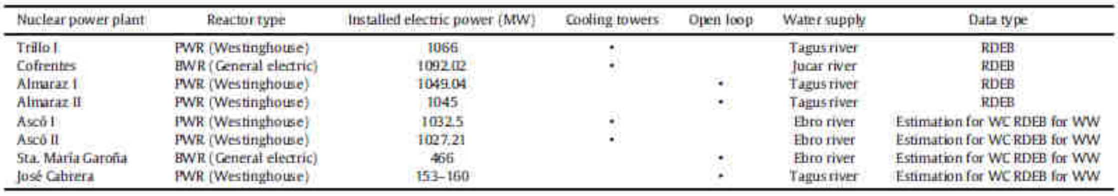
[6] The Hydrographical Basin is the basic entity of water management in Spain. See http://hispagua.cedex.es/en

cooling system. We also provide the type of data available for water needs and include the electric capacity and the source of water supply of each power plant.

Table 1. Classification of Spanish Nuclear Power Plants by Type of Technology and Data Used



Nuclear power plant	Reactor type	Installed electric power (MW)	Cooling towers	Open loop	Water supply	Data type
Trillo I	PWR (Westinghouse)	1066	•		Tagus river	RDEB
Cofrentes	BWR (General electric)	1092.02	•		Jucar river	RDEB
Almaraz I	PWR (Westinghouse)	1049.04		•	Tagus river	RDEB
Almaraz II	PWR (Westinghouse)	1045		•	Tagus river	RDEB
Ascó I	PWR (Westinghouse)	1032.5	•		Ebro river	Estimation for WC RDEB for WW
Ascó II	PWR (Westinghouse)	1027.21	•		Ebro river	Estimation for WC RDEB for WW
Sta. María Garoña	BWR (General electric)	466		•	Ebro river	Estimation for WC RDEB for WW
José Cabrera	PWR (Westinghouse)	153–160		•	Tagus river	Estimation for WC RDEB for WW

Note: PWR = Pressurised Water Reactor; BWR = Boiling Water Reactor; RDEB = Real Data Extrapolated Backwards.
Source: own elaboration from Spanish Nuclear Forum and Spanish Nuclear Security Council.

We define water withdrawals (WW) as the total volume of water removed from a source by a power plant and water consumption (WC) as the amount lost to evaporation during the cooling process. In other words, water consumption is the volume of water withdrawn that is not returned to the source and it represents the value of the water footprint. Henceforth, the discharge (D) is the volume of water withdrawn that is returned to the source, often degraded by use (altered physically or chemically) and impacting water quality.[7]

We compiled the published available data on water requirements by nuclear plant in Spain. The sources consulted include the water permissions originally granted from the State for each nuclear plant as published in Boletin Oficial del Estado (BOE), which provide the expected flow required and the maximum threshold of water withdrawals allowed for each reactor[8]; the scattered data provided by some of the Hydrographic Confederations[9]; data on water use for nuclear plants in Government publications[10]; the data provided for some plants by the Nuclear Safety Board (CSN)[11]; the utilities'

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[7] For other definitions see:
- Vickers, A. (2001). *Handbook of water use and conservation*. Amherst, MA: WaterPlow Press.
- U.S Geological Survey (USGS) (http://www.usgs.gov)
- IEA (2012). Water for Energy: is energy becoming a thirstier resource?
- Averyt, K., J. Fisher, A. Huber-Lee, A. Lewis, J. Macknick, N. Madden, J. Rogers, and S. Tellinghuisen. (2011). F*reshwater use by U.S. power plants: Electricity's thirst for a precious resource*. A report of the energy and Water in a Warming World initiative. Cambridge, MA: Union of Concerned Scientists. November.

[8] BOE, núm. 48, de 25 de febrero de 1971, pp. 3140-3441.
BOE, núm. 279, de 22 de noviembre de 1971, pp. 18801-18802.
BOE, núm. 31, de 5 de febrero de 1977, pp. 2906-2907.
BOE, núm. 200, de 22 de agosto de 1977, pp. 18744-18746.
BOE, núm. 138, de 9 de junio de 1984, p. 16717.
BOE, núm. 207, de 30 de agosto de 1999, pp. 31958-31994.
BOE, núm. 89, de 12 de abril de 2014, pp. 30535-30638.

[9] Targus Hidrographic Confederation (HC) speaks of a consumptive use of 20.50 and 46.30 hm^3/ year for Trillo and Almaraz. The Ebro River HC shows on its website the following data on freshwater demands for cooling: Ascó (2,270 hm^3/year) and Garoña (766 hm^3/year). Other figures from the same source are around 2,438.36 hm^3/year.For more information, see the uses of water for energy production in [http://www.chebro.es/contenido.visualizar.do?idContenido=2137&idMenu=2233] and water uses and demands [http://www.chtajo.es/DemarcaTajo/UsosyDemandas].

