# The use of water for power generation in the most arid country in Europe:

## The thermoelectric water footprint in Spain

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# The use of water for power generation in the most arid country in Europe:
## The thermoelectric water footprint in Spain

*El uso del agua para la generación de energía en el país más árido de Europa: La huella hídrica termoeléctrica de España*

**Doctoral Dissertation**
**Programme in Economics, Business and Law**


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## List of Papers

This dissertation is a compendium of three papers completed and published during my time as PhD student at Universidad Pública de Navarra. The complete references of the papers that constitute the core of the thesis are detailed below.

I. Sesma-Martín, D. & Rubio-Varas, M.d.M. (2019). The Weak Data on the Water–Energy Nexus in Spain. *Water Policy, 21*(2), 382-393. https://doi.org/10.2166/wp.2019.081

II. Sesma Martín, D. & Rubio-Varas, M.d.M. (2017). Freshwater for Cooling Needs: A Long-Run Approach to the Nuclear Water Footprint in Spain. *Ecological Economics*, *140*, 146-156. https://doi.org/10.1016/j.ecolecon.2017.04.032

III. Sesma-Martín, D. (2019). The River's Light: Water Needs for Thermoelectric Power Generation in the Ebro River Basin, 1969–2015. *Water*, *11*(3), 441, 1-18. https://doi.org/10.3390/w11030441

***Explanatory Note***

In accordance with the guidelines for the elaboration of theses as a compendium of publications and, in order to obtain the doctoral international mention, the Doctoral School at Public University of Navarre (EDONA) requires the abstract and conclusions to be written in both Spanish and English languages.

# Resumen

Esta tesis es un compendio de tres trabajos finalizados y publicados durante mi periodo como estudiante de doctorado. El primer trabajo muestra evidencia de la falta de estadísticas oficiales y la inconsistencia entre las diferentes fuentes de información que contienen información sobre las necesidades hídricas para producción de energía eléctrica de las centrales nucleares en España. La mejora de estos indicadores daría como resultado una mejor estimación de las necesidades de agua dulce para la generación de energía térmica y una mejor comprensión de esta problemática. El segundo artículo ofrece una estimación a largo plazo de las necesidades de agua dulce de las centrales nucleares españolas, las centrales más sedientas del sector termoeléctrico español, durante el período 1969-2014. El último artículo profundiza más en esta cuestión, analizando la evolución de los volúmenes de agua necesarios para producción de electricidad de las centrales nucleares y resto de térmicas convencionales ubicadas en la cuenca del Ebro, el mayor contribuyente a la generación eléctrica española. Todos estos resultados pretenden cubrir parte del vacío existente en la literatura española sobre el nexo agua-energía.

## Abstract

This dissertation is a compendium of three papers completed and published during my time as PhD student. The first paper provides evidence on the lack of official statistics and the inconsistency among the sources of information related to water for nuclear power generation in Spain. The improvement of these indicators would result in a better estimation of the freshwater needs for thermal power generation and a better understanding of this matter. The second paper provides a long-term estimation of the freshwater volumes needed for the operation of Spanish nuclear power plants, the thirstiest power facilities within the Spanish thermoelectric sector, for the period 1969-2014. Finally, the last paper goes further and analyses the evolution of the cooling water needs of nuclear and conventional thermal power plants located in the Ebro River basin, the major contributor to the Spanish electricity generation. All these achievements aim to cover part of the existing gap in the Spanish literature on the water-energy nexus.

# 1. Introduction

Water and energy are closely interlinked. Energy is required for the extraction, transportation, distribution, and treatment of water. Conversely, water is essential for almost all energy generation processes. Many regions worldwide are already facing serious water and energy shortages and recent forecasts indicate that demands in water and energy will increase in the future because of population growth and the spread of economies. Additionally, the effects of climate change will aggravate the problem. Thus, the interest in this mutual relationship, known as the 'water-energy nexus', has increased to tackle the challenge of securing water and energy demands in the future.

The production of electrical power results in one of the largest uses of water worldwide. In addition to hydroelectric power plants, thermal power stations (coal, nuclear, solar-thermal, geothermal, biomass, natural gas combined cycle power plants) also require vast volumes of water mainly for cooling. Thermal power plants generate around 80% of the electricity produced globally (IEA, 2013). In Spain, electricity generation from thermal power plants surpasses 55% of the national electricity production (REE, 2017), which depends directly on availability of water. Despite its high dependence on thermal power and being the driest country in Europe, Spain lacks studies on water for thermal power generation. Therefore, this dissertation presents the difficulties, the process and, the first estimations of the water requirements for thermoelectric energy production in Spain.

## 1.1. The Water-Energy Nexus

Water and energy are two of the main driving forces of economic and social development (Brundtland et al., 1987). In fact, there is a clear interdependence between both resources. Water is needed during all stages of energy production, for fossil-fuel extraction, transport and processing, power generation and irrigation of feedstock for biofuels. For its part, energy is required for a range of water-related processes, such as water transport, wastewater treatment and desalination (Gleick, 1994). This mutual linkage, commonly known as the 'water-energy nexus' in the international literature, has significant implications for both energy and water security.

According to the Organization for Economic Cooperation and Development (OECD), by 2050 the world's population will have risen to 9 billion, global energy consumption is projected to grow by 80%, and global water demands are estimated to increase by 55% (OECD, 2012). Likewise, future projections seems to indicate that water scarcity episodes and heat waves will be increasingly recurrent because of climate change (Mazdiyasni and AghaKouchak, 2015). Water is already becoming a limiting factor for the energy sector and many power plants across the globe have been forced to alter their operation, and even shut down because of heat waves and water shortages (Förster and Lilliestam, 2010). In view of these vulnerabilities, different international institutions have addressed this matter in order to try to implement integrated measures in the management of water and energy. For example, the International Energy Agency (IEA) has recently published a small excerpt attached to its annual 'World

Energy Outlook' on the water-energy nexus (IEA, 2016). This report provides information on the freshwater requirements for energy production and assesses how much energy is required for a range of processes in the water industry. Moreover, the 'Thirsty Energy' Initiative from the World Bank represents another outstanding proposal to help countries better address water and energy challenges under an uncertain future (Rodriguez et al., 2013).

Apart from these initiatives, many scholars have also analyzed the water-energy nexus in recent years as the extensive literature on the matter makes evident. The water-energy nexus in the United States has been widely analyzed from different perspectives (Stillwell et al., 2010; Ackerman and Fisher, 2013; DeNooyer et al., 2016) and scales (Perrone et al., 2011; Fang and Chen, 2017). Likewise, other researchers have carried out analysis of this nexus in countries from the Middle East and North Africa, which suffers from water scarcity (Siddiqi and Anadon, 2011), and regions with extreme variability in water availability, such as Texas (Stillwell et al., 2011). Scanlon et al., (2013) also discuss the impact of droughts on thermoelectric generation in Texas. By making use of the terms *vulnerability* and *resilience* the author is able to identify the weaknesses and strengths of thermal power plants under the effects of droughts. For its part, Kahrl and Roland-Holst (2008) focus their attention in China, a region that is experiencing rapid depletion of their natural resources due to their significant economic growth in recent years. Unlike studies that evaluate the water-energy nexus solely as a resource management approach, Scott et al., (2011) propose to take into account the policy and institutional dimensions when assessing the water–energy nexus in order to dispose of a more complete picture of this interlinkage. Finally, many others practitioners have included the food pillar to the nexus to carry out a more detailed analysis of the interdependencies among these three sectors (Bazilian et al., 2011; Bizikova et al., 2013; Biggs et al., 2015; Endo et al., 2017).

## 1.2. Water for Thermoelectric Energy Production

The production of electrical power is one of the largest uses of water worldwide. In addition to hydropower plants, conventional thermal (coal, nuclear, solar-thermal, geothermal, biomass, natural gas) and nuclear power plants (uranium) also require large volumes of water for their proper operation and, predominantly for cooling. Thermoelectric power plants account for 80% of the world's electricity generation, while hydropower plants produce around 16% of the electricity generation worldwide (IEA, 2013). In view of these previous figures, more than 95% of global electricity generation could be altered in the absence of water.

Thermoelectric facilities boil water to create steam to spin turbines that generate electricity. Conventional thermal and nuclear power plants operate on the same principle, but they differ in the way they heat the water. Whereas conventional thermal power stations obtain heat by burning fossil fuels, nuclear power plants obtain it through nuclear reactions. Later, the 'waste' heat is dissipated by the cooling systems and transferred to the surrounding environment in order to allow the facilities to operate correctly. The temperature needed to produce electricity differs depending on fuel type and, consequently, each type of thermal power plant requires different amounts of water for cooling. Cooling is the activity that involves the largest amounts of water, and hence the cooling system must be considered an integral part of the power generation process that can have a major influence on the overall power plant performance and availability. There exist different types of cooling systems (i.e., wet, dry and hybrid) that require different volumes of water (Micheletti and Burns, 2002). The most popular types of cooling system are detailed below.

- Dry cooling: dry-cooling systems use air instead of water as the heat transfer fluid and, consequently, their water volumes are zero. Yet, a power plant using this cooling system may require water for other processes.

- Wet cooling: the water needs of wet-cooling systems vary greatly. The main wet-cooling systems' designs are once-through cooling and cooling towers.

  - ✓ Once-through cooling (open-loop cooling): these systems remove water from a water body, pass it through a steam condenser, and subsequently discharge it into the water source at a higher temperature (usually limited by environmental law). This cooling technology evaporates a small fraction of the water withdrawn. However, the large amounts of water withdrawn can lead to adverse ecological impacts mainly related to the increased temperature of the water discharged and the entry of aquatic organisms into power plant systems.

  - ✓ Wet cooling tower: a cooling tower is a heat rejection mechanism, which expels the waste heat from the cooling water into the atmosphere. This cooling design withdraws far less water than open-loop systems, but requires higher water consumption. Similarly, this cooling system can raise land issues and aesthetic drawbacks.

- Hybrid cooling: a hybrid cooling system combine dry and wet cooling schemes. This type of cooling system appears as an alternative to conserve energy and water by combining the benefits of both dry and wet cooling modes.

Therefore, there is a clear trade-off in terms of water among different cooling systems. Open-loop cooling systems involve higher water withdrawals than cooling towers, while cooling towers have higher water consumption volumes. Likewise, each cooling technique results in different environmental affections. These qualitative impacts are not going to be extensively studied throughout this dissertation, but they must be taken into account.

As mentioned above, different types of generation technology and cooling systems result in different water withdrawals and consumptions, which requires being rigorous when talking about water use in power plants. Thus, 'water withdrawals' refer to the total amount of water removed from a water source, regardless of how much of that total volume is consumed. For its part, 'water consumption' is the part of water withdrawn that is evaporated during the cooling process in thermoelectric power plants, and hence removed from the immediate water environment. The part of water extracted from the water body, not consumed, and hence reverted after use to the water source (i.e., aquifer or river stream) represents the return flow or 'water discharged'. Within this framework, the terminology of the water footprint, initially proposed by Arjen Hoekstra (Hoekstra, 2003; 2011), can be extended to the electricity-water nexus. Thus, the term 'water consumption' will be used throughout this dissertation to refer to the 'blue water footprint of plants operation', understood as the amount of water consumed in cooling towers or reservoirs during the cooling process (Chini et al., 2018).

All these previous considerations have led to a comprehensive body of literature describing the water requirements for thermal power generation by technology and evaluating the implications of the thermoelectricity-water nexus. Most of these studies on water uses are focused on the Unites States (e.g., Feeley III et al., 2008; Kenny et al., 2009; Sovacool, 2009; Sovacool and Sovacool, 2009; Maupin et al., 2014). Likewise, studies consider a wide variety of approaches. For example, some examples of research addressing water uses along the life cycle of electricity generation are Gleick (1994), Fthenakis and Kim (2010), Mielke et al. (2010), McMahon and Price (2011) and Meldrum et al. (2013). Other reports only provide estimates on water withdrawal and consumption of plants operation (Macknick et al., 2011; 2012a). Moreover, some authors focus on geographic contexts. In this respect, a highlighted example is Grubert et al. (2012), whose authors estimate the potential effects of coal to natural gas fuel switching in Texas' power sector. There are other articles that evaluate the quality of data and statistics on thermoelectric power plant water use reported by official sources of information. Averyt et al. (2013) do it for the American case, while Larsen and Drews (2019) make the assessment for Europe. Relevant research on projections of water use under future scenarios are also common (e.g., Macknick et al., 2012b; Byers et al., 2014), and all those assessing the possible impacts of climate change on water resources for the thermoelectric sector (Förster and Lilliestam, 2010; Chandel et al., 2011; Van Vliet et al., 2012). Regarding this last point, Sanders (2014) defines the critical factors that will mitigate the water needs of the electricity grid in the future. Finally, some authors have applied the water footprint concept to the thermoelectricity generation process (Mekonnen et al., 2015).

## 1.3. The Spanish Context

### *The electricity market and the evolution of power generation in Spain*

In Spain, from 1944 until the 1980s, a cartel of mostly privately owned companies, under the name of UNESA, self-regulated all aspects of the electricity market. The desire for change of the first Socialist government (elected in 1982) came to fruition with the nationalization of the High Voltage Grid[1]. The ownership of the grid was transferred to Red Eléctrica de España. The unified operation as a whole was declared a state-owned public service and private intervention was maintained in generation and distribution, with administrative authorisation. The Grid was then again privatized in the late 1990s. All in all, the Spanish electricity production was organized as a private self-regulated business for most of the twentieth

[1] Law 49/1984 of 26 December 1984 on the unified operation of the national electricity system.

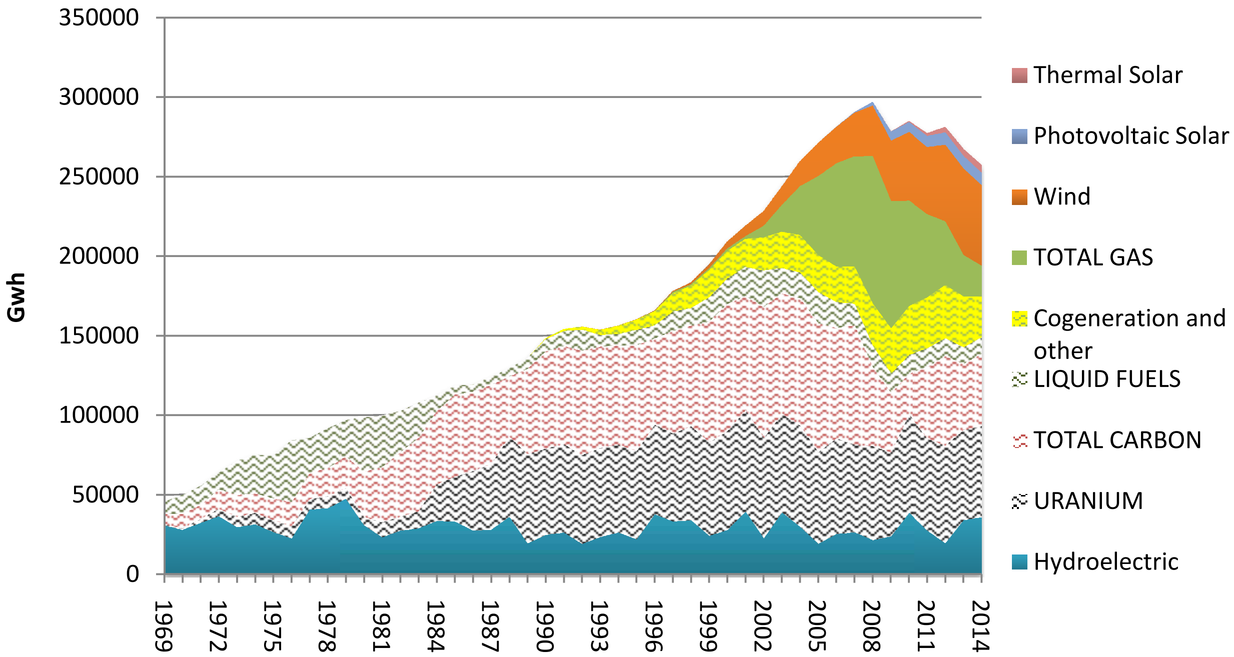
century (García et al., 2010; Garrués-Irurzun, 2016). The basic law that currently regulates the structure and operation of the sector is Law 24/2013 of 26 December on the Electricity Sector[2].

The activities aimed at the supply of electricity are generation, transmission, distribution, commercialization, technical management and economic management. The first step consists on the electricity generation. This electric energy is transmitted by network in order to be supplied to the different subjects and for the realization of international exchanges. The transmission of electric energy is a regulated activity and the owner of the transmission grid is Red Eléctrica de España (REE). Distribution is also a regulated activity and aims at the transmission of electrical energy from the transmission networks to the points of consumption with the ultimate aim of supplying it to consumers. The marketing activity is carried out by the electricity trading companies and their function is the sale of electricity to consumers and other parties in accordance with current legislation. It represents a non-regulated activity. The technical manager of the Spanish electrical system is also Red Eléctrica de España. Since it is difficult to store electrical energy, all that is consumed must be generated at all times. Finally, there is a market operator, which manages the wholesale electricity market. Buying and selling agents contract the quantities they need (MWh) at public and transparent prices

To understand the water requirements of the electricity sector, it is essential to set out the evolution of power generation in Spain in the long run and, especially from the second half of the twentieth century (Figures 1 and 2). Until the 1960s, due to the hydraulic development plans implemented by the Franco dictatorship, hydroelectricity remained the major participant to Spanish electricity generation . The economic miracle of the 1960s and early 1970s required more energy output and the entrance of Spain in the international economic system opened the doors to the import of oil, the construction of refineries and the massive use of fuel oil. In the case of electricity, it translated into more thermal power plants (coal and fuel-oil) and the beginning of nuclear power with the opening of the first generation of nuclear power plants between 1968 and 1972. Later, the oil price crisis that began in 1973 highlights the European problem of dependence on this fossil fuel and Spain focuses its preferences on nuclear energy and coal. 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). From the 1980s to the present, nuclear electricity contributed with an average 24% of the electrical generation in Spain. With the turn of the century cogeneration and renewable energies join to the electricity mix. At present, thermoelectric power generation represents about 56% of Spanish power generation (REE, 2017).

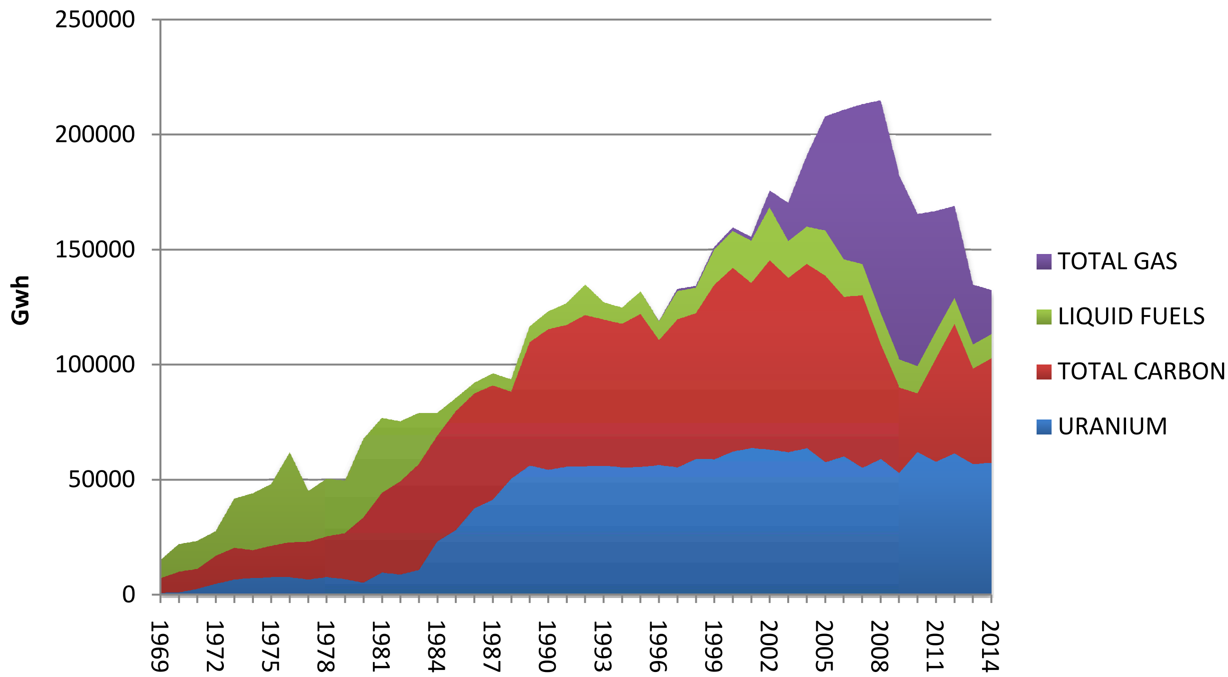
[2] The full text is available at: https://www.boe.es/eli/es/l/2013/12/26/24/con.

**Figure 1. Evolution of Spanish power generation by technology (1969-2014).**




Source: own elaboration from UNESA Annual Reports.

**Figure 2. Evolution of Spanish thermoelectric generation by fuel (1969-2014).**

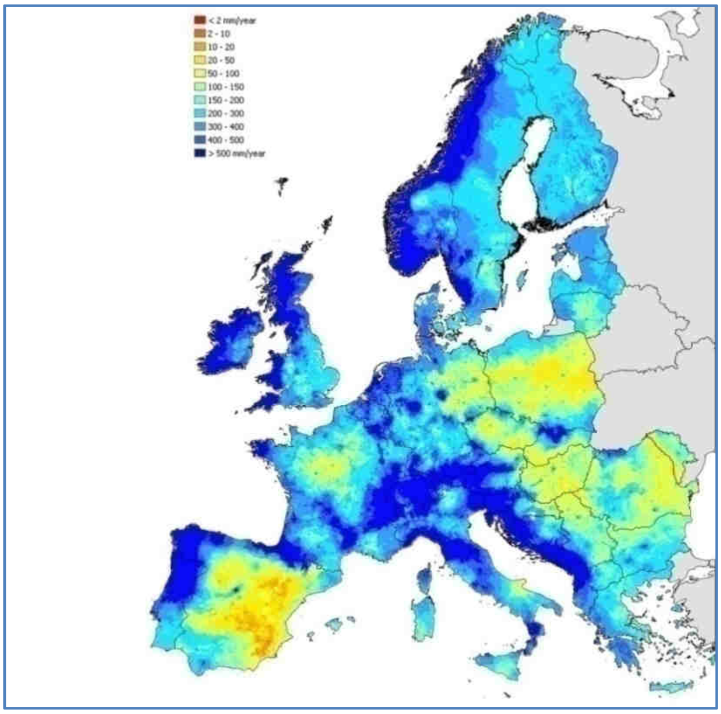



Source: own elaboration from UNESA Annual Reports.

## *Water Scarcity in Spain*

Spain is considered the most arid country in Europe (Varela-Ortega, 2008). Figure 3 shows the annual freshwater availability (mm/year) in Europe for the period 1990-2010, which reflects precipitation and snowfall minus evapotranspiration and deep groundwater looses. The graph reveals considerable differences in freshwater resources among European countries, and especially among regions within Spain. Spain is characterized by a highly irregular spatial and temporal rainfall distribution. While rainfall is abundant in the northern coastal regions, it is quite limited in southeastern regions such as Almería, Murcia and Alicante. Likewise, there is also a notable seasonality throughout the year, especially prominent in the southern half of the Spanish territory. Additionally, the reduction in rainfall is especially accused during the summer months, July being the driest month of the year (AEMET, 2011). Periods of drought are much more important for electricity generation than annual freshwater availability as proves different quantitative studies on the risks posed by droughts to electricity production at a global scale (Bartos and Chester, 2015; Van Vliet et al., 2016). Rising river temperatures also affect grid reliability by reducing electricity production during summer periods when high temperatures coincide with maximum electricity production (Förster and Lilliestam, 2010). In the Spanish context, the summer months are especially critical for water-intensive technologies as shown by the temporary closures of some nuclear power plants[3].

**Figure 3. Annual Freshwater Availability in Europe, 1990-2010 (mm/year).**




Source: De Roo et al. (2012).

[3] Kanter, J. (May 20, 2007). *Climate change puts nuclear energy into hot water*. The New York Times. Available in: https://www.nytimes.com/2007/05/20/health/20iht-nuke.1.5788480.html

Spain already suffers from large increases in temperature, heat waves, high evaporation rates and decreases in precipitation and river flows. All this features could result in important water scarcity problems and significant economic, social, and environmental consequences (Hervás-Gámez and Delgado-Ramos, 2019). In turn, intense drought episodes impose severe water restrictions to all users. Precisely, restrictions on the availability of the resource have resulted in historical conflicts among the two main water users in Spain (namely, irrigators and electricity companies) from the second half of the twentieth century. Gaviria (1977) and Naredo et al. (1978) point to this possible conflict at a national level.

### *An existing gap in the Spanish literature*

Most of studies on water use in Spain have traditionally focused on agricultural sector, the main water user (Spanish National Institute of Statistics, 2008). For example, Duarte et al. (2014) estimate the water footprint of the Spanish agricultural sector from a historical perspective. Cazcarro et al. (2015) analyse the blue and green water footprint of crop production in Spain at the provincial level and from a long-term perspective. Chapagain and Orr (2009) also apply the water footprint methodology, but on a more localized scale (namely, tomato cultivation). Other papers containing information on water uses within the agrarian sector are Duarte et al. (2016), Aldaya et al. (2010), and Salmoral et al. (2011). Furthermore, there are also research focused on analyzing the uses of water in the tourism sector (Cazcarro et al., 2014) and leisure activities such as golf (Diaz et al., 2007).

By contrast, there are only some isolated research on the water uses within the power sector in Spain. For example, Hardy et al., (2012) address the relevance of the water-energy nexus in Spain, but without going into details. Authors provide a general overview the bilateral consequences of the nexus and highlight the need of managing this mutual relationship as a whole. For their part, Carillo and Frei (2009) analyze the water withdrawals and consumption according to the energy source sector and process type. In addition to describing current freshwater uses, it makes an assessment of water needs for the energy scenarios foreseen in 2030. These references do not provide an in-depth discussion of the volumes of water needed to produce thermoelectric power in Spain, nor do they take into account the historical perspective despite the fact that the thermoelectric sector is the second thirstiest sector in Spain, just behind the agricultural uses (Spanish National Institute of Statistics, 2008).

Moreover, official public statistics on the water-electricity nexus are rather limited in Spain, and even inconsistent in some cases. Likewise, at times these available sources of information do not make correct use of the terms referring to the uses of water for the production of thermoelectric energy (namely, water withdrawals and water consumption) nor do they detail information on the methodologies used to calculate such values. These shortcomings can result in incorrect interpretations for a good estimation of the water needs thermoelectric energy production. This dissertation aims to cover part of this existing gap to achieve a better understanding on the electricity-water nexus in Spain.

The previous sections highlight the role of water as a key energy resource. They also provide a general background of the research field, deepening later the Spanish context. Furthermore, they show some of the shortcomings observed. Thus, it is important to understand the water needs for energy production of the different thermoelectricity generation technologies in Spain to incorporate the information into the decision making process and to choose the best alternative. Therefore, this thesis makes two contributions that can be categorized either in terms of new data on the water-energy nexus or in the broadening of knowledge about the historical water uses for thermal power generation in Spain.

## 1.4. Research Objectives and Scope

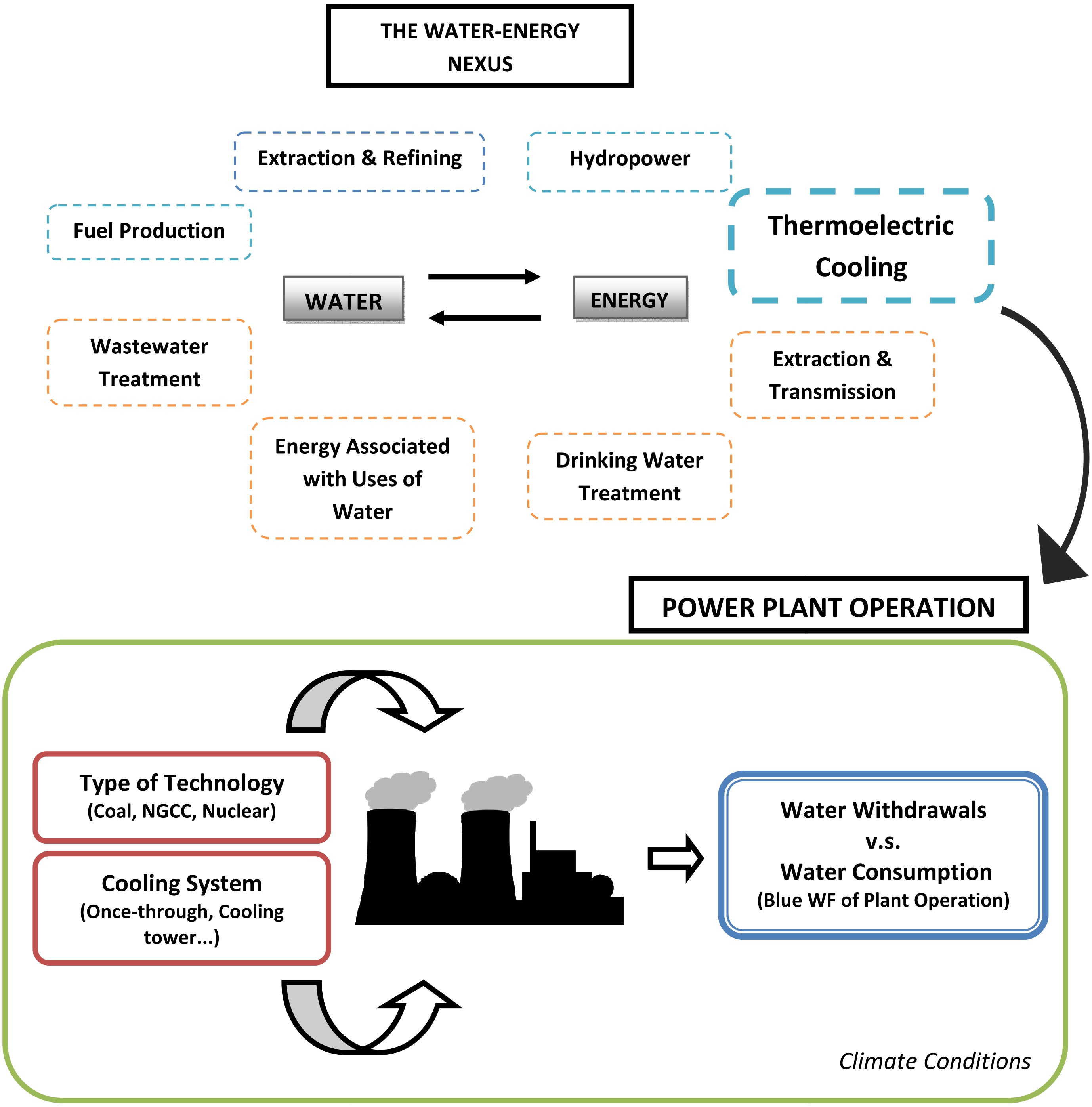
The overarching aim of this thesis is to quantify the water needs, in terms of both water withdrawal and consumption, for thermoelectric energy production in Spain in the long-run. A good part of this task is done in papers II and III that form the core of this document. Paper II assesses the freshwater volumes required to cool the Spanish nuclear power plants from 1969 to the present, classifying them by type of cooling system. Since the different thermoelectric generation technologies have different implications on water resources, paper III makes an assessment of water for electricity taking into account nuclear and conventional power plants in the Ebro River basin for a similar period of time.

Moreover, there are other secondary objectives related to the main one. For example, the assessment of the water needs of the Spanish nuclear power plants in paper II highlighted the limited availability of official public statistics on the water-energy nexus in Spain, the inconsistent sources of information and the incorrect use of terms referring to different aspects of water. These were the main motivations to publish paper I, which demonstrates the need for improved indicators as policy instruments in the water-energy nexus in Spain. Furthermore, to increase social awareness of the importance of water as an energy resource, a ranking of the different water-using activities was another of the sub objectives initially proposed. In fact, the identification of those activities that have the greatest impact on freshwater resources is a crucial matter to develop water planning and management measures. Finally, the proposal of possible water-saving measures in the face of future water scarcity scenarios in Spain represents another motivation for carrying out this research.

To sum up, all these objectives are intended to contribute to reduce the existing gap on the water-energy nexus in Spain. The understanding on the water requirements needed for thermoelectric power generation could lead to a better management of the globe freshwater resources in Spain.

This thesis evaluates the volumes of water needed for thermoelectric energy production and, more specifically, for cooling. There are other processes requiring water during the operation of thermoelectric plants, although these water need are negligible. In this regard, two aspects of water are considered: water withdrawals and water consumption (i.e., the real value of the blue water footprint of power plant operations). This research covers nuclear power plants and other conventional thermal power plants . More specifically, all the Spanish nuclear power plants and the rest of the conventional thermal plants (coal and natural gas combined-cycle) located in the Ebro River basin have been analysed. Therefore, the present study takes into account two geographical scales (at country and river basin level). Finally, the time period runs from 1969, when the first Spanish nuclear power plant comes into operation, to 2015. Figure 4 provides a brief depiction of the study design.

**Figure 4. Overview of the study design.**




Source: own elaboration.

## 1.5. Data and Methods

### *Data*

This thesis is based mainly on two sets of data: data on electricity production and data on operational water withdrawal and consumption factors.

Electricity production data come from the official statistics provided by Red Eléctrica de España (REE) and the Spanish Electricity Industry Association (UNESA). REE provides statistics on annual and monthly electricity production by generation technology. However, this institution lacks disaggregated statistics for power plant and year. UNESA covers this need in its annual reports.

Water data come from both official and secondary sources. Official statistics from the environmental reports of the electric utilities were not made available to the public until the early 2000s, which represents a disadvantage when carrying out long-term analyses in Spain. Macknick et al. (2012a) solve part of this shortcoming by providing estimates of operational water withdrawal and water consumption factors for electricity generating technologies and type of cooling system used. Although these water factors refer to U.S. power plant data, they represent a good support for conducting water use impact assessments of the power sector. Moreover, all Spanish reactors are of American manufacturing except two of them, which could justify the use of standard factors from American literature to those Spanish reactors with similar characteristics. With regard to studies on Spain, both Hardy et al. (2012) and Carrillo and Frei (2009) offer some generic water factors for generation technologies, but without differentiating among cooling systems. Other reports show figures on the uses of water for electricity generation, but without specifying what water aspect the water refer to (water withdrawal or water consumption). In this sense, Macknick et al. (2012a) comprises a more complete reference.

### *Methods*

For the calculation of the water requirements of the thermoelectric plants (papers II and III), first it is necessary to identify and classify each plant by type of generation technology and cooling system. Subsequently, the electricity production data and the water factors selected according to the characteristics of each power facility make it possible to obtain the cooling-water needs in term of both water withdrawal and consumption of the thermoelectric power plants in Spain. This methodology is in line with other international research. For example, Vassolo and Döll (2005) compute the total amount of water withdrawn by multiplying the annual electricity production with the water intensity of the power station. The authors make this calculation for each of the 63,590 plants considered on a global scale. Huang et al. (2017) and Liao et al. (2016) apply similar methods for the quantification of water needs in China's power sector, while Liu et al., (2015) use very similar equations for the estimation of the water demands for electricity generation in the Unites States. Other outstanding references including some aspects of this methodology are Byers et al. (2014) and Yuan et al. (2014).

Other quantitative techniques and methods are also applied throughout this thesis. Thus, Paper I collects different statistical variables (i.e. arithmetic mean, standard deviation and coefficient of variation) to demonstrate, in absolute and relative terms, the insufficient precision and inconsistency among the different data available on the water uses of the Spanish nuclear power plants. By contrast, different sensitivity analyses (Saltelli, 2002) were carried out in the second paper to quantify the extent to which the change of the different technical water coefficients affect the final result. As a result, paper II contains the best scenario for minimum water uses, the worst scenario for maximum water uses and the most likely scenario for the water uses of the Spanish nuclear power plants over a combination of cooling systems. References providing minimum, median and maximum water intensity factors allow to evaluate these configurations (Meldrum et al., 2013; Spang et al., 2014). Finally, paper III includes the simulation of possible water-saving scenarios. In this case, no specific methodology from international literature is followed.

## 1.6. Contribution and Outline

This thesis emerges from the need to provide an estimate of the freshwater needs for thermoelectric energy production in Spain. The initial conceptualization of this question was posed by my thesis supervisor, Mar Rubio Varas. She was also in charge of reviewing the final documents before sending them to the different journals. I was responsible for the entire execution of the analysis. This included to review the existing literature and analyze the state of the issue at national and international level, the search for appropriate methods, the collection of primary and secondary data, the estimation and calibration of water consumption and withdrawal data, the elaboration of graphics and the preparation of papers for publication. Among all these tasks, the collection of primary data was particularly complex and tedious since in many occasions it required the signing of confidentiality agreements with the electricity companies to dispose of the available data. More precisely, confidentiality agreements were signed to personally visit and check the available documents from two power plants in late 2017 and early 2018. Later, two additional agreements were necessary to receive by email the requested information from other thermal power plants. The names of these power stations cannot be disclosed due to the terms of the confidentiality agreements signed. Therefore, as I already mentioned previously, this thesis makes two main contributions that can be categorized either in terms of new data on the water-energy nexus or in the broadening of knowledge about the historical water uses for thermal power generation in Spain.

The first paper of this thesis is concerned with the deficiencies observed in the water-energy nexus in Spain. One was directly related to the lack of studies on the uses of water for thermoelectricity generation in Spain. The second shortcoming had to do with the absence of official statistics on the subject, the lack of homogeneity between the scarce data offered by the different sources of information consulted, and the inconsistency when defining two basic terms on this subject (water withdrawal and consumption). The main objective of this study is to highlight the need to improve indicators on the water-energy nexus in Spain for a better estimation of the water needs of the Spain's power sector. This paper uses different statistical measures to prove, in absolute and relative terms, the insufficient precision and inconsistency among the different data available on the water uses of the Spanish nuclear power plants.

The second paper focuses on the use of fresh water for cooling purposes by nuclear power plants in Spain since, for each available cooling technology, this water needs tend to be larger per megawatt/hour produced (IEA, 2012). Thus, this paper aims to cover one of the gaps mentioned in the previous paper. The choice between a type of cooling system or another has different implications on water uses for thermoelectric power generation. Thus, this paper identifies the cooling systems installed in each power facility. Since the Spanish Hydrographic Confederations impose maximum thresholds on water withdrawals from thermal power plants, the paper evaluates whether the power plants exceed these limits in the long term. Finally, these paper also makes a sectoral comparison to see the water impact of the operation of nuclear power plants on the other uses at national level.

Each type of thermal power plant requires different amounts of water for cooling. The third paper makes an assessment of water for electricity, not only for nuclear power but also for conventional power plants in the Ebro River basin, the most important long-term contributor to Spanish electricity generation. Once again this paper aims to increase social awareness on the significant volumes of fresh water required for the operation of the Spanish thermal power plants by making a sectoral comparison. Finally, the paper evaluates possible water-saving measures to future water scarcity scenarios.