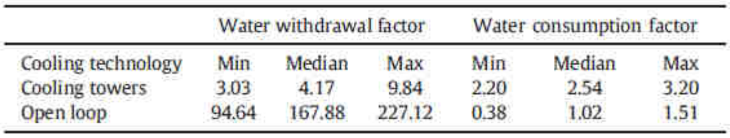
[10] Spanish Government. Ministerio de Medio Ambiente. Secretaria de Estado de Aguas y Costas. Dirección General de Obras Hidráulicas y Calidad de Aguas (2000), *Libro Blanco del Agua* [available online at: http://hispagua.cedex.es/node/66958]

[11] - Consejo de Seguridad Nuclear (1999). *Las centrales nucleares españolas*. 2ªed. Madrid: Consejo de Seguridad Nuclear, 218 p.
- Barahona and Ramos (1999). *Los efluentes radiactivos en las centrales nucleares españolas: (1980-1997).* Madrid: Consejo de Seguridad Nuclear, 109 p.
- Palancar (2004). *Proyecto TRACER: estudios de dispersión de contaminantes en ríos y embalses*. Madrid: Consejo de Seguridad Nuclear, 279 p.

environmental reports[12]; the nuclear power plants information pages[13]; sustainability projects including any of the nuclear plants[14]; NGOs environmental reports[15], etc. We found large inconsistencies among this sources, both in the magnitudes provided for individual reactors but also in the precision about the indicators used**.** In most cases, available data cover either WW or WC but rarely both. In other occasions the sources obviate to define whether the figure provided refers to WW or WC.

There are reactors for which no published figure on water withdrawals and/or consumption could not be fetched, or the available data were inconsistent or ill defined. There exit however, estimations based on the international literature. All Spanish reactors are of American manufacturing, except two of them: Vandellós I and Trillo, French and German manufacturing respectively (De la Torre and Rubio-Varas, 2015). Therefore, by reviewing the American literature on cooling technology and water factors (Torcellini et al., 2003; Spang et al., 2014; Macknick et al., 2012) the same standard factors can be used the Spanish equivalent reactor. We transformed the literature factors into cubic meters to facilitate comparison with results from other Spanish studies (see Table 2).

Table 2. Withdrawals and Consumption Factors of nuclear power plants by Cooling technology, based on the international literature$(\mathbf{m^3\ MW^{-1}h^{-1}})$



	Water withdrawal factor			Water consumption factor		
Cooling technology	Min	Median	Max	Min	Median	Max
Cooling towers	3.03	4.17	9.84	2.20	2.54	3.20
Open loop	94.64	167.88	227.12	0.38	1.02	1.51

Source: elaborated based on data from Macknick et al. (2012).

For each nuclear reactor we obtained a theoretical technical factors of water use according to the international literature (Table 2), plus and array of published figures regarding the water use (undefined in some of the sources), water withdrawal and consumption for most plants. In the few cases where we could identify consistently defined published data –which tend to fell within the upper range of the theoretical ranges for either water consumption or withdrawal- we used them in Table 3, after the appropriate unit transformations, which required some assumptions in some cases[16]. In the remaining cases, the technical factors belong to the theoretical literature. According to the Hydrographic Confederations, the coefficients of consumption and

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[12] Since 2008, Iberdrola has published the annual environmental reports for Cofrentes nuclear power plant with data on the volume of water abstraction authorized. This source states that Confrentes´ water withdrawals are around 34.7 hm^3/year and water consumption around 21 hm^3/year. For more information, see:
[http://www.cncofrentes.es/wcofrnts/corporativa/iberdrola?IDPAG=ESCOFMEDINF]

[13] In http://www.cncofrentes.es can be observed a limitation on the water consumed by the nuclear power plant. Thus, it is stated that the average flow of the river Júcar in the area where the plant is located is 43 $\mathrm{m^3}$/s, having been granted for the use there of a flow rate of 1.1 $\mathrm{m^3}$/s, with an annual limitation maximum total consumption volume of 20 $\mathrm{hm^3}$/year and an amount of water catchment of 34.7 authorized $\mathrm{hm^3}$/year. From this flow, a portion close to 0.75 $\mathrm{m^3}$/s, evaporates in natural draft towers and the remaining 0.35 $\mathrm{m^3}$/s, returns again to the river through a single point of land filling.
Data on water consumption for Trillo I and Almaraz in recent years can be found in [http://www.cnat.es].

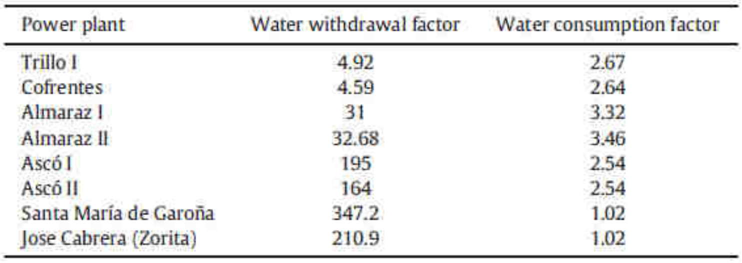
[14] Asensio et al. (2000) cite that consumption for cooling in the Cofrentes nuclear plant is around 21 $\mathrm{hm^3}$/ year).

[15] Greenpeace cites that consumption in the Trillo is 21 $\mathrm{hm^3}$/year; Nuclear Jose Cabrera (Zorita de los Canes) consumes 15 $\mathrm{hm^3}$/ year; Almaraz nuclear plant, 16 $\mathrm{hm^3}$/ year, all the banks of the Tagus River.On the other hand, Greenpeace estimates that Garoña employs 720 $\mathrm{hm^3}$/year for cooling. Publication available in
[http://www.greenpeace.org/espana/Global/espana/report/other/cuenca-hidrografica-del-tajo.pdf]

[16] For instance, we have assumed that nuclear power plants run 24 h 365 days a year to transform the available data in cubic meter per year (m3/year) to cubic meter per MWh.

withdrawals have not varied substantially over time, so we have applied coefficients for each plant over time. Contrasting the factors resulting from the different sources of information and the factors of the international literature, we obtained average factors for the whole period analyzed.