# 2. Paper I

Water Policy 21 (2019) 382–393

# The weak data on the water–energy nexus in Spain

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**Abstract**

This paper focuses on the fact that the water–energy nexus remains an irrelevant issue on the energy policy agenda and on the priorities of the energy leaders in Spain. This is a striking fact given that this takes place in the most arid country in Europe, where almost two-thirds of electricity generation would have to be halted in the absence of an adequate water supply. We contend that part of the explanation may lie in the lack of official statistics and inconsistent sources of information on the water–energy nexus in Spain. To illustrate this point, we provide examples of the uneven data available for one of the most intensive freshwater users in the thermoelectric sector in Spain: nuclear power plants. Our research demonstrates the need for improved indicators as policy instruments in the water–energy nexus in Spain since it is impossible to improve what cannot be measured.

*Keywords:* Cooling technologies; Indicators; Policy evaluation; Policy instruments; Spain; Water–energy nexus

## Introduction

The crucial role of water for human life is a scientific fact well recognized by society. Yet most people would not consider water as a basic input in our energy system. If asked about the issue, the average person would surely identify the link of energy and water by just evoking power dams. However, according to IEA (2013) and Delgado *et al*. (2015), nearly 80% of the world's electricity is generated in thermoelectric power plants which require water in their operation. Adding the 15% corresponding to hydroelectricity generation, the vast majority of today's global electricity generation would cease in the absence of water (that is, all hydroelectric production plus all thermal generation regardless of technology). In fact, the production of electrical power is one of the largest uses of water worldwide and, consequently, the mutual vulnerability of water and energy is considered as one of the most important concerns of the future (IEA, 2012b). Vast amounts of water are needed in power generation, mainly for cooling processes. In turn, there exists a vast international body of literature and technical reports

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describing the water requirements for power generation by technology. Some examples are Kenny *et al.* (2009), Macknick *et al.* (2012), and Meldrum *et al.* (2013).

In this context, some international institutions have developed proposals to address the challenges of energy resources planning and water (for example, the Thirsty Energy Initiative from the World Bank)[1] and many authors have researched this matter from different perspectives (IEA, 2012a, 2012b; WWAP, 2014; Delgado *et al*., 2015). Water shortages have already impacted the energy sector in many countries albeit in different ways. For example, whereas in India, several thermal power plants have shut down due to water scarcity, in the USA or France, power stations have reduced their energy production as a result of high water temperatures preventing the proper functioning of cooling systems (Rodriguez *et al*., 2013). In line with this, the French case is especially relevant since the country currently gets about 75% of the total electricity from nuclear power plants and most of its reactors are cooled by water from rivers (World Nuclear Association, 2018). Moreover, several trends point to rising demands on energy and water due to the rapid population growth and expansion of economies due to globalization. Therefore, ensuring the future provision of water and energy is essential to guarantee the social and economic development of many countries.

According to the State Meteorological Agency (AEMET, for its Spanish acronym), in Spain the hydrological year ended in 2017 with a shortfall of 15% when compared to the historical average (1981–2010) and, hence, freshwater reservoirs of the country in 2017 were at their lowest state this century, representing the fifth driest year since 1990 (http://www.aemet.es/). While there is a long list of studies that have calculated the water footprint in agriculture, industry or even the tourism sector in Spain (De Stefano & Llamas, 2012; Cazcarro *et al*., 2014; Duarte *et al*., 2014), the few studies on the water issue in relation to energy within the electricity sector have mostly referred to hydroelectric power plants and have ignored thermoelectric uses unlike the international literature. Some rare exceptions to this oversight are Carrillo & Frei (2009), Hardy *et al*. (2012) and Sesma-Martín & Rubio-Varas (2017).

The world at large has begun to think of the water–energy nexus as one of the priority issues at the global level. However, the energy–water nexus seems to remain irrelevant on the Spanish energy policy agenda. According to the data reported in the *World Energy Issues Monitor* (WEC, 2014, 2015, 2016, 2017), which ranks the most important issues according to the world's energy leaders, the water–energy nexus is not considered to be a matter of priority action in Spain. At a global scale, Spain ranks in a less prominent position than the other regions (e.g., OECD, North America, Asia, Africa, Latin America) and even behind the European average[2]. More specifically, this can be seen in Figures 1 and 2 that show some of the latest *Energy Issues Monitor* for Spain where the water–energy nexus is found at the bottom left margin of the graph, a position corresponding to issues perceived to be of lesser importance or those that are still not fully understood and require further investigation. Furthermore, comparing the size of the bubble corresponding to the water–energy nexus between the years 2014 (Figure 1) and 2017 (Figure 2), it can be seen how the water–energy nexus has lost relevance over the years (the larger the bubble, the greater the level of urgency). It was, in fact, regarded in 2017 as the issue with the least potential impact on energy in Spain (Figure 2). This contrasts with the social

[1] For more information, see: http://www.worldbank.org/en/topic/sustainabledevelopment/brief/water-energy-nexus.

[2] This statement can be demonstrated by comparing *Figure 8-The Energy-Water Nexus* on p. 23 and the figure corresponding to Spain on p. 117 from WEC (2016).

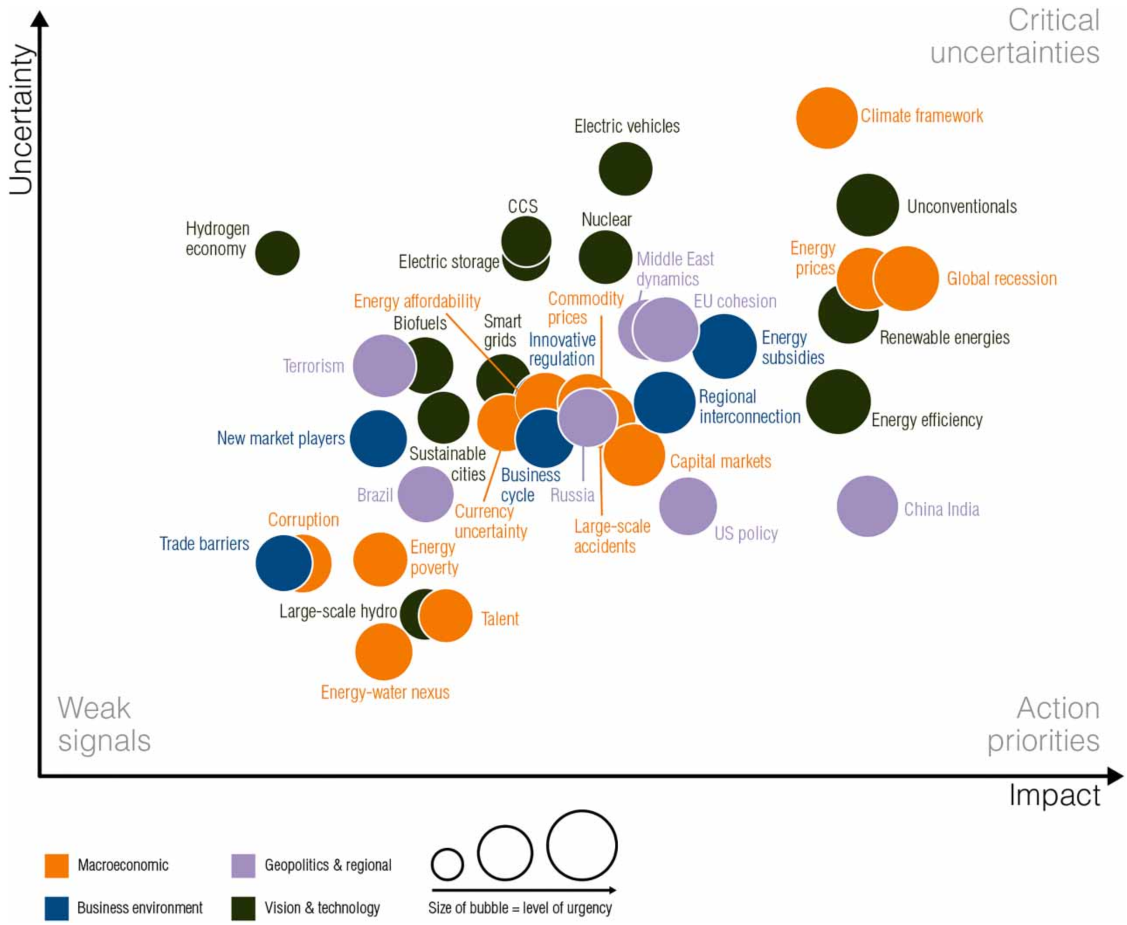


Fig. 1. WEC's 2014 *World Energy Issues Monitor*, Spain. *Source:* WEC (2014) (used by permission of the World Energy Council, London, www.worldenergy.org).

concern about water in Spain illustrated by the fact that the United Nations World Water Day is one of the three days that attracts most attention among the Spanish population (UN Water, 2016).

Our hypothesis is that two issues lie behind the fact that the water–energy nexus is not considered a primary issue in the Spanish policy agenda. First, the absence of appropriate data (in other words, factual information such as measurements or statistics) to understand the water–energy nexus, as we will show, is evident from the inconsistencies in the available sources of information published for analyzing the water needs of the energy sector in Spain. Second, the deficient understanding of the basic concepts with respect to water use (water withdrawal vs. water consumption) on the available sources which, in turn, omit information about the particular procedures or methodologies utilized to calculate such figures. These two sets of discrepancies (namely, in the available data and the unfitting use of inappropriate definitions) can result in incorrect interpretations that prevent a good estimate of the thermoelectric water footprint. At the same time, this can weaken the development of good management practices and the establishment of an efficient policy around the water–energy nexus. What is evident

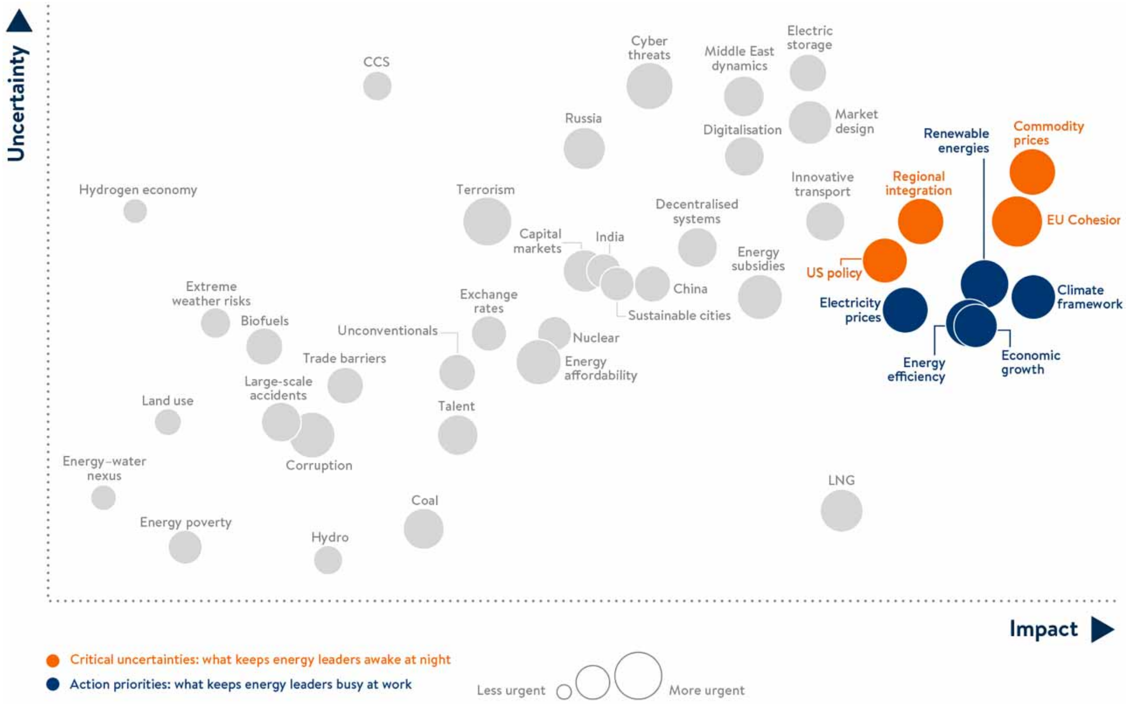


Fig. 2. WEC's 2017 *World Energy Issues Monitor*, Spain. *Source:* WEC (2017) (used by permission of the World Energy Council, London. www.worldenergy.org).

from the figures above is that there exists a lack of awareness among the stakeholders and Spanish society about the importance of water within the power sector.

Typically, the regulation of the electricity market acts on four components: generation, transmission, distribution, and commercialization. In Spain, from 1944 until the 1980s, a cartel of mostly privately owned companies, under the name of UNESA, self-regulated all aspects of the electricity market. The desire for change of the first Socialist government (elected in 1982) came to fruition with the nationalization of the High Voltage Grid, which was then again privatized in the late 1990s. 'What is certain is that the new model of regulation established in Spain brought about a first phase of vertical disintegration in the old regional private monopolies and created the means to achieve an optimization of the Spanish electricity system' (Garrues & López-García, 2009). But it is relevant that the Spanish electricity production was organized as a private self-regulated business for most of the 20th century. Maybe as a consequence of this institutional setting, another aspect that emerges from the Spanish context is that thermal power stations in Spain do not pay for the water they use. Spanish legislation only included a fee for the amount of water used by hydropower plants from 2013[3] but does not impose any fee for

[3] This fee was created by Law 15/2012, of 27 December, on fiscal measures for energy sustainability. However, Royal Decree 198/2015, of 23 March, which implements article 112 bis of the consolidated text of the Water Act and regulates the charge for the use of inland waters for the production of electricity in inter-community districts, specifies the aspects necessary for levying the charge and obliges hydroelectric plant owners to make the payment with effect from 1 January 2013, the date on which Law 15/2012 took effect.

thermal power plants despite the large water volumes they require[4]. This legislative gap represents an additional argument to think about how the lack of political interest on the matter could be behind the lack of consistent evidence on the water–energy nexus.

These shortcomings put the correct management of water resources in Spain at risk. This seems particularly worrisome when it is the most arid country in Europe, where almost two-thirds of electricity generation would have to be halted in the absence of an adequate water supply (in 2017, 56% thermoelectric plus close to 10% hydroelectric) (REE, 2017). Therefore, our aim in this communication is to expose these inconsistencies in the sources of information available in Spain when accounting for the thermoelectric water footprint. In this context, the thermoelectric water footprint refers to the volume of fresh water used for electricity generation in thermal power plants. We expose these issues by comparing and contrasting the available published sources of data of water use for the nuclear sector in Spain, the most water intensive of all thermal technologies, as collected by Sesma-Martín & Rubio-Varas (2017).

## Methods

There exist two key concepts when estimating the water requirements of a thermoelectric power plant: water withdrawals and water consumption. Water withdrawals are the total volume of water removed from a source by a power plant and water consumption is the amount lost to evaporation during the cooling process (Kenny *et al.*, 2009; Sesma-Martín & Rubio-Varas, 2017). In other words, water consumption is the volume of water withdrawn that is not returned to the source. In this way, differentiating between withdrawals and consumption is fundamental because even if large portions of the water return to the rivers, yet the opportunity cost exists for such water volumes. Likewise, water consumption and withdrawals have different associated environmental adversities (e.g., warmer water discharges, death of fish caught in the catchment systems) where appropriate public measures are needed to mitigate them; although in this paper, we only focus on the quantitative aspects.

In general, for elaborating a proper estimation of the water footprint for the thermoelectricity sector, first, power plants should be classified by type of fuel (coal, fuel-oil, gas, and uranium) and cooling technology (the most common systems are cooling towers and once-through systems). Each fuel and cooling system involves different water requirements and, consequently, produces different water withdrawals and consumption factors (e.g., open-loop systems withdraw much more water than cooling towers, but cooling towers evaporate much more water than open-loop systems) and, in turn, each region has specific geographical features that can condition water availability. Therefore, understanding the advantages and disadvantages of each cooling technology is essential for the correct management of freshwater resources.

For the sake of this communication, we concentrated on the water requirements of the nuclear power facilities, but our claims regarding the inconsistencies of water use data in the electricity sector in Spain apply to the whole thermoelectricity sector (Sesma-Martín, 2017). Nuclear water requirements tend to be larger per MWh (megawatt hour) generated than alternative thermal technologies (IEA, 2012a,

[4] There is an exception at regional level in Catalonia. Since 2004, the Catalan Government, through the Catalan Water Agency, imposes a tax (namely, *Canon del agua*) on freshwater resources used to refrigerate all those thermal and nuclear power stations of the region. This *Canon del Agua* is regulated by Legislative Decree 3/2003, of 4 November. The complete resolution can be found at https://www.boe.es/buscar/pdf/2003/DOGC-f-2003-90016-consolidado.pdf.

2012b). We initiated this study on the basis of the data collected from a variety of sources in Sesma-Martín & Rubio-Varas (2017), which included Spanish nuclear facilities operating with fresh water that has been withdrawn from rivers or lakes. Plants working with sea water or refrigerating with gas were omitted. Therefore, the investigated nuclear power plants were Trillo I, Cofrentes, Almaraz I and II, Ascó I and II, Santa María de Garoña, and José Cabrera (known as Zorita). In their study, the authors excluded the Vandellós units I and II which use gas and sea water for cooling, respectively. For the plants considered, the authors did extensive research in public and private institutions to decipher the technical factors in order to estimate the water required to produce atomic energy in Spain (see Supplementary material from Sesma-Martín & Rubio-Varas (2017)).

The information sources consulted included data from the Spanish Nuclear Safety Council (CSN for its Spanish acronym) and from the Libro Blanco del Agua, which represents the main references on water problems in Spain. Moreover, the data appearing on the websites of the River Basin Confederations (the main basin agencies in Spain) to which the different nuclear power plants correspond as well as water data published at the Spanish Official Bulletin (BOE) and the theoretical maximum water concessions of each power plant were reviewed. Greenpeace and the nuclear power plants themselves also collect some data in their environmental reports. Finally, the TRACER Project, a technical study on pollutants in rivers, also provided some timely data on the possible withdrawals of water from Spanish nuclear power plants.

The collected data show the few cases where actual, reliable, and well-defined figures are provided. According to the Supplementary material in Sesma-Martín & Rubio-Varas (2017), in some of the data sources the numbers provided cover either water withdrawals or water consumption, but not both. On other occasions, the sources omitted specifying whether the figure provided referred to withdrawals or consumptions. Moreover, in recent years, electric utilities have produced environmental reports, that among others, provide data on their water consumption. However, these figures are useless for the purpose of estimating the water requirements of a given power plant as these reports only provide the total aggregated data on water usage without differentiating between cooling technologies or individual facilities. As explicit data for each nuclear power plant are lacking for most Spanish reactors, Sesma-Martín & Rubio-Varas (2017) resorted to estimations based on the international literature. All Spanish reactors are of American manufacture, except for two of them (De la Torre & Rubio-Varas, 2016). Therefore, by reviewing the American literature on cooling technology and water factors, Sesma-Martín & Rubio-Varas (2017) applied those standard factors for the equivalent reactors and produced their estimated time series of the water footprint for nuclear plants in Spain. However, they did not compare and contrast the different estimates they collected, nor compare them with their own estimations based on water factors from the international literature. We conducted such comparisons to expose the insufficient precision and inconsistent data available on the water–energy nexus in Spain.

## Results

Figures 3 and 4 show the comparison between the different water withdrawals and consumption factors for each of the Spanish nuclear reactors from the available published sources on water needs provided in Sesma-Martín & Rubio-Varas (2017). In turn, these figures are associated with Tables 1 and 2, which show some statistics for evaluating the absolute and the relative quality of the data.