Table 3. Adjusted Water Withdrawals and Consumption Factors $(\mathbf{m^3\,MW^{-1}h^{-1}})$



Power plant	Water withdrawal factor	Water consumption factor
Trillo I	4.92	2.67
Cofrentes	4.59	2.64
Almaraz I	31	3.32
Almaraz II	32.68	3.46
Ascó I	195	2.54
Ascó II	164	2.54
Santa María de Garoña	347.2	1.02
Jose Cabrera (Zorita)	210.9	1.02

Note: water consumption factors for Ascó I and II, Santa María de Garoña, and Zorita represent theoretical values for which we could not find published data. The remaining values correspond estimated factors.
Source: elaborated based on real data from Spanish Nuclear Safety Council, Libro Blanco del Agua, BOE and Hydrographical Confederations, and estimated data from Macknick et al. (2012).

Having decided on the water factors, we are now in position to calculate the water needs for the Spanish nuclear power. We designate with "t" to the period of time and "i" to the number of nuclear power plant, being:

t= 1969, 1970, ..., 2014.

i= 1,2,3, ... , 8.

Water Consumption (Withdrawals) Coefficients are calculated as follow

WCC = $\frac{WE}{Energy\ Generated\ (Output)}$, where the term WE means water evaporated, and

WWC = $\frac{WW}{Energy\ Generated\ (Output)}$, where the term WW means water withdrawn.

In this way, if we want to calculate the amount of water withdrawals or consumptions per power plant/year, the water equations are:

$$WCC_t^i * TO_t^i \qquad (1)$$

and

$$WWC_t^i * TO_t^i \qquad (2)$$

being WWC_t^i the water withdrawal coefficient and WCC_t^i the water consumption coefficient by power plant. Thermoelectric output (TO) corresponds the total generation of electricity by nuclear power plants, which data comes from UNESA.
Thus, for a given year, we have the total amounts as follow:

$$Total\ WW^i = \sum_t^i (WWC^i * TO^i) \qquad (3)$$

and

$$Total\ WC^i = \sum_t^i (WCC^i * TO^i) \qquad (4)$$

Accordingly , for a given year Discharge equations can be formulated taking Eq. (3) minus Eq. (4) as follow:

$$Total\ D^i = Total\ WW^i - Total\ WC^i = \sum_t^i (WWC^i * TO^i) - \sum_t^i (WCC^i * TO^i) \qquad (5)$$

Finally, dividing total amounts from Eqs. (3) and (4) by the total Spanish population we obtain water consumptions and withdrawals per capita. Thus, for a given year we have:

$$WWpc = \frac{total\ WW^i}{Population} \qquad (6)$$

and

$$WCpc = \frac{total\ WC^i}{Population} \qquad (7)$$

As noted before, we always calculate both withdrawals and consumptions because it is necessary to know if there is enough running water for the nuclear power plants to operate properly. Hence, we can talk about opportunity cost.

4. Results & Conclusions.

We can divide the whole period in three differentiated stages. The first one, from 1969 to 1980; the second, until early 1990, and the last one, from 1990 to now.

The first period is characterized by a scarce water consumption because most facilities were disconnected to the grid. In 1969, just Zorita´s nuclear power plant was operative. Zorita was the smallest nuclear plant of Spain (153-160 MW). From 1971, Santa María de Garoña joints to the nuclear activity. The second period goes from 1980 to the early 1990s. This decade is characterized by the incorporation of the remaining nuclear plants to the Spanish industrial scene. We can observe a spectacular nuclear production growth and subsequent increase in water consumption. For the period 1978-1988, Spanish electricity generation deriving from uranium increased from 7650 GWh to 50,400 GWh, corresponding to a percentage increase of 558% (including Vandellós I and II, refrigerated by means different from freshwater) whereas water withdrawals for cooling reactors increased from 1370 to 4213 hm^3, corresponding to a percentage increase of 208%.[17] Finally, in the last sub period nuclear power plants continue to grow, but much more moderately. In 1989, Vandellós I reactor was decommissioned due to an accident, which does not impact in our water estimations since it used gas as coolant. In the years 2007 and 2012, Zorita and Santa

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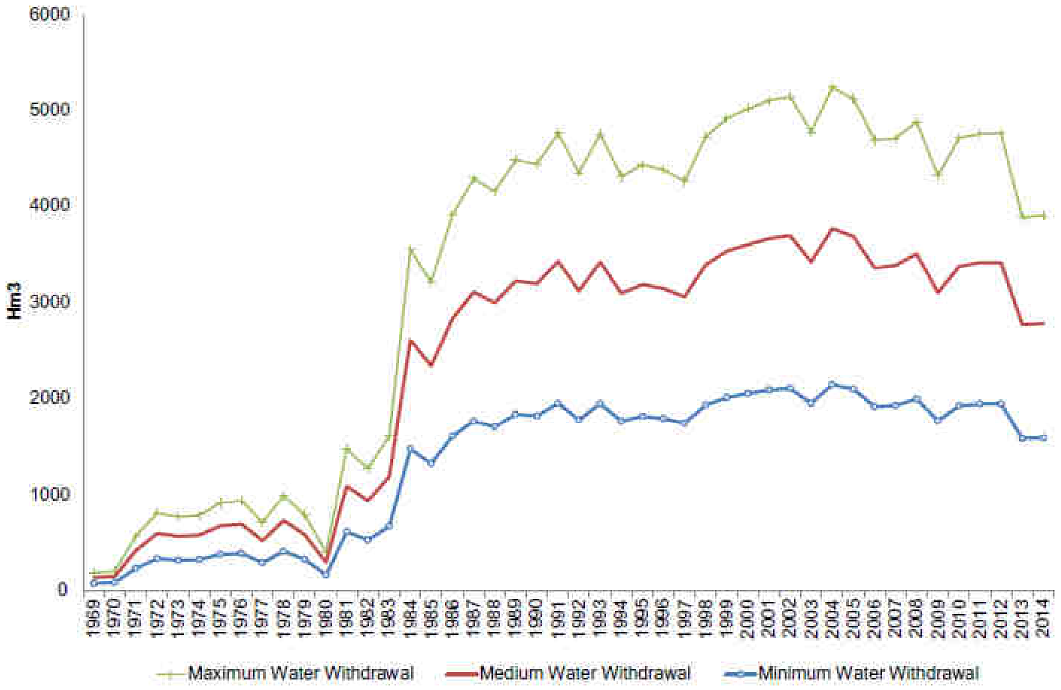
[17] Our Water Footprint calculations ignore Vandellós reactors I and II, refrigerating with gas and seawater, respectively.

María de Garoña shut down, respectively, which effects are more observable in the estimates of WW than in those of WC given both used open loops (more intense in WW than in WC).

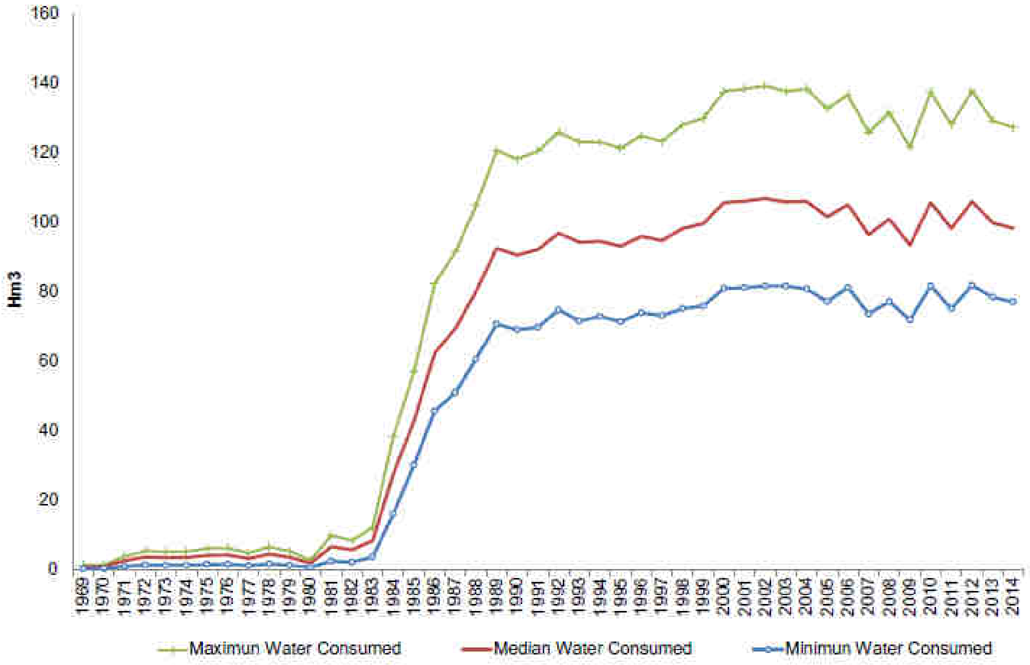
Figs. 2 and 3 show, for the period 1969-2014, the evolution of water withdrawals and consumptions when performing minimum, median, and maximum estimations based on the international factors of Table 2. As expected, the general trend for the whole period is the same from both perspectives. Water withdrawals and consumptions carry on the tendency of the nuclear electricity generation.

Figure 2. Evolution of total Water Withdrawals of Spanish nuclear power plants (1969-2014), by using literature factors.



Source: own elaboration using water factors of Table 2 and electricity generation from nuclear reactors using fresh water for cooling from UNESA.

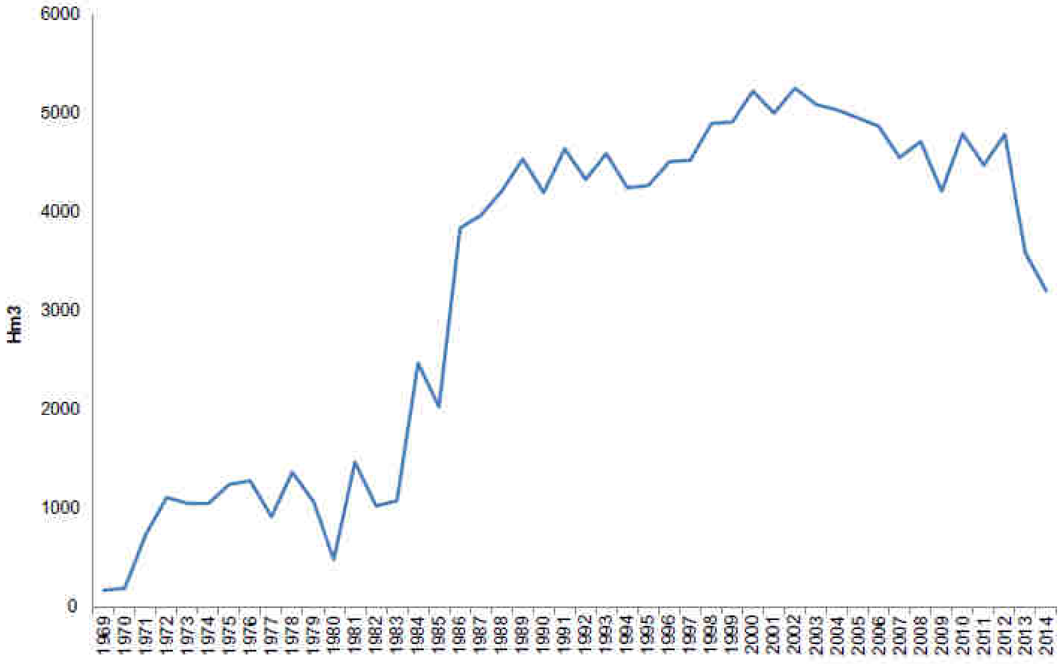
Figure 3.Evolution of total Water Consumptions of Spanish nuclear power plants (1969-2014), by using literature factors.