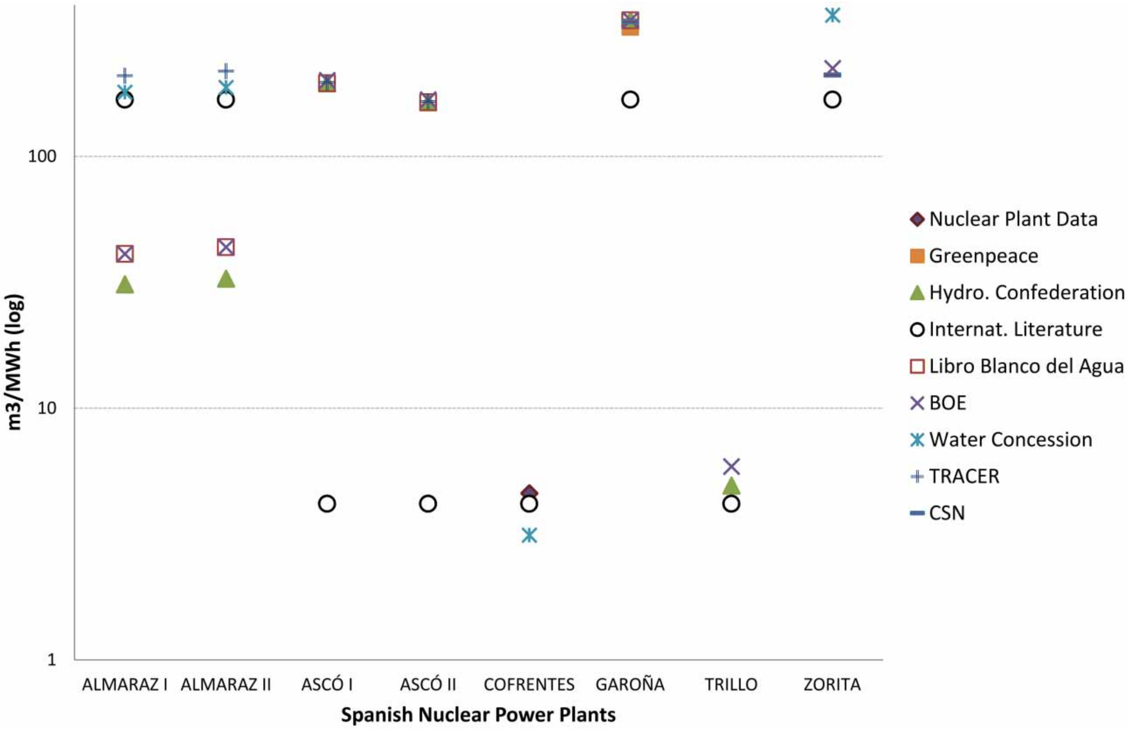


Fig. 3. Sample data of the water withdrawal factors for Spanish nuclear power plants. *Note:* $m^3$ = cubic meter. *Source:* Elaborated from individual reactor published data available from the Supplementary material in Sesma-Martín & Rubio-Varas (2017).

As we can see, the differences are of several orders of magnitude, especially when comparing the water withdrawal coefficients deducted from the different sources for each nuclear power plant in Figure 3. More specifically, while data exist for the technical factor on water withdrawals for all nuclear power plants, there have been no data published for three of the eight nuclear plants in the case of water consumption, except for the data estimated based on the literature review (Figure 4). In this way, when evaluating in absolute terms in the case of water withdrawals (Table 1), the nuclear power stations with the lowest range, in other words, lesser distance or dispersion among data, are Cofrentes and Trillo. In all other cases (i.e., Almaraz I-II, Ascó I-II, Garoña, and Zorita) the range is wider, as the data are further apart from each other. Likewise, for evaluating the relative quality of data we have calculated the coefficient of variation (CV) which shows the dispersion of data in relation to the average. Now the power plants with the lowest values are Trillo (0.17), Cofrentes (0.19), Garoña (0.23), and even Zorita (0.35). However, Almaraz I-II and Ascó I-II have a greater coefficient (0.74, 0.73, and 0.54, respectively). Conversely, the picture for water consumption is very different. No official data exist for the Garoña and Ascó nuclear power plants and the data for the rest of the cases present differences of various orders of magnitude. Thus, whereas Cofrentes, Trillo, and Almaraz I-II capture the lowest ranges (0.10, 0.19, 2.30, and 2.44 respectively), Zorita's range (14.08) stands out extremely among the rest. Finally, when assessing the relative differences, we find in Cofrentes and Trillo the lowest

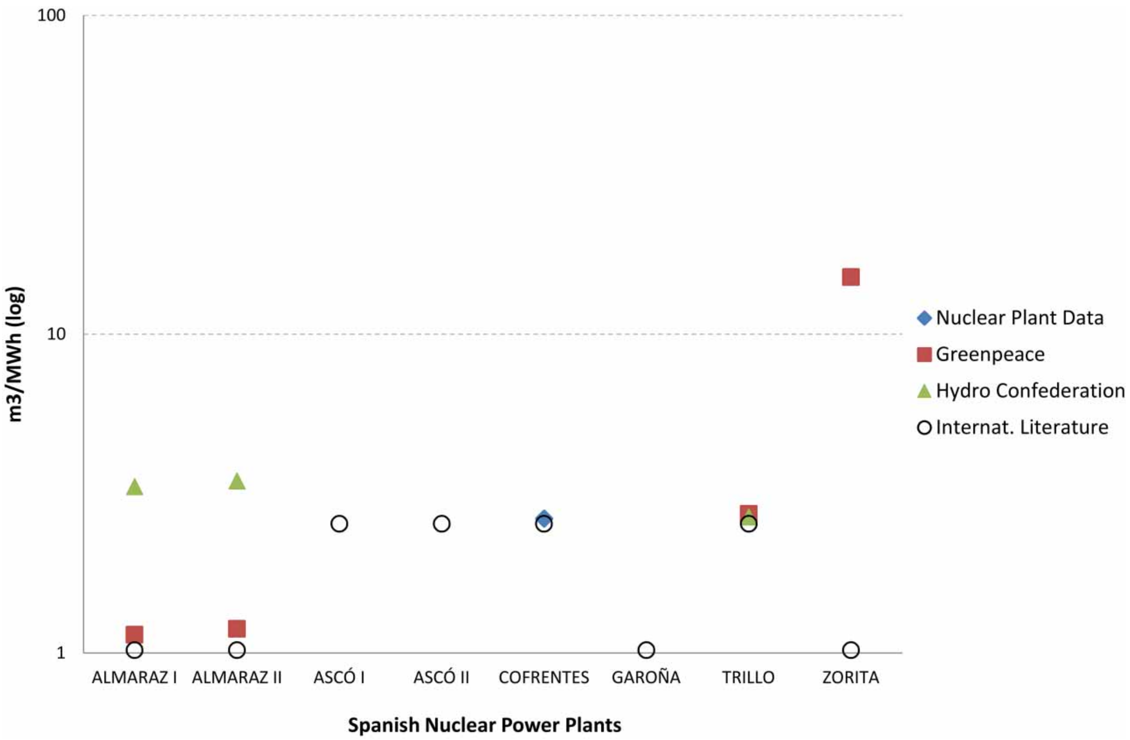


Fig. 4. Sample data of the water consumption factors for Spanish nuclear power plants. *Note:* $m^3$ = cubic meter. *Source:* Elaborated from individual reactor published data available from the Supplementary material in Sesma-Martín & Rubio-Varas (2017).

Table 1. Statistics for data on water withdrawals' factors ($m^3$/MWh).

| | ALMARAZ I | ALMARAZ II | ASCÓ I | ASCÓ II | COFRENTES | GAROÑA | TRILLO | ZORITA |
|---|---|---|---|---|---|---|---|---|
| N | 6 | 6 | 5 | 5 | 3 | 6 | 3 | 4 |
| Max | 209.00 | 218.00 | 200.60 | 168.00 | 4.59 | 347.70 | 5.86 | 364.15 |
| Min | 31.00 | 32.68 | 4.17 | 4.17 | 3.13 | 167.88 | 4.17 | 167.88 |
| Range | 178.00 | 185.32 | 196.43 | 163.83 | 1.46 | 179.82 | 1.69 | 196.27 |
| Median | 111.65 | 115.63 | 158.31 | 133.03 | 3.96 | 313.18 | 4.98 | 241.73 |
| SD | 82.22 | 84.50 | 86.20 | 72.06 | 0.75 | 71.64 | 0.85 | 85.06 |
| CV | 0.74 | 0.73 | 0.54 | 0.54 | 0.19 | 0.23 | 0.17 | 0.35 |

*Note:* $N$ = data frequency; Max = maximum value; Min = minimum value; Median = arithmetic average; SD = standard deviation; CV = coefficient of variation.
*Source:* Elaborated from individual reactor published data available from the Supplementary material in Sesma-Martín & Rubio-Varas (2017).

coefficients of variation, units I and II of Almaraz nuclear power plant involve an intermediate value (0.71 and 0.72) and Zorita presents again the highest value, although far less remarkable than before (1.24).

Table 2. Statistics for data on water consumption factors ($m^3$/MWh).

| | ALMARAZ I | ALMARAZ II | ASCÓ I | ASCÓ II | COFRENTES | GAROÑA | TRILLO | ZORITA |
|---|---|---|---|---|---|---|---|---|
| N | 3 | 3 | 1 | 1 | 2 | 1 | 3 | 2 |
| Max | 3.32 | 3.46 | 2.54 | 2.54 | 2.64 | 1.02 | 2.73 | 15.10 |
| Min | 1.02 | 1.02 | 2.54 | 2.54 | 2.54 | 1.02 | 2.54 | 1.02 |
| Range | 2.30 | 2.44 | 0 | 0 | 0.10 | 0 | 0.19 | 14.08 |
| Median | 1.83 | 1.89 | 2.54 | 2.54 | 2.59 | 1.02 | 2.65 | 8.06 |
| SD | 1.29 | 1.36 | – | – | 0.07 | – | 0.10 | 9.96 |
| CV | 0.71 | 0.72 | – | – | 0.03 | – | 0.04 | 1.24 |

*Note:* N = data frequency; Max = maximum value; Min = minimum value; Median = arithmetic average; SD = standard deviation; CV = coefficient of variation.
*Source:* Elaborated from individual reactor published data available from the Supplementary material in Sesma-Martín & Rubio-Varas (2017).

## Discussion

In the case of the Spanish water–energy nexus, we have identified a number of sources (suppliers of information) that provide inconsistent and, at times, contradictory factual information for the amount of water required to operate the thermoelectric power plants (data), without specifying the particular procedures utilized to calculate such figures (no methodology). Furthermore, the data identified refer to benchmark estimates. There exists no statistical evidence on the evolution of the water requirements (neither withdrawals nor consumption) over time for any of the Spanish thermoelectric plants. Moreover, as mentioned above, 'while data exist for the technical factor for water withdrawals for all nuclear power plants, there have been no data published for three of the eight nuclear plants in the case of water consumption'. Thus, our claim that the data on the water–energy nexus in Spain is weak.

Effectively, the problem lies mainly in the impossibility to identify from the sources that we collected, what concepts are being measured and estimated (water withdrawals, water consumption, or both). In other words, it is impossible to identify the methodologies utilized, which, in turn, contributes to make the little available data even feebler. The figures above show the evident lack of consensus among the different sources of information that collect water data regarding the estimation of freshwater resources needed for thermoelectric production. Management thinker Peter Drucker is often quoted as stating that 'you can't manage what you can't measure' and physicist Lord Kelvin, in a similar vein, has been attributed with the phrase 'if you cannot measure it, you cannot improve it'. With a clearly established metric for success, it is possible to quantify progress and adjust processes to produce the desired outcome. Without a clear indication of the size of a problem there is no reason to worry or act to solve it. For example, in the USA, water withdrawal and consumption data have been available for almost all thermoelectric power generating units and cooling systems in the country for many years and, hence, the water–energy nexus is a matter of greater relevance for American policy-makers. Thus, we contend that the fact that the water–energy nexus has not been considered a critical issue in the Spanish policy agenda has largely to do with the lack of consistent indicators about it. Moreover, lack of studies on the estimation of the water requirements for thermal power generation so far in Spain could be related to the limited official statistics on the water–energy nexus, which makes this type of analysis impossible. In this respect, in 2013, Spain signed an agreement for the construction of a more transparent and open government through the approval of the Transparency Law (Law 19/2013, December 9, of

Transparency, Access to Public Information and Good Governance). Likewise, this country also signed the creation of a specific portal on open data. However, there has been little compliance with these agreements. According to the Index of Water Management elaborated by the non-governmental organization International Transparency[5], in Spain there are still significant gaps in publicly available information in some areas of public management. Furthermore, when ranking by data typology, all those data related to uses of water are the most limited, appearing in the last position of the ranking. De Stefano *et al.* (2018) in a recent study about open data in the Spanish water sector also confirm these statements.

We plead that Spanish energy leaders and those responsible for the energy policy of the country consider water as the critical energy resource that it is. In this sense, working in producing accurate data on the evolution of the water withdrawals and consumption seems to be a key issue to move towards a better estimation of the thermoelectric water footprint. Better data will also help to improve the awareness of the different tradeoffs between water uses (i.e., withdrawals and consumptions) according to different cooling technologies and alternative ways of producing electricity. This is particularly important, not only when taking water policy measures and planning future energy systems, but also when analyzing special cases such as Spain, with increasingly frequent episodes of drought. Moreover, the publication of data related to uses of water within the energy sector in official and open sources of information would also contribute to the generation of new knowledge and studies on this matter. Ultimately, a better understanding of this problem in Spain could provide short- and long-term strategies to cope with vulnerability and resilience in power plants in future water stress scenarios.

After the analysis of sources of information carried out in this paper, we conclude that the environmental reports produced by thermal power plants are the best sources to estimate the annual water footprint. However, this improvement in data production and collection would be of little value if the environmental reports remain inaccessible (although for some plants they are already public, in most cases they are not). There exists no systematic effort to make them public. Thus, the Spanish Ministry of Agriculture, Fisheries, Food and Environment (MAPAMA, as known by the Spanish acronym) or the Hydrographic Confederations, as public regulatory bodies of the Spanish river basins and dependent on the Spanish Ministry of Environment, could represent the most relevant authorities to collect and publish on their websites these kinds of data. Additionally, we believe that some of this information should also be included in the Libro Blanco del Agua, the most representative reference on water problems in Spain, where only eight of the 637 pages of the full text are dedicated to the water–energy nexus.

Finally, making strict use of the definition of 'Economy' as the discipline that studies the distribution of scarce resources among competing needs, our interest as economists is to assess the amounts of fresh water required for thermoelectric production. Therefore, in this paper, we only focus on the quantitative importance of water, leaving aside the qualitative aspects (i.e., temperature, liquid effluents, or radioactive solid wastes) which require a different approach. This could be a potential issue to be addressed in future analyses, especially in the Iberian Peninsula, where three main rivers cross the border flowing from Spain into Portugal and four nuclear reactors have used water from the Tagus River for cooling from the middle of the 20th century onwards (Rubio-Varas *et al.*, 2018).

In summary, we hope this information will encourage better data collection on the water–energy nexus in Spain, as well as a more transparent and consistent publication of the data in open platforms

[5] More information about International Transparency-Spain can be found at https://transparencia.org.es/.

in order to improve future studies that are crucial for policy-makers. Will water limit our energy future? How should water be taken into account when planning the electricity mix of the future? Questions like these will become crucial in the coming years.

## Acknowledgments

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## References

Carrillo, A. M. R. & Frei, C. (2009). Water: a key resource in energy production. *Energy Policy 37*(11), 4303–4312.

Cazcarro, I., Hoekstra, A. Y. & Chóliz, J. S. (2014). The water footprint of tourism in Spain. *Tourism Management 40*, 90–101. DOI: http://dx.doi.org/10.1016/j.tourman.2013.05.010.

De la Torre, J. & Rubio-Varas, M. (2016). Nuclear power for a dictatorship: state and business involvement in the Spanish atomic program, 1950–85. *Journal of Contemporary History 51*(2), 385–411. DOI: https://doi.org/10.1177/0022009415599448.

Delgado, A., Rodriguez, D. J. & Sohns, A. A. (2015). *Thirsty Energy: Understanding the Linkages Between Energy and Water*. Live wire knowledge notes series; no. 2015/41. World Bank Group, Washington, DC, USA. http://documents.worldbank.org/curated/en/2015/01/24084417/thirstyenergyunderstanding-linkages-between-energy-water (accessed 4 January 2018).

De Stefano, L. & Llamas, M. R. (2012). *Water, Agriculture and the Environment in Spain: Can We Square the Circle?* CRC Press, Boca Raton, FL, USA.

De Stefano, L., Cabello, V. & Hernández-Mora, N. (2018). Datos Abiertos en el Sector del Agua en España (*Open Data in the Water Sector in Spain*) Fundación Botín.

Duarte, R., Pinilla, V. & Serrano, A. (2014). The water footprint of the Spanish agricultural sector: 1860–2010. *Ecological Economics 108*, 200–207. DOI: https://doi.org/10.1016/j.ecolecon.2014.10.020.

Garrues-Irurzun, J. & López-García, S. (2009). Red Eléctrica de España SA: instrument of regulation and liberalization of the Spanish electricity market (1944–2004). *Renewable and Sustainable Energy Reviews 13*(8), 2061–2069.

Hardy, L., Garrido, A. & Juana, L. (2012). Evaluation of Spain's water-energy nexus. *International Journal of Water Resources Development 28*(1), 151–170.

IEA (International Energy Agency) (2012a). *World Energy Outlook 2012*. Paris, France. https://www.iea.org/newsroom/news/2012/november/world-energy-outlook-2012.html (accessed 24 February 2018).

IEA (International Energy Agency) (2012b). *Water for Energy: is Energy Becoming A Thirstier Resource?* Paris, France. http://www.worldenergyoutlook.org/media/weowebsite/2012/WEO_2012_Water_Excerpt.pdf (accessed 4 January 2018).

IEA (International Energy Agency) (2013). *World Energy Outlook 2013*. Paris, France. https://www.iea.org/publications/freepublications/publication/WEO2013.pdf (accessed 24 February 2018).

Kenny, J. F., Barber, N. L., Hutson, S. S., Linsey, K. S., Lovelace, J. K. & Maupin, M. A. (2009). *Estimated use of Water in the United States in 2005*. U.S. Geological Survey Circular 1344, p. 52. https://pubs.usgs.gov/circ/1344/ (accessed 4 January 2018).

Macknick, J., Newmark, R., Heath, G. & Hallett, K. C. (2012). Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature. *Environmental Research Letters 7*(4), 045802. DOI: https://doi.org/10.1088/1748-9326/7/4/045802.

Meldrum, J., Nettles-Anderson, S., Heath, G. & Macknick, J. (2013). Life cycle water use for electricity generation: a review and harmonization of literature estimates. *Environmental Research Letters 8*(1), 015031. DOI: https://doi.org/10.1088/1748-9326/8/1/015031.

REE (Red Eléctrica de España) (2017). *The Spanish Electricity System*. Preliminary report 2017. Madrid. http://www.ree.es/sites/default/files/downloadable/avance_informe_sistema_electrico_2017_eng.pdf (accessed 24 February 2018).

Rodriguez, D., Delgado, A., DeLaquil, P. & Sohns, A. (2013). *Thirsty Energy. Water Papers*. World Bank, Washington, DC, USA. http://documents.worldbank.org/curated/en/835051468168842442/Thirsty-energy (accessed 4 January 2018).

Rubio-Varas, M. d. M., Carvalho, A. & De la Torre, J. (2018). Siting (and mining) at the border: Spain-Portugal nuclear trans-boundary issues. *Journal of History, Environment and Society 3*, 33–69.

Sesma-Martín, D. (2017). Water for Power Generation: Vulnerability, Conflicts, and Competition in the Ebro River Basin. In: *Conference Proceedings of the XLIII Reunión de Estudios Regionales – International Conference on Regional Science, Sevilla*. Spanish and Andalusian Regional Science Associations (eds). http://old.reunionesdeestudiosregionales.org/sevilla2017/es/xliii-reunion-de-estudios-regionales/papers.html (accessed 24 February 2018).

Sesma-Martín, D. & Rubio-Varas, M. (2017). Freshwater for cooling needs: a long-run approach to the nuclear water footprint in Spain. *Ecological Economics 140*, 146–156. DOI: https://doi.org/10.1016/j.ecolecon.2017.04.032.

UN Water (23 November 2016). Para qué sirven los Días Internacionales? (What are International Days for?) https://blogs.un.org/es/2016/11/23/para-que-sirven-los-dias-internacionales/ (accessed 29 March 2018).

WEC (World Energy Council) (2014). *World Energy Council Issues Monitor 2014*. What keeps Energy leaders awake at night?, London. https://www.worldenergy.org/wp-content/uploads/2014/01/World-Energy-Issues-Monitor-2014.pdf (accessed 4 January 2018).

WEC (World Energy Council) (2015). *World Energy Council Issues Monitor 2015*. Energy price volatility: the new normal, London. https://www.worldenergy.org/wp-content/uploads/2015/01/2015-World-Energy-Issues-Monitor.pdf (accessed 4 January 2018).

WEC (World Energy Council) (2016). *World Energy Council Issues Monitor 2016*. A climate of innovation-responding to the commodity price storm, London. https://www.worldenergy.org/wp-content/uploads/2016/03/2016-World-Energy-Issues-Monitor-Full-report.pdf (accessed 4 January 2018).

WEC (World Energy Council) (2017). *World Energy Council Issues Monitor 2017*. Exposing the New Energy Realities, London. https://www.worldenergy.org/wp-content/uploads/2017/04/1.-World-Energy-Issues-Monitor-2017-Full-Report.pdf (accessed 4 January 2018).

World Nuclear Association (2018). *Nuclear Power in France*. http://www.world-nuclear.org/information-library/country-profiles/countries-a-f/france.aspx (accessed 29 March 2018).

WWAP (World Water Assessment Programme) (2014). *The United Nations World Water Development Report 2014: Water and Energy*. UNESCO, Paris. http://www.unesco.org/new/en/natural-sciences/environment/water/wwap/wwdr/2014-water-and-energy/ (accessed 4 January 2018)

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The Nuclear Water Footprint in Spain

# 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 2014. Our results show that while water consumed by Spanish nuclear power plants are around 3 $m^3$ per 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.



## 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% of freshwater withdrawals were dedicated to electric production from thermoelectric plants, mainly for cooling (Kenny et al., 2009). Likewise, in the year 2010, France withdrew 22 $km^3$ of water for cooling purposes and 20 $km^3$ in the case of Germany (EUROSTAT, 2014). Moreover, about 80% of the world's electricity is generated in thermal power plants (IEA, 2013). In other words, 80% 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%. 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,

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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 (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.

[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 l of water at the coal mining stage and an additional 1200 to 2000 l when the energy in the coal is converted to electricity, totaling 1220 to 2270 l of water consumed per MWh. In comparison, nuclear energy uses 170 to 570 l of water per MWh during the mining of uranium and production of the reactor fuel and an additional 2700 l per MWh as the energy from nuclear fission is converted to electricity, for a total of 2870 to 3270 l of water consumed per MWh*'. [www.foe.org.au/anti-nuclearJanuary 2013]

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. Rodriguez 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 talk 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 behaviour 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 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)

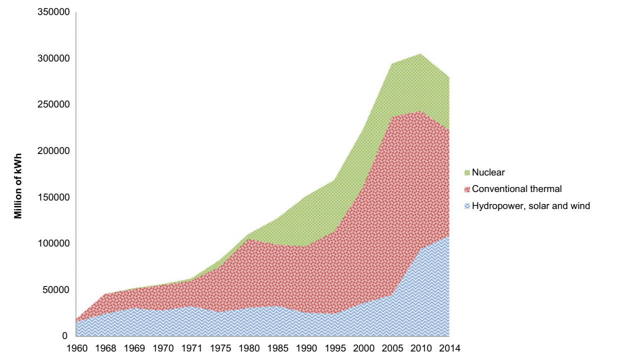


**Fig. 1.** Evolution of Spanish Power Generation by technology (1960–2015) Note: Solar and wind power are included coupled with hydropower from 2003. Conventional thermal includes coal, fuel-oil, gas and combined cycle plants.
(Source: own elaboration from UNESA's Annual Reports)

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 opnened 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 del Mar Rubio-Varas, 2016). The utilities projected over 22,000 MW of nuclear installed capacity in the frenzy of atomic optimism, of which only 7000 MW 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.

## 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.

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

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

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 exists 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 withdrawn 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% 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 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.

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' 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 these 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 del Mar Rubio-Varas, 2016). 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).

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 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.

[7] For other definitions see:
- Vickers (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 et al. (2011). *Freshwater 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. 18801–18,802.
BOE, núm. 31, de 5 de febrero de 1977, pp. 2906–2907.
BOE, núm. 200, de 22 de agosto de 1977, pp. 18744–18,746.
BOE, núm. 138, de 9 de junio de 1984, p. 16717.
BOE, núm. 207, de 30 de agosto de 1999, pp. 31958–31,994.
BOE, núm. 89, de 12 de abril de 2014, pp. 30535–30,638.

[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 (2270 hm$^3$/year) and Garoña (766 hm$^3$/-year). Other figures from the same source are around 2438.36 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 et al. (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.

[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 m$^3$/s, having been granted for the use there of a flow rate of 1.1 m$^3$/s, with an annual limitation maximum total consumption volume of 20 hm$^3$/year and an amount of water catchment of 34.7 authorized hm$^3$/year. From this flow, a portion close to 0.75 m$^3$/s, evaporates in natural draft towers and the remaining 0.35 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 hm$^3$/year).

[15] Greenpeace cites that consumption in the Trillo is 21 hm$^3$/year; Nuclear Jose Cabrera (Zorita de los Canes) consumes 15 hm$^3$/year; Almaraz nuclear plant, 16 hm$^3$/year, all the banks of the Tagus River.On the other hand, Greenpeace estimates that Garoña employs 720 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 (m$^3$/year) to cubic meter per MWh.

**Table 1**
Classification of 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.

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:

$$t = 1969, 1970, \ldots\ldots, 2014$$

$$i = 1, 2, 3, \ldots\ldots, 8$$

Water Consumption (Withdrawals) Coefficients are calculated as follow.

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

$WWC = \dfrac{WW}{Energy\ \ Generated\ \ (Output)}$ 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:

$$WCC_t^i * TO_t^i \tag{1}$$

and

$$WWC_t^i * TO_t^i \tag{2}$$

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 follows:

$$\text{Total}\ \ WW^i = \sum_t^i \left(WWC^i * TO^i\right) \tag{3}$$

and

$$\text{Total}\ \ WC^i = \sum_t^i \left(WCC^i * TO^i\right) \tag{4}$$

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

| | 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).

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

$$\begin{aligned}\text{Total}\ \ D^i &= \text{Total}\ \ WW^i - \text{Total}\ WC^i \\ &= \sum_t^i \left(WWC^i * TO^i\right) - \sum_t^i \left(WCC^i * TO^i\right)\end{aligned} \tag{5}$$

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:

$$WWpc = \frac{total\ \ WW^i}{population} \tag{6}$$

and

$$WCpc = \frac{total\ \ WC^i}{population} \tag{7}$$

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

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

| 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 & II, Santa María de Garoña, and Zorita represent theoretical values for which we don't dispose of real data. The remaining values represent adjusted 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).

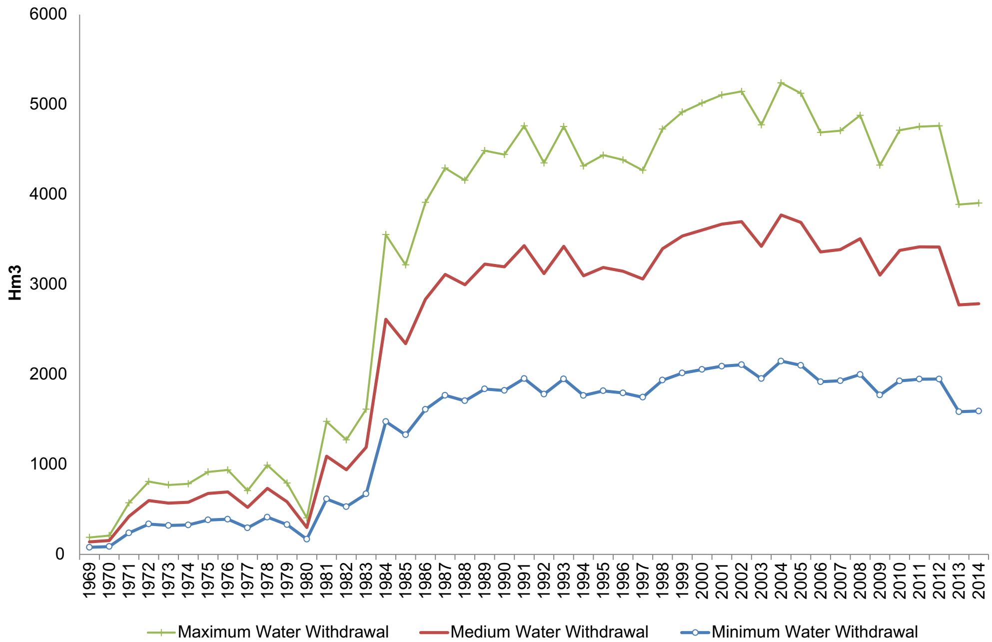


**Fig. 2.** Evolution of total Water Withdrawals of Spanish nuclear power plants (1969–2014), by using literature factors. Source: own elaboration using water factors of Table 2 and electricity generation from nuclear reactors using fresh water for cooling from UNESA.

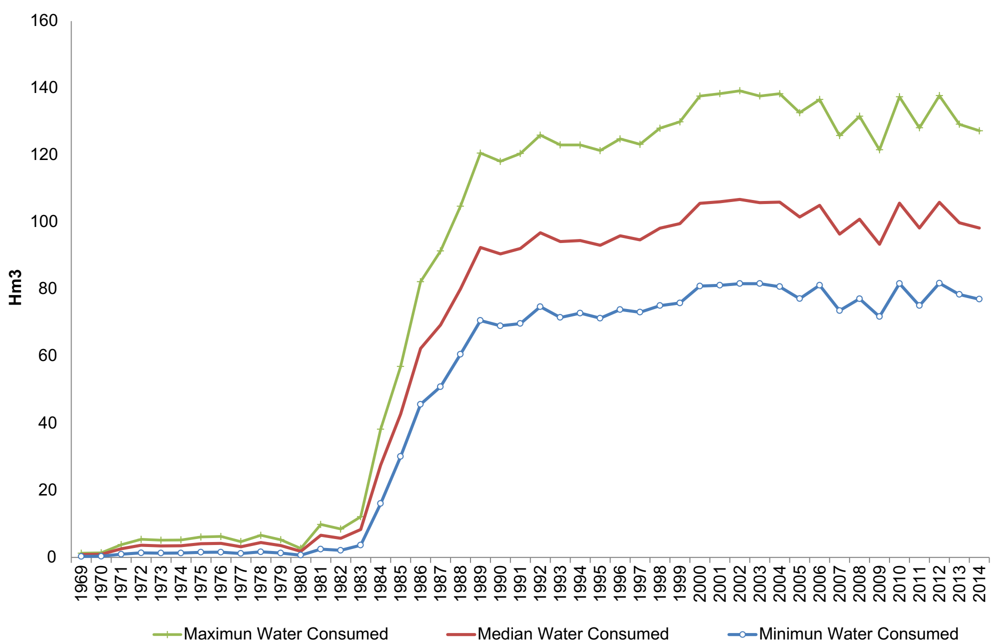


**Fig. 3.** Evolution of total Water Consumptions of Spanish nuclear power plants (1969–2014), by using literature factors. Source: own elaboration using water factors of Table 2 and electricity generation from nuclear reactors using fresh water for cooling from UNESA.

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 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

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

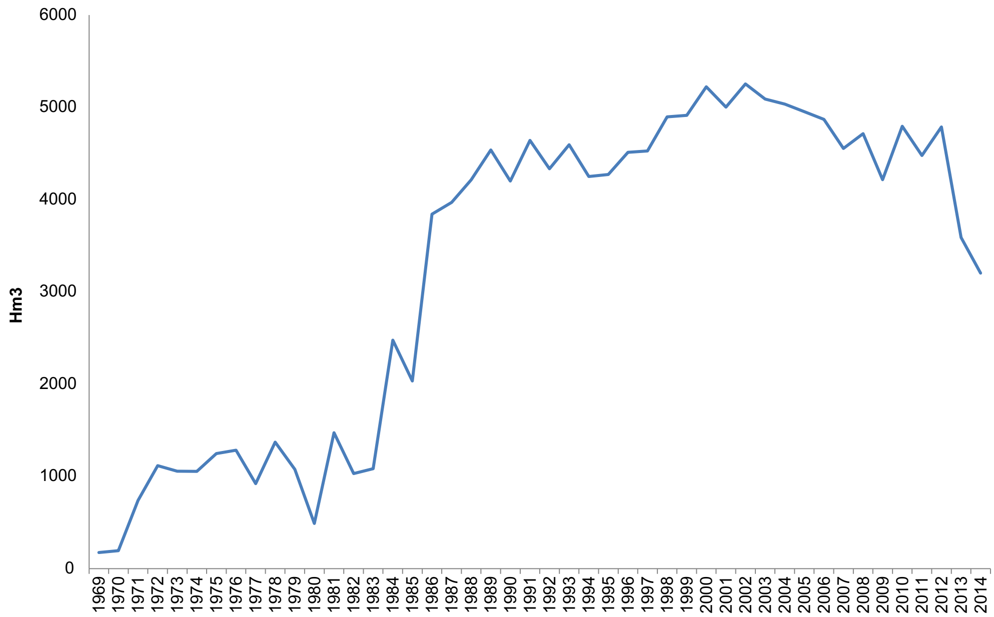


**Fig. 4.** Evolution of total Water Withdrawals of Spanish nuclear power plants (1969–2014), by using adjusted factors. Source: own elaboration using water factors of Table 3 and electricity generation from nuclear reactors using fresh water for cooling from UNESA.

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.

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

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

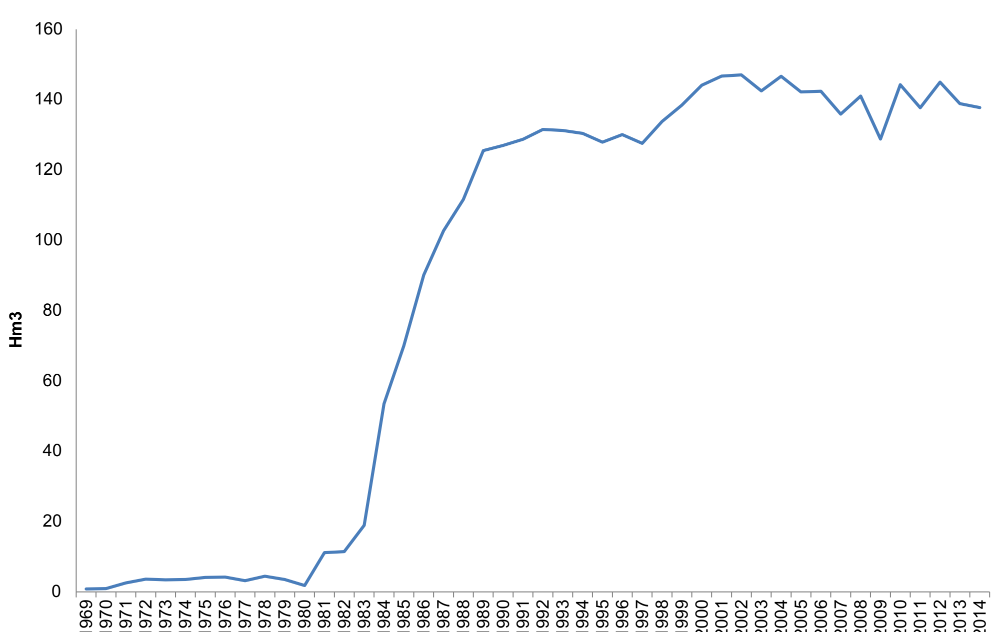


**Fig. 5.** Evolution of total Water Consumptions of Spanish nuclear power plants (1969–2014), by using adjusted factors Source: own elaboration using water factors of Table 3 and electricity generation from nuclear reactors using fresh water for cooling from UNESA.

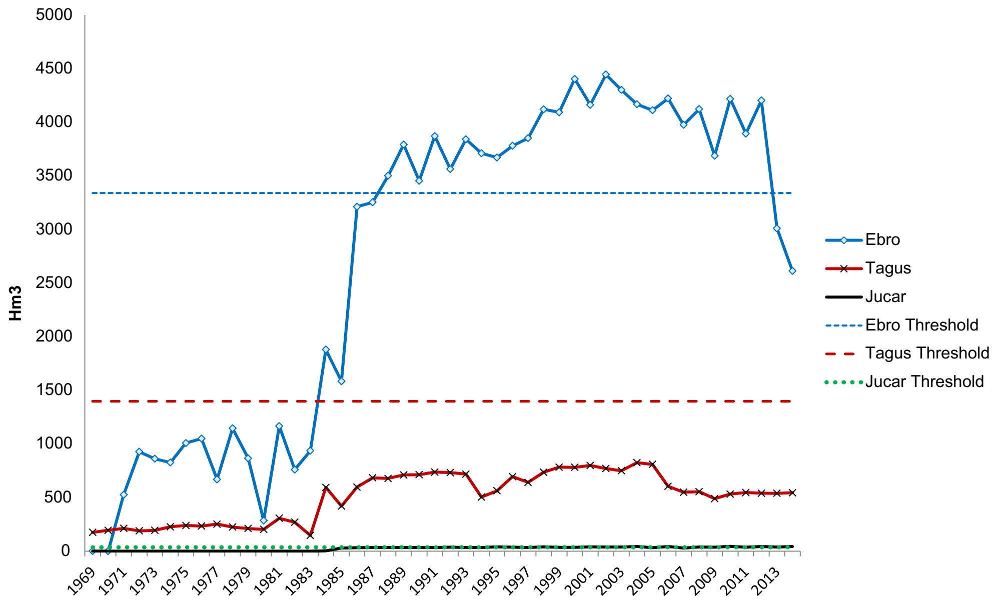


**Fig. 6.** Evolution of total Water Withdrawals of Spanish nuclear power plants by River Basins Source: own elaboration using water factors of Table 3 and electricity generation from nuclear reactors using fresh water for cooling from UNESA.

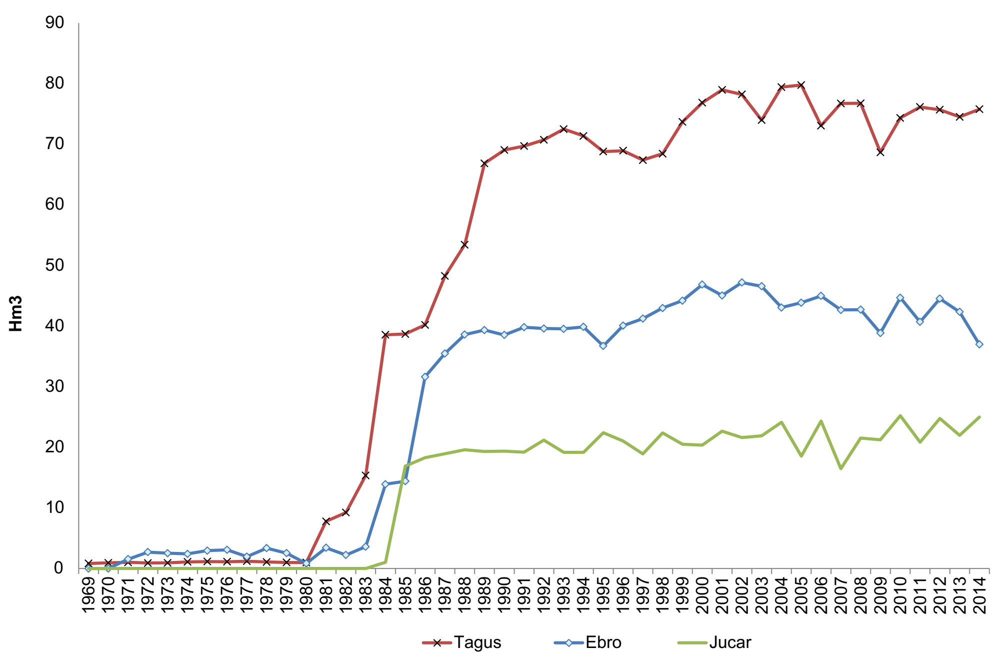


**Fig. 7.** Evolution of total Water Consumptions of Spanish nuclear power plants by River Basins Source: own elaboration using water factors of Table 3 and electricity generation from nuclear reactors using fresh water for cooling from UNESA.