Source: own elaboration using water factors of Table 2 and electricity generation from nuclear reactors using fresh water for cooling from UNESA

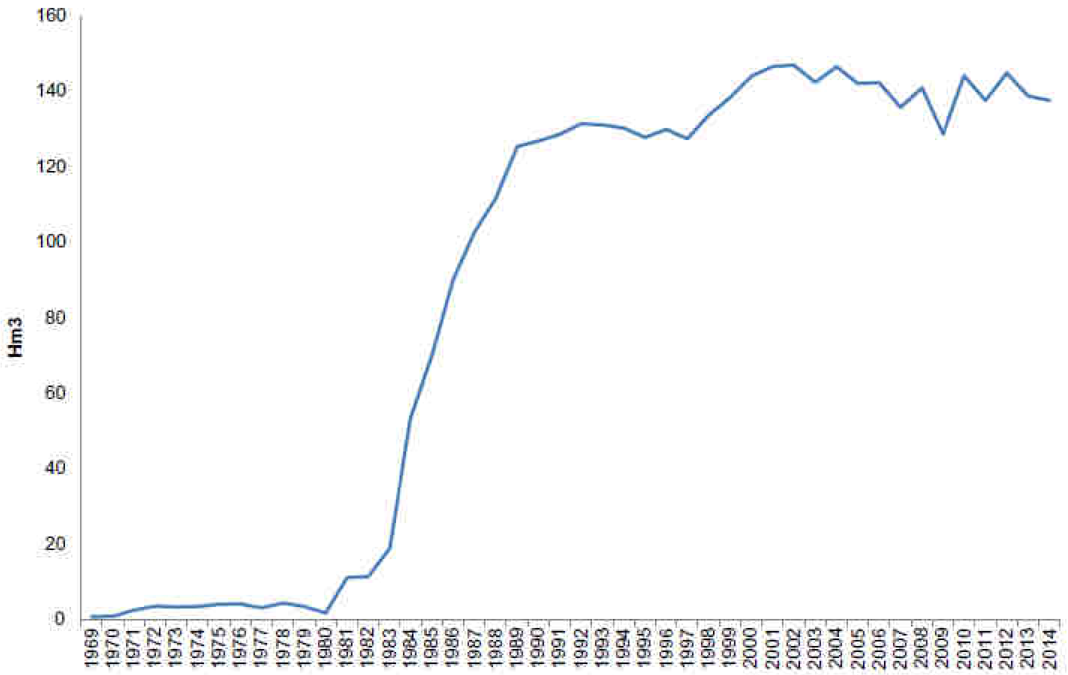
In Figs. 4 and 5 we show the WW and WC using the adjusted factors shown in Table 3.

Figure 4. Evolution of total Water Withdrawals of Spanish nuclear power plants (1969-2014), by using adjusted factors.



Source: own elaboration using water factors of Table 3 and electricity generation from nuclear reactors using fresh water for cooling from UNESA

Figure 5.Evolution of total Water Consumptions of Spanish nuclear power plants (1969-2014), by using adjusted factors