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.

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 $hm^3$per 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*

[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 (2270 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

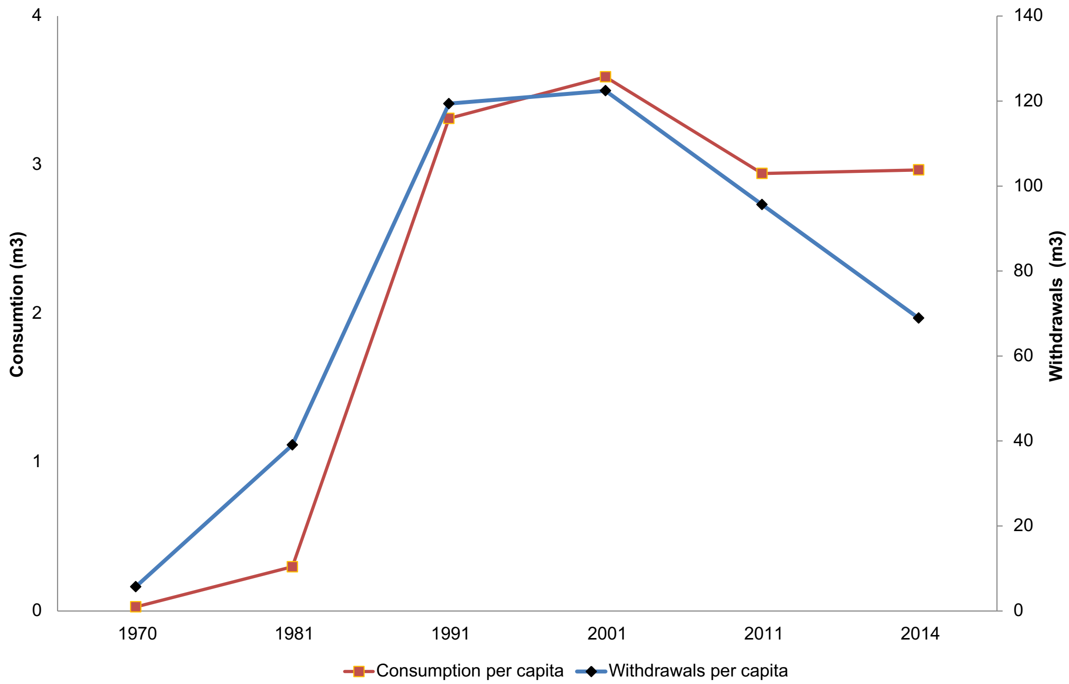


**Fig. 8.** Evolution of Water Consumptions (left axis) and Withdrawals (right axis) per capita of Spanish nuclear power plants.
Source: own elaboration.

*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 is around 3 m$^3$, water withdrawals per capita are around 70 m$^3$ in 2014.

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 among 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

[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.

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.

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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## Appendix A. Supplementary material

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.ecolecon.2017.04.032.

## References

Aldaya, M.M., Llamas, M.R., 2008. Water Footprint Analysis for the Guadiana River Basin.
Aldaya, M.M., Garrido, A., Llamas, M.R., Varela-Ortega, C., Novo, P., Casado, R.R., 2010. Water footprint and virtual water trade in Spain. Water policy in Spain 49–59.
Asensio, R.A., Martínez, E.B., García, E.G., 2000. La sostenibilidad del desarrollo: el caso valenciano. Universitat de Valencia.
Averyt, K., Fisher, J., Huber-Lee, A., Lewis, A., Macknick, J., Madden, N., Rogers, J., Tellinghuisen, S., 2011. Freshwater 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. Union of Concerned Scientists, Cambridge, MA November.
Barahona, M.J., Ramos, L.M., 1999. Los efluentes radiactivos en las centrales nucleares españolas (1980–1997): Situación en el marco internacional. Consejo de Seguridad Nuclear, Madrid.
Berbel, J., Gómez-Limón, J.A., 2000. The impact of water-pricing policy in Spain: an analysis of three irrigated areas. Agric. Water Manag. 43 (2), 219–238.
Brundtland, G., Khalid, M., Agnelli, S., Al-Athel, S., Chidzero, B., Fadika, L., ... Singh, M., 1987. Our Common Future (\'Brundtland report\'). UN.
Cazcarro, I., Duarte, R., Sánchez-Chóliz, J., 2013. Economic growth and the evolution of water consumption in Spain: a structural decomposition analysis. Ecol. Econ. 96, 51–61.
Cazcarro, I., Hoekstra, A.Y., Chóliz, J.S., 2014. The water footprint of tourism in Spain. Tour. Manag. 40, 90–101.
Cazcarro, I., Duarte, R., Sánchez-Chóliz, J., 2015a. Downscaling the grey water footprints of production and consumption. J. Clean. Prod.
Cazcarro, I., Duarte, R., Martín-Retortillo, M., Pinilla, V., Serrano, A., 2015b. How sustainable is the increase in the water footprint of the Spanish agricultural sector? A Provincial Analysis between 1955 and 2005–2010. Sustainability 7 (5), 5094–5119.
Consejo de Seguridad Nuclear, 1999. Las centrales nucleares españolas. 2ª. Consejo de Seguridad Nuclear, Madrid, p. 218.
De la Torre, J., del Mar Rubio-Varas, M., 2016. Nuclear power for a dictatorship: state and business involvement in the Spanish atomic program, 1950–85. J. Contemp. Hist. 51 (2), 385–411.
Delgado Martín, A., 2012. Water Footprint Of Electric Power Generation: Modeling its Use and Analyzing Options for a Water-Scarce Future. Doctoral dissertation. Massachusetts Institute of Technology.
Delgado, Anna, Rodriguez, Diego J., Sohns, Antonia A., 2015. Thirsty energy: understanding the linkages between energy and water. Live Wire Knowledge Notes Series. World Bank Group, Washington, DC No. 2015/41. [available online at: http://

[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.

documents.worldbank.org/curated/en/2015/01/24084417/thirstyenergyunderstanding-linkages-between-energy-water].
Dodder, R.S., 2014. A review of water use in the US electric power sector: insights from systems-level perspectives. Curr. Opin. Chem. Eng. 5, 7–14.
Duarte, R., Sanchez-Choliz, J., Bielsa, J., 2002. Water use in the Spanish economy: an input–output approach. Ecol. Econ. 43 (1), 71–85.
Duarte, R., Pinilla, V., Serrano, A., 2014. The water footprint of the Spanish agricultural sector: 1860–2010. Ecol. Econ. 108, 200–207.
Elimelech, M., Phillip, W.A., 2011. The future of seawater desalination: energy, technology, and the environment. Science 333 (6043), 712–717.
EPRI (Electric Power Research Institute), 2000. Water and Sustainability: U.S. Electricity Consumption for Water Supply & Treatment—The Next Half Century. EPRI, Palo Alto, CA, p. 1006787 2000.
EUROSTAT, 2014. [Data set] title: Annual freshwater abstraction by source and sector Code:env_wat_abs.
Feeley, T.J., Skone, T.J., Stiegel, G.J., McNemar, A., Nemeth, M., Schimmoller, B., ... Manfredo, L., 2008. Water: a critical resource in the thermoelectric power industry. Energy 33 (1), 1–11.
Flörke, M., Teichert, E., Bärlund, I., 2011. Future changes of freshwater needs in European power plants. Manag. Environ. Qual. 22 (1), 89–104 An International Journal.
Gunter, L., Gunter, P., Cullen, S., Burton, N., 2001. Licensed to Kill: How the Nuclear Power Industry Destroys Endangered Marine Wildlife and Ocean Habitat to Save Money. Grace Foundation and Norcross Foundation, February, New York.
Hoekstra, A.Y., 2008. The Water Footprint of Food.
Hoekstra, A.Y., Hung, P.Q., 2002. Virtual water trade. *A quantification of virtual water flows between nations in relation to international crop trade*. Value of Water Research Report Series. 11, p. 166.
IAEA (International Atomic Energy Agency), 2012. Efficient Water Management in Water Cooled Reactors. IAEA Nuclear Energy Series No. NP-T-2.6.
IAEA (International Atomic Energy Agency), 2015. Nuclear Power Reactors in the World 2015 Edition. Reference Data Series No. 2. IAEA, Vienna.
IEA (International Energy Agency), 2012. Water for Energy: is energy becoming a thirstier resource?
IEA (International Energy Agency), 2013. World Energy Outlook. [available online at: http://www.iea.org/publications/freepublications/publication/WEO2013.pdf].
Jägerskog, A., Clausen, T.J., Holmgren, T., Lexén, K., 2014. Energy and Water: the Vital Link for a Sustainable Future. SIWI, Stockholm (Report Nr. 33).
Jeswani, H.K., Azapagic, A., 2011. Water footprint: methodologies and a case study for assessing the impacts of water use. J. Clean. Prod. 19 (12), 1288–1299.
Kahrl, F., Roland-Holst, D., 2008. China's water–energy nexus. Water Policy 10 (S1), 51–65.
Kenny, J.F., Barber, N.L., Hutson, S.S., Linsey, K.S., Lovelace, J.K., Maupin, M.A., 2009. Estimated Use of Water in the United States in 2005. (No. 1344). US Geological Survey.
Kohli, A., Frenken, K., 2011. Cooling Water For Energy Generation and Its Impact on National-Level Water Statistics. Food and Agriculture Organization, Rome.
Macknick, J., Newmark, R., Heath, G., Hallett, K.C., 2012. Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature. Environ. Res. Lett. 7 (4), 045802.
Malik, R.P.S., 2002. Water-energy nexus in resource-poor economies: the Indian experience. International Journal of Water Resources Development 18 (1), 47–58.
Mekonnen, M.M., Hoekstra, A.Y., 2011. The green, blue and grey water footprint of crops and derived crop products. Hydrol. Earth Syst. Sci. 15 (5), 1577–1600.
Meldrum, J., Nettles-Anderson, S., Heath, G., Macknick, J., 2013. Life cycle water use for electricity generation: a review and harmonization of literature estimates. Environ. Res. Lett. 8 (1), 015031.
Morrison, J., Morikawa, M., Murphy, M., Schulte, P., 2009. Water scarcity & climate change. Growing Risks for Business and Investors. Pacific Institute, Oakland, California.
Palancar, María del Carmen, 2004. Proyecto TRACER: estudios de dispersión de contaminantes en ríos y embalses. Consejo de Seguridad Nuclear, Madrid, p. 279.
Perrone, D., Murphy, J., Hornberger, G.M., 2011. Gaining Perspective on the Water—Energy Nexus at the Community Scale.
Reddy, K.V., Ghaffour, N., 2007. Overview of the cost of desalinated water and costing methodologies. Desalination 205 (1), 340–353.
Rodriguez Casado, R., Garrido Colmenero, A., Llamas Madurga, M.R., Varela Ortega, C., 2008. La huella hidrológica de la agricultura española. Papeles de Agua virtual 2, 1–38.
Rodriguez, D., Delgado, A., DeLaquil, P. and A. Sohns. (2013).'Thirsty Energy: Securing Energy in a Water-Constrained World', World Bank working paper, June 2013.
Rost, S., Gerten, D., Bondeau, A., Lucht, W., Rohwer, J., Schaphoff, S., 2008. Agricultural green and blue water consumption and its influence on the global water system. Water Resour. Res. 44 (9).
Siddiqi, A., Anadon, L.D., 2011. The water–energy nexus in Middle East and North Africa. Energy Policy 39 (8), 4529–4540.
Spang, E.S., Moomaw, W.R., Gallagher, K.S., Kirshen, P.H., Marks, D.H., 2014. The water consumption of energy production: an international comparison. Environ. Res. Lett. 9 (10), 105002.
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].
Tello, E., Ostos, J.R., 2012. Water consumption in Barcelona and its regional environmental imprint: a long-term history (1717–2008). Reg. Environ. Chang. 12 (2), 347–361.
Torcellini, P.A., Long, N., Judkoff, R., 2003. Consumptive Water Use for US Power Production.
Vanham, D.A.V.Y., Bidoglio, G., 2014. The water footprint of Milan. Water Sci. Technol. 69 (4), 789–795.
Velazquez, E., 2006. An input–output model of water consumption: analysing intersectoral water relationships in Andalusia. Ecol. Econ. 56 (2), 226–240.
Vicente-Serrano, S.M., 2006. Spatial and temporal analysis of droughts in the Iberian Peninsula (1910–2000). Hydrol. Sci. J. 51 (1), 83–97.
Vickers, A., 2001. Handbook of Water Use and Conservation. WaterPlow Press, Amherst, MA.
Wackernagel, M., Rees, W.E., 1997. Perceptual and structural barriers to investing in natural capital: Economics from an ecological footprint perspective. Ecol. Econ. 20 (1), 3–24.
WWAP (United Nations World Water Assessment Programme), 2014. The United Nations World Water Development Report 2014:Water and Energy. UNESCO, Paris.
Zhou, Y., Tol, R.S., 2005. Evaluating the costs of desalination and water transport. Water Resour. Res. 41 (3).
Zohuri, B., 2016. Nuclear energy for hydrogen generation: Through intermediate heat exchangers. Springer.

# 4. Paper III

*water*

MDPI

*Article*

# The River's Light: Water Needs for Thermoelectric Power Generation in the Ebro River Basin, 1969–2015

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**Abstract:** Water is essential for almost all energy processes. This paper analyses the evolution of the cooling water needs of thermal power plants in the Ebro River basin, the largest contributor to the Spanish electricity grid, over the period 1969–2015. It makes several contributions. First, the cooling water needs for the plants are estimated. Second, these water requirements are compared to other water-using activities in the region. Third, a long-term water-use efficiency analysis is carried out. Finally, water-saving measures are proposed to counter possible future water scarcities. The results show that thermoelectric water consumption per capita is around 7 $m^3$/year. Estimated future thermal power generation water withdrawals (around 500 $m^3$ per capita/year) might compromise flows for other water uses in periods of drought.

**Keywords:** thermoelectricity; water consumption; water withdrawals; cooling technologies; Ebro River

## 1. Introduction

Water is essential for almost all energy generation processes. Electrical power production is one of the largest water-intensive activities worldwide [1]. Growing global concern about this link, known as the 'water-energy nexus', has led to an increase in the number of related studies in the international literature in recent years [2–6]. Most of the research focuses on regions vulnerable to drought, such as Africa, the Middle East, and some areas in the U.S. [7–12]. Other studies examine areas of high population density, such as China, where electricity and, hence, water demand, is expected to rise critically [13–15]. Other studies assess the electricity mix under water scarcity scenarios [16–18].

Water scarcity episodes and heat waves appear to be increasing due to climate change; many areas are already suffering from both these climatic effects, even simultaneously [19]. Similarly, future projections indicate that electricity demand will continue to rise because of population growth. In fact, water is now a constraining factor for power plants across the globe [20]. Given these forecasts, many international institutions, notably the International Energy Agency and the World Bank, have begun to address this issue to ensure the future provision of water and energy. Every year, the International Energy Agency publishes the 'World Energy Outlook' (for more information, see [21]), which provides critical analyses and information on energy demand and supply trends and their implications for energy security, environmental protection and economic development. The World Bank in 2014 launched the 'Thirsty Energy' (for more information, see [22]) initiative to identify interdependencies in the water and energy sectors, to address water and energy challenges, to design evaluation and resource management tools to help coordinate decision-making, and to promote sustainable development [20,23]. Other institutions extensively reporting on the water-energy nexus are the US Department of Energy (DOE), the Energy Research Centre of the Netherlands (ECN), and the World Policy Institution [24,25].

The relation between water and energy tends to bring to mind hydroelectric facilities. However, not only hydropower plants need water to function. Thermoelectric-power plants, fueled by coal, fuel-oil, gas, and uranium, also need water—freshwater for the most part. For example, in 2005, thermoelectric production accounted for 41% of freshwater withdrawals in the United States, surpassing even agriculture [26]. Unlike hydroelectric power plants, thermoelectric facilities boil water to create steam to spin turbines that generate electricity. Conventional thermal and nuclear power plants operate on the same principle, but they differ in the way they heat the water. Whereas conventional thermal power stations obtain heat by burning fossil fuels, nuclear power plants obtain it through nuclear reactions. Later, the heat must be dissipated in cooling systems to allow the facilities to operate correctly. The temperature needed to produce electricity differs depending on fuel type and, consequently, each type of thermal power plant requires different amounts of water for cooling. Cooling is the activity that requires the largest amounts of water in the process and, among the current thermoelectric generating technologies, the water needs of nuclear power plants are the largest per megawatt hour generated [27]. In turn, the different types of cooling systems (i.e., wet or dry) require different quantities of water. Thus, whereas dry-cooling systems require minimum volumes of water to cool, the water needs of wet-cooling systems vary greatly. The main wet-cooling systems' designs are open-loop (or once-through cooling) and cooling towers. Open-loop systems remove water from a body of water, pass it through a steam condenser, and subsequently discharge it into the same body of water at a higher temperature (usually limited by environmental law). By contrast, cooling towers expel the waste heat from the cooling water into the atmosphere. As a result, open-loop cooling systems involve higher water withdrawals than cooling towers, while cooling towers have higher water consumption volumes [28]. It is essential to understand the distinction between water withdrawals and water consumption in power generation. According to the US Geological Survey (USGS), water withdrawals are the total volume of water removed from a source (even if it is later partially returned to the flow), and water consumption is the amount of withdrawn water lost to evaporation [26]. Several studies on the energy-water nexus link these concepts to the terminology of the water footprint initially addressed by Hoekstra, among others [29–35]. In this context, the blue water footprint corresponds to the amount of water consumed during the cooling process. Similarly, water withdrawals are indirectly related to the grey water footprint of thermoelectric power plants (see [36] for more information).

This study assesses the water needs for thermoelectric power generation in the Ebro River basin, the most important long-term contributor to Spanish electricity generation. By calculating the water withdrawals and consumption for thermoelectricity generation in the Ebro River basin, this study increases the knowledge about the relationship between water and energy in Spain and bridges a gap in the literature on the matter in this country. There is some isolated research on the matter [37,38], but studies rarely take a long-term perspective and are limited to single technologies [39]. In addition, unlike in other countries, the water-energy nexus is not yet a priority in the Spanish policy agenda. A lack of official statistics and inconsistency in the information sources on the water–energy nexus in Spain could be behind this surprising fact [40]. Furthermore, to increase social awareness of the importance of water as an energy resource, a sectoral comparison and an analysis of the water efficiency of the plants in the Ebro basin is carried out. Finally, an evaluation on the different combinations of power generation technologies and cooling systems is carried out, to offer possible water-saving solutions to future water scarcity scenarios. To sum up, this analysis provides a tool for better decision-making in the implementation of integrated water and energy policies.

How much water is used for thermal power generation in the Ebro River basin? What are the effects on water of the different electricity production methods? Is water really an opportunity cost for alternative uses in this region? Will lack of water limit the region's energy production in the future? These are some of the issues the present study addresses.

The paper is organized as follows. Section 2 highlights the importance of the Ebro River basin for Spain as a whole. Section 3 describes the methodology and data sources. Section 4 presents the main findings. The discussion and future research proposals are set out in Section 5. Finally, Section 6 summarizes the main conclusions.

## 2. The Ebro River Basin

Spain has a long history of water management. The first attempt to regulate water use in Spain was the Water Law of 1866, which laid down the basic principles of the rational use of shared water resources. The Water Law of 1866 was never passed due to the revolutionary period that resulted in the First Republic. However, the subsequent Water Law of 1879 included almost all the basic principles of the first one. Spanish water bodies (rivers, lakes and streams) are grouped by river basins, with regulatory agencies, the Hydrographic Confederations, created in the early 20th century [41]. The first Spanish hydrographic confederation was the Hydrographic Confederation of the Ebro, created in 1926. In 1926, this Hydrographic Confederation was named *Confederación Sindical Hidrográfica del Ebro*; its name was later modified to its present title [42]. Geographically, the Ebro River basin is the largest in Spain, representing 17.3% of the national territory and covering the area of nine autonomous communities. Due to its extension, the climate in the basin is not at all homogeneous, which is reflected in parameters such as rainfall, temperature, wind and water balance [43,44].

The Ebro River basin makes the largest water contribution of all the basins to the country's electricity generation, considering all the generating technologies, including hydroelectricity. The use of water for hydropower generation has been analyzed [45]. However, the volume of water needed for thermoelectricity has been overlooked in the literature. Looking just at thermoelectricity, there are eight conventional thermal and nuclear power plants operating in the Ebro River basin, the first dating from the 1950s. There are isolated cases of thermal power stations prior to 1950, but they had a very local characters as they were dedicated to supplying electricity to mining installations and villages. This is the case for the Utrillas and Ariño thermoelectric power plants in Aragon (See [46], pp. 240–248). Figure 1 shows the locations of the thermoelectric plants (conventional and nuclear) in the basin. The great variety of generation technologies, and different cooling systems, installed in the facilities make the Ebro River basin especially appropriate for assessing the freshwater needs of thermoelectric power generation.

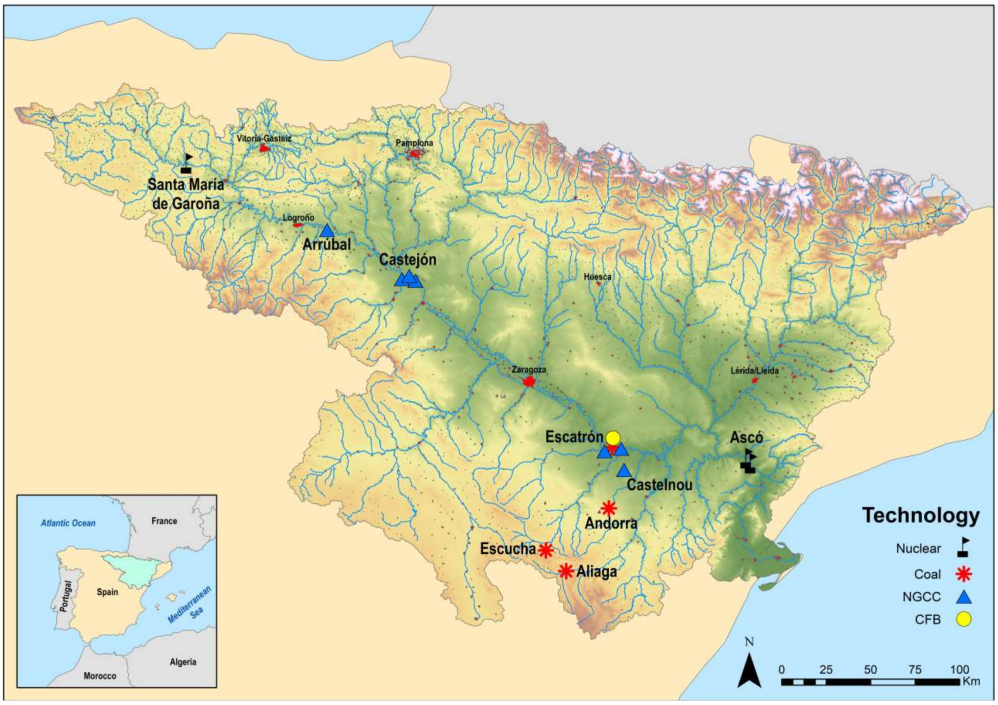



**Figure 1.** Thermoelectric power plants in the Ebro River basin by type of technology, 1950–2017. Note: NGCC = Natural Gas Combined-Cycle; CFB = Circulating Fluidized Bed. Source: own design using data from the Ebro Hydrographic Confederation and the Spanish National Geographic Institute.

Approximately 15% (22,131,246 megawatt hours) of the total thermoelectricity generation in Spain uses water passing through the Ebro River basin. This percentage was even higher some years ago, prior to the closure of the Garoña nuclear power plant and the low output of the combined-cycle power plants in the region from 2010 onwards. In fact, thermoelectric generation in the Ebro River basin multiplied almost 30 times from 1969 to 2000 (from 988,554 to 28,886,000 megawatt hours), and represented more than 20 percent of national thermoelectric generation in the 1980s (Figure 2). Thermal power generation in the river basin reached its historical record in 1985, when it provided more than 25% of domestic thermoelectric production. Until 1969, only coal plants used the river for thermoelectric production. Then, a nuclear power plant, Garoña, was connected to the grid, followed by two more in Ascó, which meant an increase in water needs for cooling. Finally, in the early 2000s, the first combined-cycle power plants began operation, which again raised water needs. Thus, at its maximum, in 2008, twelve thermal power plants (coal, gas, and uranium), producing around 39 TWh, depended on Ebro River water (Figure 3). The Ebro River basin is crucial to Spanish electricity generation, which, in turn, underlines the importance of water as an energy resource in this territory.

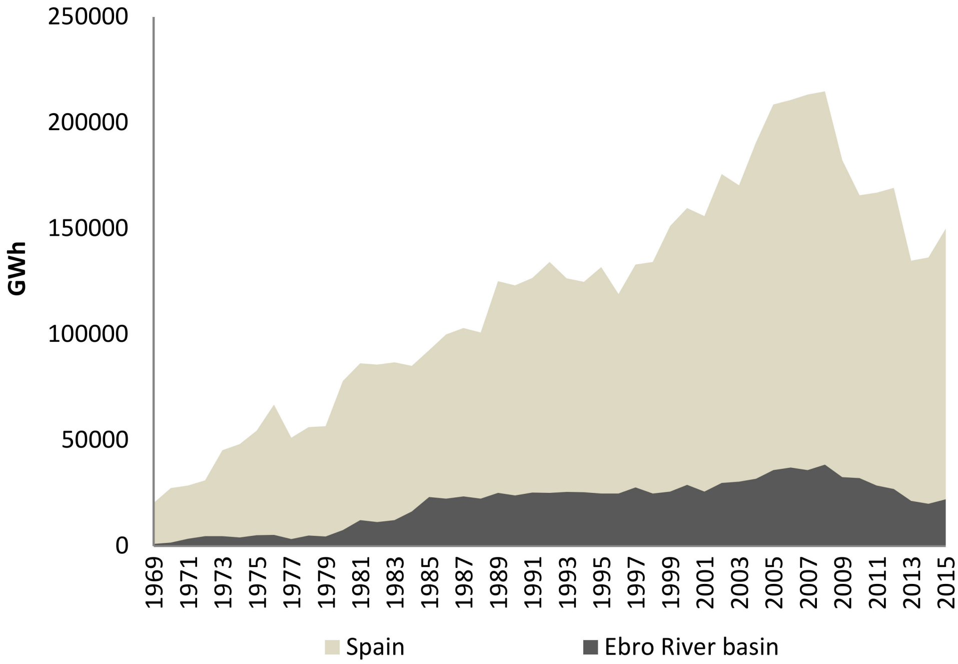



**Figure 2.** Evolution of thermal power generation in the Ebro River basin within the Spanish thermal power generation system, 1969–2015. Source: own design using data from Spanish Association of Electrical Industry (UNESA) and Red Eléctrica de España (REE).

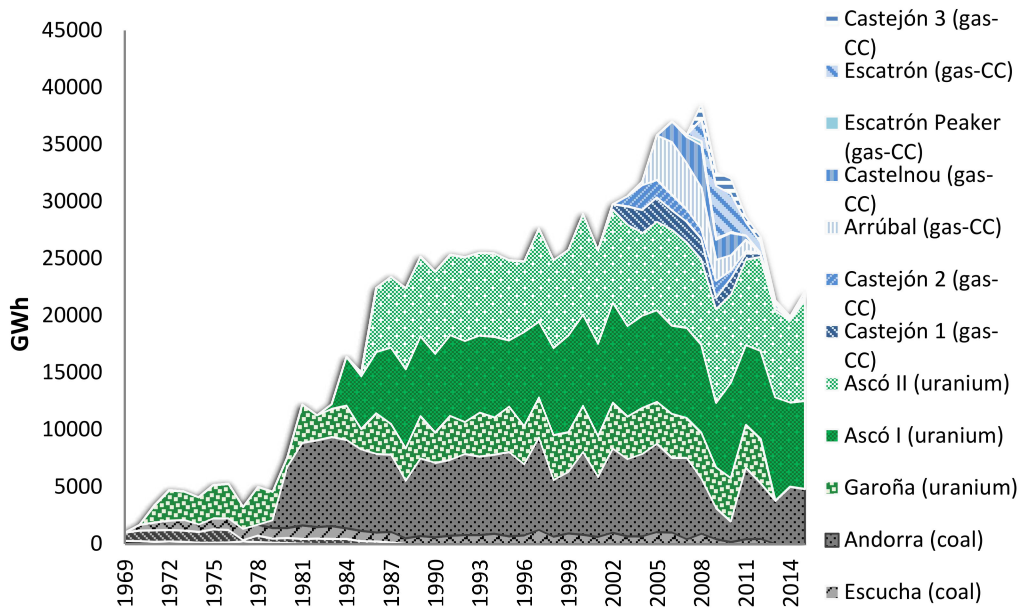



**Figure 3.** Evolution of thermal power generation by power plant and technology in the Ebro River basin, 1969–2015. Source: own design using UNESA's and REE's annual reports.

## 3. Materials and Methods

### *3.1. Water Needs for Cooling*

The thermoelectric power plants withdrawing fresh water in the Ebro River basin during the period 1969–2015 are identified, classified by type of fossil fuel and cooling system (Table 1). Historical and technical information about the Escatrón, Escucha and Teruel thermoelectric power stations is at [46]. Similarly, technical information on the Castejón combined cycle thermal power plant can be found in the environmental impact study published in 2003 by ELEREBRO (now EDP HC Energía). The complete report can be found at [47]. Furthermore, the Spanish Ministry of Industry and Energy published a document on the mining industry in Teruel and Catalonia, which provides technical data from the coal-fired power plants of Andorra, Escucha, and Escatrón. This document can be found at [48]. This classification is crucial, as each thermoelectric technology and cooling system have different water requirements in terms of both withdrawals and consumption.

The thermoelectric power plants in the Ebro River basin work with two cooling technologies: once-through (or open-loop) systems and cooling towers. However, some thermoelectric power stations located in areas of high water stress use air-cooled systems (or dry-recirculating cooling systems) as an alternative, to reduce water demands. These plants, operating with air-cooled condensers (Escucha and Castelnou), are omitted from this analysis, as their cooling systems need little or no water to operate.

To calculate water needs for thermal power generation, it is necessary to obtain data on electricity generation and water intensity factors (both water withdrawals and consumption). Concerning electricity generation, the annual energy output data for the thermal power facilities comes from the UNESA (Spanish Association of Electrical Industry) and REE (Red Eléctrica de España) annual reports for the period 1969–2015. The data on the water-energy nexus in Spain are still limited and, in many cases, the various sources of information are inconsistent [40]. An extensive search provided, in some cases, data from primary sources and from the environmental reports of the electricity companies for most of the power plants currently operating. In other cases, the international literature has provided some information on technical water factors, but it has been impossible to obtain more extensive data (see Table 2). There is a vast body of international literature on the calculation of technical water coefficients for the various types of power generation and cooling technologies. One of the first comprehensive references is [49], although since then many others have emerged [50–52].

**Table 1.** Classification of thermoelectric power plants located in the Ebro River basin by type of technology and cooling system.

| Power Plant | Technology | Installed Power Capacity (MW) | Cooling System | Water Supply | Operation |
|---|---|---|---|---|---|
| Aliaga | Coal | 45 | Cooling towers | Guadalope and Val Rivers | (1952–1981) |
| Escatrón | Coal | 172.5 | Once-through | Ebro River | (1953–1987) |
| Escucha | Coal | 160 | Air-cooled condensers | — | (1970–2012) |
| Andorra | Coal | 1101.4 | Cooling towers | Calanda Dam | (1979–present) |
| Garoña | Nuclear | 466 | Once-through | Sobrón Reservoir | (1971–2012) |
| Ascó I | Nuclear | 1032.5 | Cooling tower | Ebro River | (1984–present) |
| Ascó II | Nuclear | 1027.21 | Cooling tower | Ebro River | (1986–present) |
| Escatrón | NGCC | 818 | Cooling towers | Ebro River | (2008–present) |
| Escatrón Peaker | NGCC | 277 | Cooling towers | Mequinenza Dam | (2007–present) |
| Castelnou | NGCC | 800 | Air-cooled condensers | — | (2006–present) |
| Arrúbal | NGCC | 800 | Cooling towers | Ebro River | (2005–present) |
| Castejón 1 | NGCC | 429.24 | Cooling towers | Ebro River | (2002–present) |
| Castejón 2 | NGCC | 386.10 | Cooling towers | Ebro River | (2003–present) |
| Castejón 3 | NGCC | 426.11 | Cooling towers | Ebro River | (2008–present) |

Note: NGCC = Natural Gas Combined Cycle. Source: own design using data from UNESA's and REE's annual reports, BOE, technical reports of the electricity companies, Spanish Nuclear Forum, and Spanish Nuclear Security Council.

**Table 2.** Average water use factors for thermal power plants by type of technology and cooling system in the Ebro River basin.

| Power Plant | Technology | Cooling System | Withdrawal ($m^3$/MWh) | Source | Consumption ($m^3$/MWh) | Source |
|---|---|---|---|---|---|---|
| Aliaga | Coal | Cooling tower | 3.80 | (a) | 2.60 | (a) |
| Andorra | | Cooling tower | 2.31 | (b),(c) | 1.11 | (b),(c) |
| Escatrón | | Once-through | 137.60 | (a) | 0.95 | (a) |
| Castejón 1 | NGCC | Cooling tower | 1.35 | (b),(c) | 0.97 | (b),(c) |
| Castejón 2 | | Cooling tower | 1.72 | (b),(c) | 0.97 | (b),(c) |
| Castejón 3 | | Cooling tower | 1.50 | (b),(c) | 1.00 | (b),(c) |
| Arrúbal | | Cooling tower | 1.72 | (b),(c) | 0.57 | (b),(c) |
| Escatrón Peaker | | Cooling tower | 0.97 | (a) | 0.78 | (a) |
| Escatrón | | Cooling tower | 0.97 | (a) | 0.78 | (a) |
| Ascó (units I-II) | Nuclear | Cooling tower | 103.58 | (b),(c) | 1.04* | (b),(c) |
| Sta. María Garoña | | Once-through | 154.13 | (b),(c) | 1.02 | (a) |

Notes: NGCC = Natural Gas Combined-Cycle; (a) [50]; (b) Real data; (c) Environmental Report. *This average factor has been estimated on the basis of primary information sources. However, it is questionable as its value is much lower than the literature suggests should be the case. Source: own design using real data, environmental reports and [50]. Appendix A completes the extensive data search.

The approach followed for performing the analysis in this study is similar to that followed by [39] in calculating the water needs of Spanish nuclear power plants.

The time periods (years) are designated as $t$ and the thermoelectric power stations as $n$. $WCF^n$ is the amount of water needed to produce a unit of electricity by power plant $n$, while $WWF^n$ is the intensity factor for water withdrawals by power plant $n$. Thus, water consumption (WC) by each power plant $n$ in year $t$ can be calculated by multiplying the intensity factor and the electricity generated (EG). A similar process is followed to obtain water withdrawals (WW). The difference between water withdrawal and consumption is return flow. Formally:

$$WC_t^n = WCF_t^n \times EG_t^n \tag{1}$$

and

$$WW_t^n = WWF_t^n \times EG_t^n \tag{2}$$

Thus, for a given year, the total amounts are:

$$\text{Total } WC^n = \sum^n (WCF^{\,n} \times \; EG^n) \tag{3}$$

and

$$\text{Total } WW^n = \sum^n (WWF^{\,n} \times \; EG^n) \tag{4}$$

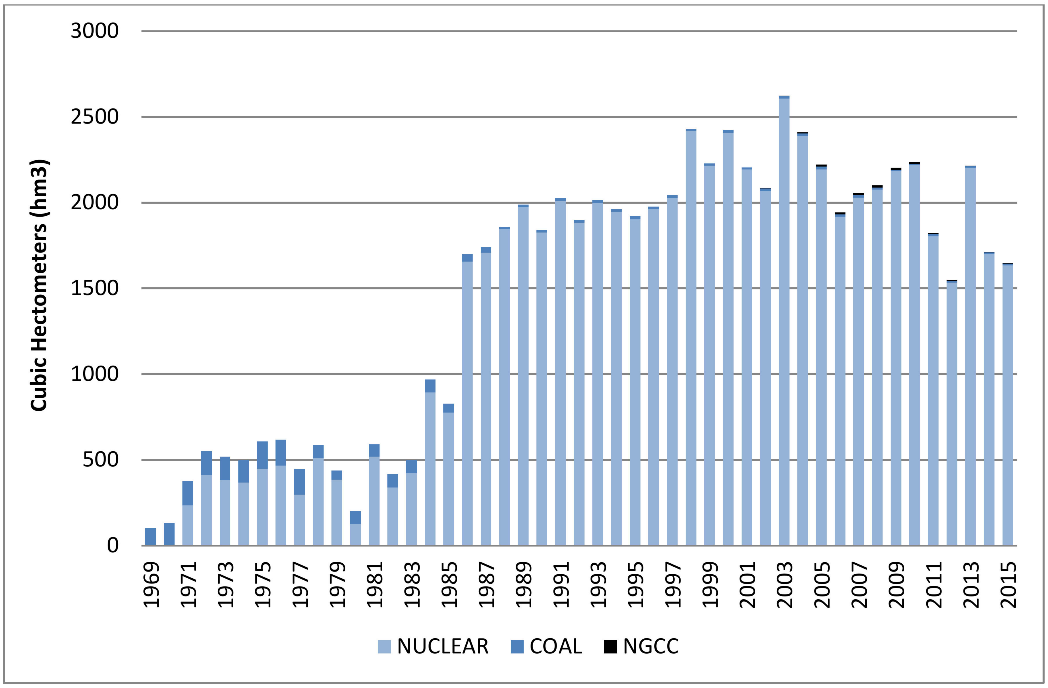
Therefore, this approach differentiates between water consumption and water withdrawals, since not all the water removed by thermoelectric plants evaporates and is lost. It is crucial to consider total withdrawals, as the facilities require large volumes of water to constantly pass through their systems to function properly. Therefore, these volumes of water could represent an opportunity cost for other productive sectors in the river basin (agriculture, domestic and urban uses, among others) under water stress conditions.