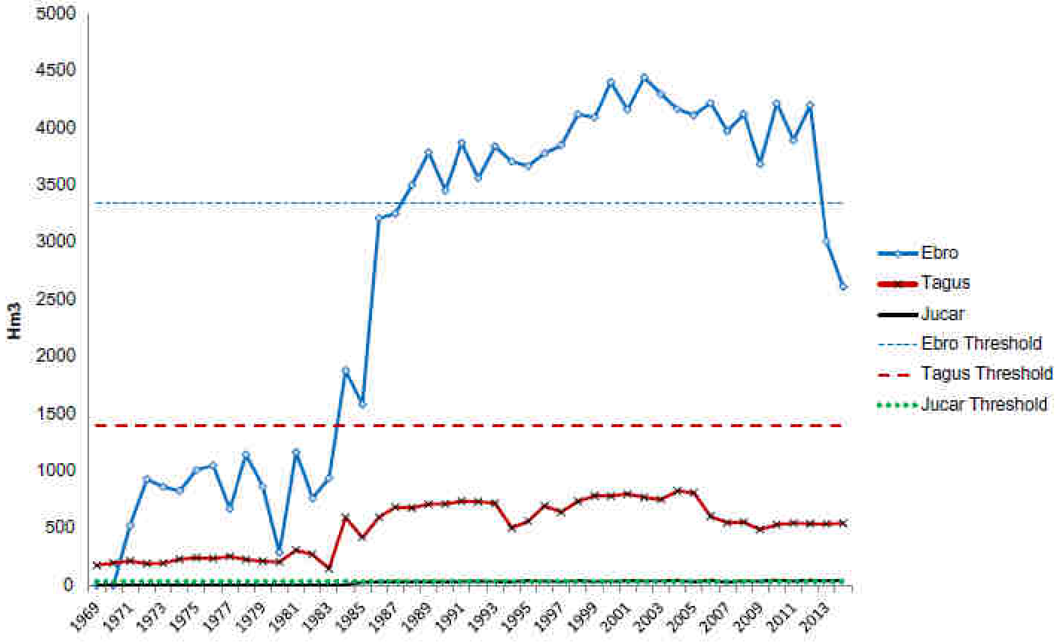


Source: own elaboration using water factors of Table 3 and electricity generation from nuclear reactors using fresh water for cooling from UNESA

Water consumption of nuclear power plants increased on average more than 100 hm^3 from the level of 1969 up to the present. In this way, we can determine a key date: the decade of 1980s. From that moment, there is a change in trend of water withdrawals of Spanish nuclear power plants and, therefore, a change in trend of water consumptions. From then on, the figures increase enormously. For example, water withdrawals grew from 1472 hm^3 to 4641 hm^3 between 1981 and 1991. Likewise, water consumptions grew from 11 hm^3 to more than 128 hm^3 in the same period. These increases are stabilized in the 1990s up to the present. As in the estimation figure, we can observe an important decrease in water withdrawals due to the closure of Garoña, whose cooling system withdraws large amounts of water, but does not consume as much.

Moreover, when analyzing the results in terms of river basins (see Figs. 6 and 7) we can get additional conclusions for decision-making by public bodies. We have also added in Fig. 6 the maximum authorized withdrawal for cooling power plants by planning areas. These thresholds refer to the maximum volumes authorized in the original concessions by the Spanish Hydrographic Confederations, here taken from Libro Blanco del Agua. In this point, it is necessary to explain that water demand used for cooling thermal power plants, especially if it is done in open circuit, is very little consumptive, since it returns around 95% of the water used at a short distance from the point of capture. However, this type of use can greatly condition the operation of the systems, since they require the availability of large volumes of regulated and guaranteed water and therefore, representing an opportunity cost for other alternative usages.[18] As we can see, the water demands for cooling purposes from Spanish nuclear power plants associated with the Ebro River seem to exceed the maximum borderline stipulated, and having endangered the available water for other alternative uses. Water withdrawals in the Tagus River are below the restriction and in the case of Jucar River, the results are aligned perfectly with the threshold.

Figure 6. Evolution of total Water Withdrawals of Spanish nuclear power plants by River Basins



Source: own elaboration using water factors of Table 3 and electricity generation from nuclear reactors using fresh water for cooling from UNESA.

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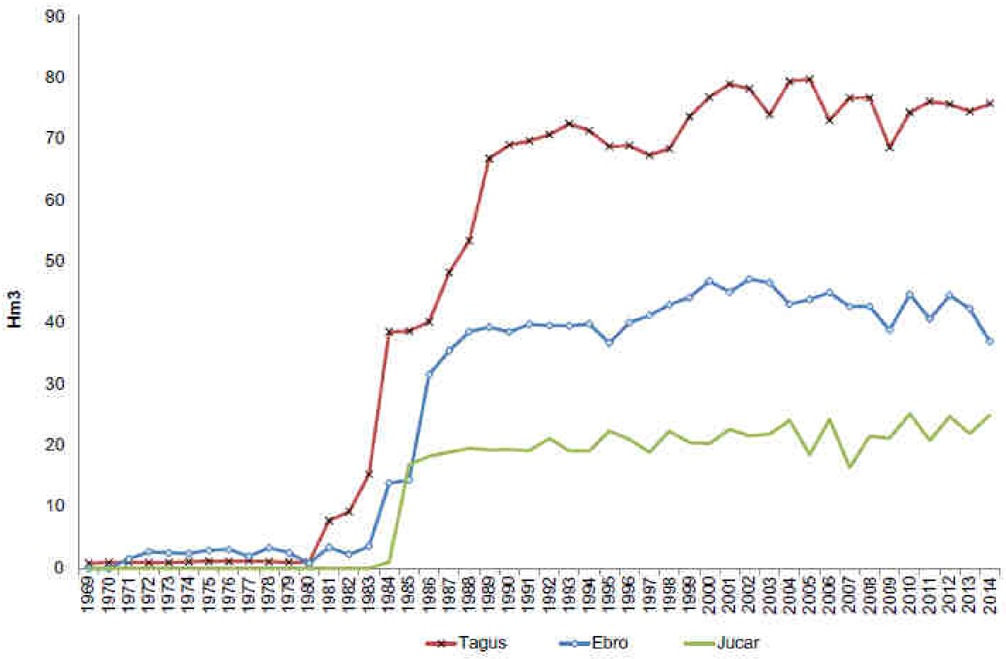
[18] The Libro Blanco del Agua extends this information saying that the main demands for open-circuit cooling are the nuclear power plants at Ascó (2,270 hm3 / year) and Santa María de Garoña (766 hm3 / year) in the Ebro River, and Almaraz (583 hm3 / year) in the Tagus River. For more information, see : http://hispagua.cedex.es/node/66958

Figure 7. Evolution of total Water Consumptions of Spanish nuclear power plants by River Basins



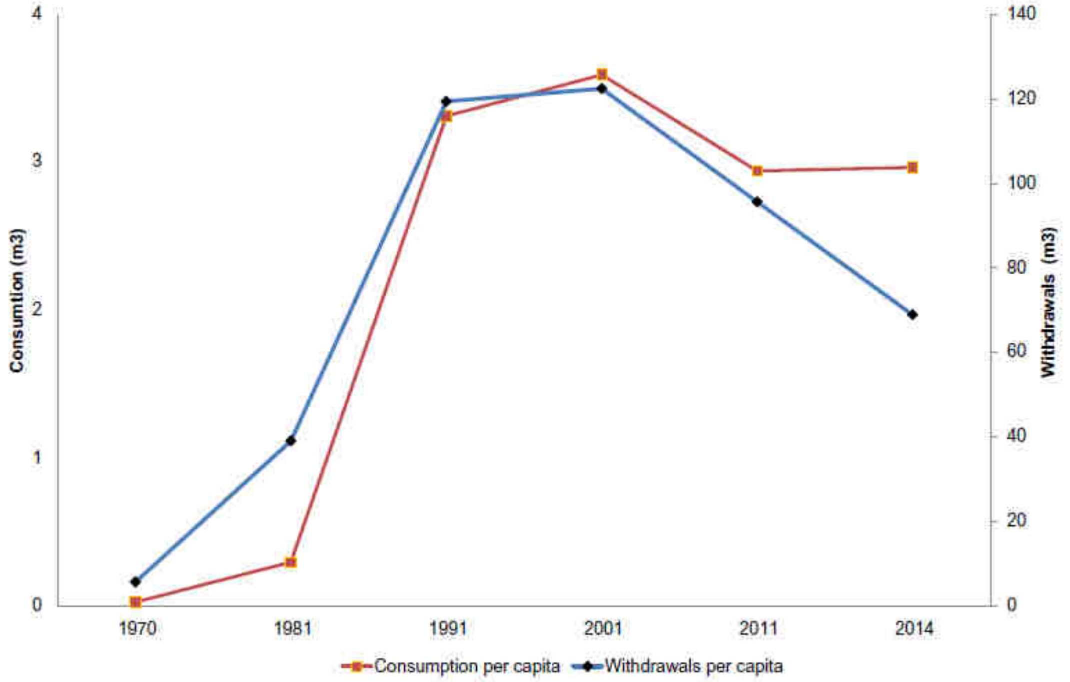
Source: own elaboration using water factors of Table 3 and electricity generation from nuclear reactors using fresh water for cooling from UNESA.

When comparing our results with water demands for other sectors, we observe the agricultural sector as the major water consumer. Thus, whereas our nuclear water footprint (i.e. water consumptions) ranges from 80 to 130 hm^3per year, Hoekstra and Hung (2002) show that blue water figures for Spanish agricultural sector are around 31,000 hm^3. In contrast, the Libro Blanco del Agua shows that agricultural sector involves around 25,000 hm^3 per year. Likewise, Duarte et al. (2014) estimate the water footprint of agriculture from a historical point of view. In this way, since 1950s '*an intense modernization process associated with production and productivity growth took place, entailing the end of traditional agriculture in Spain*'. As in the case of energy, increases in agricultural production implied increases in water consumption. The trend from 1962 to the recent years shows a strong growth in agri-food production and, therefore, strong extra water demands. In other words, water embodied in Spanish agricultural production soared from 65,186 hm^3 to 80,486 hm^3.

Urban uses are another sector that consumes large amounts of water. For example, in 1997 total water flow of Barcelona city is 230.5 hm^3 whereas total water consumption of Spanish nuclear power plants was of 127 hm^3 in the same year according to our estimates with a water withdrawal of 4525 hm^3 in the same year.

From another point of view, the water footprint per capita of Spanish nuclear power plants is shown in Fig. 8. As we observe, while water footprint per capita are around 3 m^3, water withdrawals per capita are around 70 m^3 in 2014.

Figure 8. Evolution of Water Consumptions (left axis) and Withdrawals (right axis) per capita of Spanish nuclear power plants.



Source: own elaboration

Moreover, to understand the implications of our results we must remark that in 1980 an important drought took place in Spain and continued up to 1995 (Berbel and Gómez-Limón, 2000; Vicente-Serrano, 2006). This period represents a total of 15 years, which coincide with the great increases of water requirements by nuclear power plants. Our results point at further research for the water history in Spain.

Although droughts are related to a decrease or absence of rainfall, low rainfall of the time along coupled with the large increase in water withdrawals from rivers by Spanish nuclear power plants could be a source of aggravation for the economic development of country, leaving no water available for other uses (for example, agriculture and urban uses) and, therefore, assuming an opportunity cost for the populations of the different regions. As important as it might be to understand the reasons for the drought it is also important to comprehend that the effects of a drought can last over time, even when this is over. Consequently, further research must consider this overlap between the increases of water withdrawals due to nuclear power and decreases of precipitations in this period to understand the importance of the matter.

In many cases, drought can be extremely localized. Thus, differences in spatial patterns are also important and Iberian Peninsula is an excellent example of such areas. Precipitations and its variability are determined by different atmospheric patterns that cause significant spatial differences (Vicente-Serrano, 2006). In this way, the southern half of Spain has usually less precipitation than the northern half of the country throughout the year. Therefore, areas with fewer rainfall and a greater number of power nuclear plants installed taking water from rivers basins in the area have a higher predisposition to suffer the serious consequences of droughts, affecting economic activity the area and, therefore, the welfare of the population. Accordingly, the problems of water shortages become a regional problem or even local.

In conclusion, the consumption of water resources for cooling purposes by nuclear power plants in Spain could be considered a relevant issue when studying the available water resources and its different alternative uses. In our context, it is important to estimate the water footprint distinguishing amount the two types of cooling systems that use the Spanish nuclear power plants (i.e. open loop and cooling towers) at the time of incorporating this information into the decision-making process and improve the future policy. In this way, diverse measures to reduce the water stress should be implemented. For example, all those related to water conservation, protection of infrastructures or the improvement of the catchment, treatment, and distribution systems. Similarly, another option could be a shift from open loop cooling systems to cooling towers since last one is a less-intensive water user in terms of withdrawals (i.e. the nuclear plant of Zorita originally built as open loop circuit, was reformed in 1999 adding a cooling tower in order reduce the water needs of the plant). However, these measures can only be implemented on the existing water supply. Thus, to expand the current freshwater surface other methods are needed.

Since decades, water desalination has moved from being a secondary option in the Spanish water policy to be an important issue (Barahona and Ramos, 1999). Until recently, this technique was employed exclusively in the Canary Islands because of their water scarcity. However, this matter has also increased in the last years within the Iberian Peninsula[19]. In this way, advances in new technologies have allowed desalination costs have diminished in recent years, making it possible to establish desalination plants near the coast and nuclear power plants for cooling process (Elimelech and Phillip, 2011; Zhou and Tol, 2005; Reddy and Ghaffour, 2007). Another option considered in order to expand water resources is the reuse of water.[20]

Consequently, the location of nuclear power plants on the territory should be another important factor to analyze. We can conclude that locating nuclear facilities on the coastal sites would provide ample seawater supply for cooling. Moreover, desalination plants could be located near a nuclear plant to make use of its heat or electricity. Improvements in technologies could contribute in the opposite direction, pushing reductions in freshwater consumption for the power sector and improving water resource management practices. Yet, coastal locations meet competing uses of the territory in a country where the coast has an alternative lucrative use: tourism. Conversely, sitting nuclear power plants near coastal areas may represent a higher risk in the event of a major nuclear meltdown: the spread of radioactive contamination through sea would be added to the atmospheric contamination.

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[19] One of the first firm intents of supporting this techniques in Spain was the water policy introduce by the socialist government (2004-2008), included in the AGUA Program (Actions for the Management and Use of Water), Concretely, the Law 11/2005 of 22 June, and its predecessor, the Royal Decree-Law 2/2004 of 18 June.

[20] This concept refers to the discharge of treated effluent to watercourses and dilution with circulating flows. This reclaimed water may be used for urban water uses or industrial usages. Also for agricultural irrigation, ornamental purposes and groundwater recharge.

Our results show that water consumed by all Spanish nuclear power plants can be compared with the consumption of water in a big city like Barcelona, and the impact of water withdrawals in some watersheds like the Ebro Basin attain worrisome levels considering the likelihood of severe droughts in the region, and the prospects of being worsened by climate change. This study contributes to a better understanding of the necessary freshwater resources to produce nuclear electricity in Spain and raise awareness about the importance of this issue in a country where the water-energy nexus is not a priority on the political agenda. It is likely that waste water limit the Spanish energy future. Therefore, we claim that water should be considered when planning the electricity mix in the future.

5. Uncertainties & Limitations

Certain aspects have been excluded in the paper and we believe that they could serve as a possible extension further of this work. First, this section deals with some questions related to the loss of efficiency of nuclear power plants. Second, the amount of potentially polluted water returned to the ecosystem. Third, the impact on the aquatic organisms due to the vast amounts of water withdrawn, and finally, it is complicated to carry out reliable economic policy measures due to the absence of state regulations and taxes on the power sector related to water withdrawals.

It is important to explain that the loss of efficiency of nuclear power plants might be due to two facts. These are the course of time (i.e. their usage time) and the increase of the global temperature. First of them is clear. As any tangible asset or infrastructure, nuclear power plants loss their efficiency rate due to the passage of time and systems need to be repaired or replaced by other. The second fact is not trivial. As we have just explained, nuclear power plants need water mainly for their cooling processes. The global average temperature is increasing for over last decades and it is causing that some nuclear power facilities to shut down. In other words, if the water withdrawn by power plants is hot, they cannot refrigerate properly.

For measuring the loss of efficiency of nuclear power plants we might calculate the heat rate. It is a measure of the efficiency of a generator or power plant that converts a fuel into heat and into electricity (EIA, U.S. Energy Information Administration). Generally, this organization expresses heat rate in British thermal units (Btu) per net kilowatt hour calculated. But as we have said, this is not the target in this paper.

Another question that we have excluded from the analysis is the amount of potentially polluted water that returns to the source once finished the cooling process. Whether the water returned to the source poses a risk to the environment, is an entirely different question from this paper aim of proving the dependence nuclear power (and in fact, of the whole thermoelectric production) on large amounts of available freshwater in Spain. Our research results however, contribute to tackle such a question in the future, since it makes possible to state the volume of freshwater potentially affected.

Finally, this paper refers only to nuclear power, a fifth of the Spanish electricity generation today, ignoring the rest of the thermal plants (i.e. those burning coal, oil or gas) which also require water for functioning. The estimation of the water withdrawals for the rest of technologies is the next step of the research agenda, but we can only hypothesise that will enlarge the importance of water as an energetic input.

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