### *3.2. Scenario Analysis*

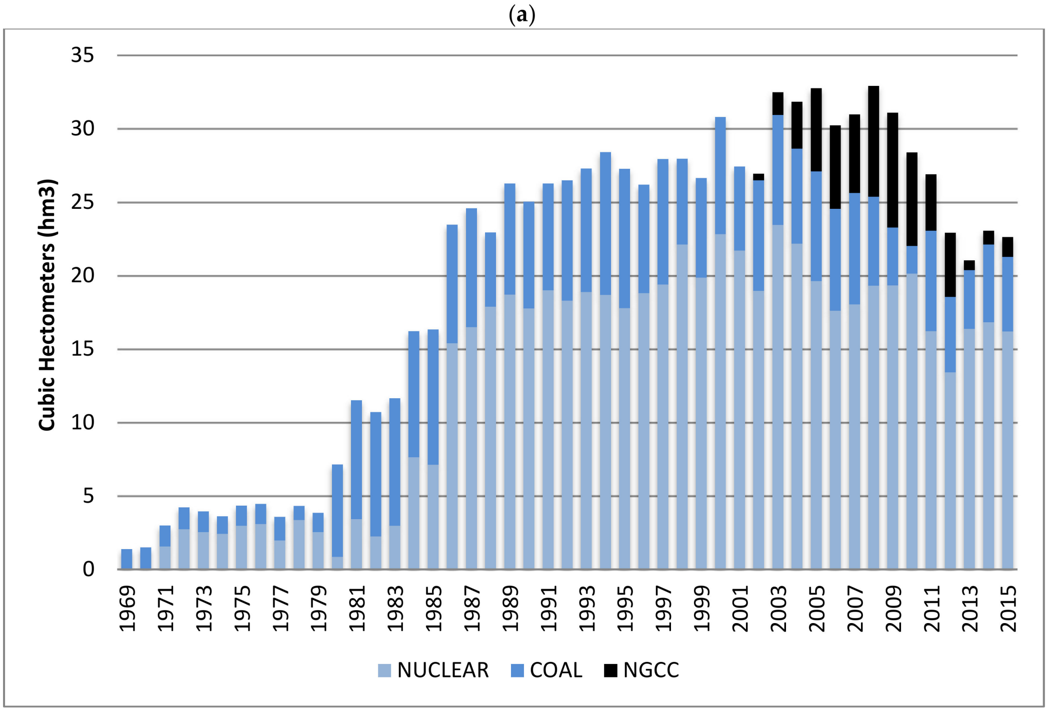
To perform the scenario analyses, all the thermoelectric power plants operating in the river basin (including those using air-cooled condensers) were considered. First, it was necessary to obtain the current energy output data and capacity factors for each power plant. These data allowed the estimation of the maximum attainable energy output. When this maximum output was obtained, the maximum water withdrawals and consumption (in other words, the maximum water needs of a power plant operating at 100% of capacity) could be calculated by multiplying the maximum energy output and the corresponding average technical water coefficient (see Table 2). Finally, after analyzing all possible combinations that satisfy the restrictions imposed (namely, the maximum nuclear output), the best combinations could be chosen for each scenario.

## 4. Results

Applying Formulas (3) and (4) we see that total water withdrawals and consumption in the basin follow the same trend as thermoelectricity production over time (see Figure 3). Thus, whereas water withdrawals range from 100 to 2600 $hm^3$ cubic hectometers over the period, reaching peak volumes in 2003, water consumption ranges through a minor order of magnitude (i.e., from 1.3 to 33 $hm^3$). The greatest increases took place in the 1980s, mainly due to the beginning of operations at the Ascó nuclear power plant. More specifically, Figure 4a,b drill further down and show the share of water withdrawals and consumption by generation technology over time. Figure 4a indicates that most water withdrawals were due to the operation of the nuclear power plants (more than 60% from 1971). By contrast, water withdrawals from coal-fired power plants were important only in the first half of the period, and water withdrawals from combined-cycle power stations are almost non-existent compared to the other generating technologies. There are two explanations for this. On the one hand, combined-cycle power plants use less water (see Table 2), and on the other, many of the plants were under-utilized due to low electricity demand after 2012. Figure 4b shows that, from the 2000s, nuclear once again consumed the most water, followed by coal and natural gas combined-cycle technology.




(**a**)




(**b**)

**Figure 4.** (**a**) Evolution of total water withdrawals by type of technology in the Ebro River basin, 1969–2015. Source: own design (see 'Data File S1' in Supplementary Materials). (**b**) Evolution of total water consumption by type of technology in the Ebro River basin,1969–2015. Source: own design (see 'Data File S1' in Supplementary Materials).

The population of the Ebro River basin is around 3.2 million, i.e., 37 inhabitants per square kilometer [53]. The blue water footprint per capita (the result of dividing water consumption from thermal power plants by population) oscillated around 7 $m^3$/year between 2013 and 2015. The Ebro Hydrographical Confederation provides data on the theoretical demands and consumption of the most important productive sectors in the basin (Table 3), which, interestingly, excludes the thermoelectricity sector. Thus, a sectoral comparison can be made between the above results and the other economic activities to rank the different uses of water in the region.

**Table 3.** Comparison between water withdrawals and consumption by type of productive activity in the Ebro River basin, 2010–2015.

| Productive Activity | Withdrawals ($hm^3$/year) | Consumption ($hm^3$/year) |
|---|---|---|
| Agricultural uses | 7681 | 4574 |
| Water for thermoelectricity (this study) | 1550–2234 | 22–28 |
| Urban water supply | 358 | 71 |
| Industrial uses (excluding power sector) | 147 | 29 |
| Livestock | 57 | 11 |

Source: For thermoelectricity requirements, see text. All other figures are theoretical amounts taken from the Ebro Hydrographic Confederation website [53].

According to these figures, water removals for thermal power generation in the basin moved between 1550 and 2234 $hm^3$ during 2010–2015. Thus, the thermoelectric power sector is the second thirstiest in the basin, just behind agriculture. Conversely, water consumption from thermal power stations reached 28 $hm^3$ in the same period. Thus, the thermoelectric power sector ranks fourth, almost equaling industrial use.

The measurement of the evolution of water intensity (i.e., the cubic meters needed to produce 1 MWh) in thermal power stations may be a useful political tool with which to argue for more rational use of water for cooling in the Ebro River basin. This metric, known as 'technological water intensity' in the international literature, is defined as the measure of the overall efficiency of water consumption (or withdrawal) for energy production [54]. Thus, increases in the ratio ($\frac{m^3}{MWh}$) lead to a loss of water efficiency, as more cubic meters are needed to generate a unit of electricity, and vice versa. Figure 5 shows a general downward trend in terms of withdrawals and consumption. Specifically, the ratio for water withdrawals rose between 1969 and 1972, reached its peak in 1975 (around 145 $m^3$/MWh), and remained stagnant until 1979. Thereafter, from 1980, the ratio plummeted to its lowest value (29 $m^3$/MWh). This major drop is explained by the commissioning of the Andorra coal-fired power plant, with its 1101.4 MW of installed power and cooling towers, which involved a substantial increase in thermoelectric production and very limited water withdrawals due to its cooling system. The ratio increased again in the 1980's, due to the beginning of operations at the Ascó nuclear power plant, which caused higher volumes of water withdrawals (see Table 2 above). From that point, the ratio fluctuated, but remained below 105 $m^3$/MWh. By contrast, the water consumption ratio fluctuated little, and around much lower values (i.e., between 0.8 and 1.4 $m^3$/MWh), as expected. However, in some cases, the understanding of this ratio may not be as simple as mentioned above. For example, regional electricity demand can increase or decrease, such that factors affecting the ratio may lead to an overall increase or decrease in water requirements.

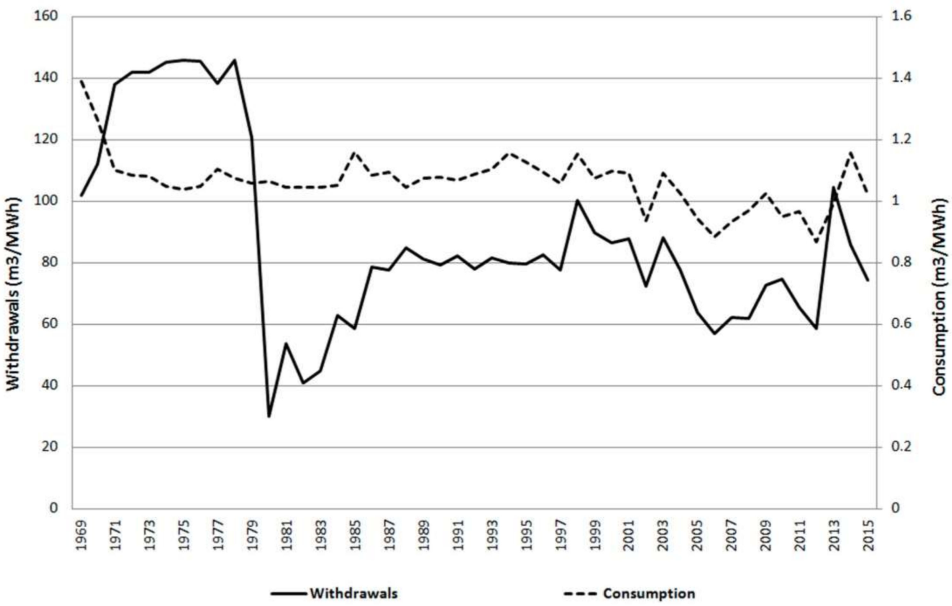



**Figure 5.** Evolution of technological water intensity in terms of water withdrawals (left axis) and water consumption (right axis) of thermal power stations in the Ebro River basin, 1969–2015. Note: The Escucha and Castelnou coal-fired power stations-using air-cooled condensers-are excluded. Source: own design (see 'Data File S1' in Supplementary Materials).

These results suggest that substantial water savings could be achieved by shutting down the two generation units of the Ascó nuclear power plant, although their electrical power would have to be supplied by other types of plants (e.g., coal or natural gas combined-cycle power stations). Given that some combined-cycle plants in the Ebro River basin are under-utilized, a reasonable option would be to determine whether these plants, working at maximum power, could replace the output of the Ascó nuclear power plant. For this purpose, the maximum output, water withdrawals and water consumption have been estimated on the basis of actual output data, the capacity factors and the technical water coefficients of each thermal power plant operating (see Table 4).

**Table 4.** Estimation of the maximum output, water withdrawals and water consumption attainable by the thermal power plants of the Ebro River basin.

| Power Plant | Actual Output (GWh) | (1) Capacity Factor (%) | Maximum Output (GWh) Estimated from (1) | Maximum Water Withdrawals ($hm^3$) | Maximum Water Consumption ($hm^3$) |
|---|---|---|---|---|---|
| Ascó (all units) | 15,850 | 97.6 | 16,240 | 1682 | 16.9 |
| Andorra (all units) | 4,459 | 49.1 | 9082 | 21 | 10 |
| Castejón 1 | 337 | 9.3 | 3623 | 4.9 | 3.5 |
| Castejón 2 | 7 | 0.2 | 3500 | 6 | 3.4 |
| Castejón 3 | 387 | 10.6 | 3650 | 5.5 | 3.7 |
| Arrúbal (all units) | 163 | 2.4 | 6795 | 11.7 | 3.9 |
| EscatrónPeaker | 27 | 1.1 | 2454 | 2.4 | 1.2 |
| Escatrón | 65 | 0.9 | 7222 | 7 | 5.6 |
| Castelnou * | 86 | 1.3 | 6615 | 0 | 0 |

Notes: The data refer to figures for year 2015, except for Castejón 2 and the two generation units of the Arrúbal combined-cycle power plant, which show data for 2013 and 2014, respectively. Due to low electricity demand, the production of these plants in later years was zero. The Aliaga and Escatrón coal-fired power stations and the Garoña nuclear power plant have been omitted; they have already been dismantled. * This power plant is cooled via air-condensers and its water requirements are zero or almost zero. Therefore, a technical water coefficient of zero has been applied. (1) This is the ratio between actual production and possible or maximum production that the plant could reach operating at nominal power. Source: own design based on the reports of the Spanish Electricity System published by Red Eléctrica de España (REE).

Table 4 shows that, although the two generation units of the Ascó nuclear power plant are operating at almost their maximum (i.e., utilization ratios very close to 100%), the Andorra coal-fired power station is barely reaching 50% of its maximum. As previously mentioned, the other power plants (the combined-cycle power stations) are under-utilized, with ratios close to 10% and even lower. The maximum output of the Ascó nuclear power plant is around 16,240 GWh. Thus, different scenarios could come into play if the other thermal power plants began to operate at full capacity to replace nuclear production; we may face a future without nuclear power plants. These scenarios are detailed below.

Scenario 1. A mix of coal-fired and combined-cycle power plants (without Castelnou).

This scenario covers the three best combinations of coal-fired and combined-cycle power plants (see Table 5) which, operating at maximum capacity, can reach an output equal to or greater than 16,240 GWh, while consuming little water. Therefore, this set of power plants would be enough to cover predicted electricity supply if the existing nuclear power plants in the Ebro River basin closed down.

**Table 5.** Set of combinations from Scenario 1.

| Power Plants | Maximum Output (GWh) | Maximum Water Withdrawal ($hm^3$) | Maximum Water Consumption ($hm^3$) |
|---|---|---|---|
| C.1 (Andorra, Escatrón) | 16,304 | 28 | 15.7 |
| C.2 (Andorra, Castejón 1, Castejón 3) | 16,357 | 31.4 | 17.2 |
| C.3 (Andorra, Arrúbal, Escatrón Peaker) | 18,332 | 35 | 15.9 |

The water withdrawal combinations possible in this scenario use around 2% of the water withdrawals from nuclear power plants (1682 $hm^3$). By contrast, water consumption is over 90% in the three cases analyzed. Furthermore, the second combination of power plants (i.e., Andorra, Castejón 1, and Castejón 3) is particularly important; water consumption here slightly exceeds that of the Ascó nuclear power plants (17.2 versus 16.9 $hm^3$).

Scenario 2. A mix of coal-fired and combined-cycle power plants (with Castelnou)

More water-saving combinations are possible based on the water requirements of each cooling system. The Castelnou combined-cycle power plant (with a maximum output very similar to that of the Escatrón and Arrúbal power stations) cools through air-condensers and, hence, its water requirements are almost zero. Therefore, this scenario (see Table 6) is a much better alternative in terms of both water withdrawal and consumption than Scenario 1. For example, while water withdrawal ranges from 23 to 27 $hm^3$, water consumption revolves around 13 $hm^3$. Thus, savings in water withdrawal from thermal power stations in this scenario are around 98%, while savings in water consumption are around 20–30% (See Figure 5 below).

**Table 6.** Set of combinations in Scenario 2.

| Power Plants | Maximum Output (GWh) | Maximum Water Withdrawal ($hm^3$) | Maximum Water Consumption ($hm^3$) |
|---|---|---|---|
| C.1 (Andorra, Escatrón Peaker, Castelnou) | 18,152 | 23.3 | 12 |
| C.2 (Andorra, Castejón 2, Castelnou) | 19,198 | 27 | 13.4 |
| C.3 (Andorra, Castejón 1, Castelnou) | 19,321 | 25.9 | 13.6 |

Scenario 3. A setup consisting solely of combined-cycle power plants (without Castelnou).

An even more efficient scenario would use only combined-cycle power plants (Table 7), which are much more water-saving than coal-fired plants (see Table 2). Electricity production of 16,240 GWh could be achieved using less water than the two previous scenarios. Water withdrawals would account for only 1% and water consumption around 70% of nuclear power plants. In other words, water savings achieved in this scenario are around 99% and 30% respectively (see Figure 6).

**Table 7.** Set of combinations in Scenario 3.

| Power Plants | Maximum Output (GWh) | Maximum Water Withdrawal ($hm^3$) | Maximum Water Consumption ($hm^3$) |
|---|---|---|---|
| C.1 (Castejón 1, Castejón 2, Arrúbal, Escatrón Peaker) | 16,373 | 25 | 12.7 |
| C.2 (Castejón 2, Castejón 3, Arrúbal, Escatrón Peaker) | 16,400 | 25.6 | 12.8 |
| C.3 (Arrúbal, Escatrón Peaker, Escatrón) | 16,472 | 21 | 11.4 |

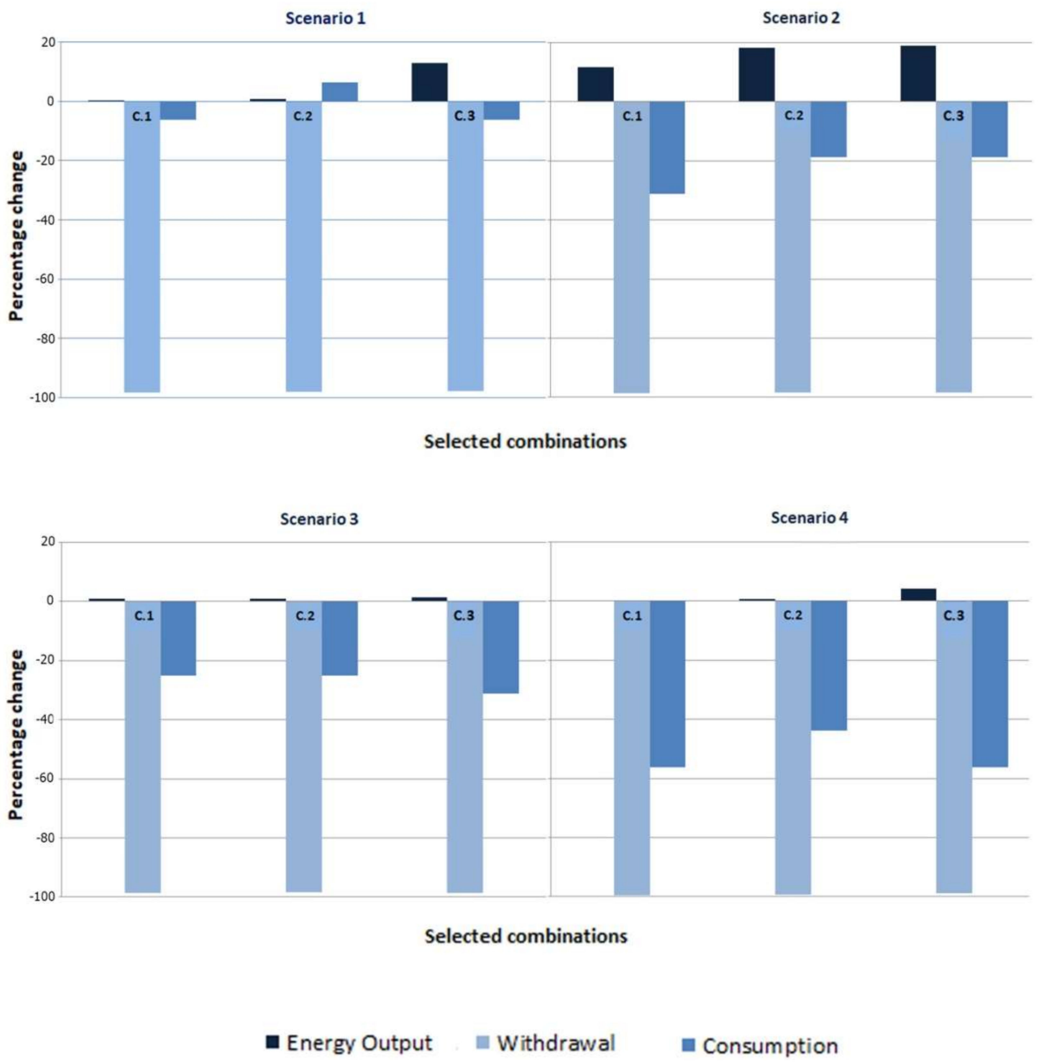



**Figure 6.** Summary of scenarios compared to the baseline. Note: the maximum output, water withdrawals, and water consumption attainable by nuclear power plants represent the baseline. Values above zero show increases in energy output or water use compared to the baseline. Values below zero show water savings compared to the baseline. Source: own design.

Scenario 4. A setup consisting solely of combined-cycle power plants (with Castelnou).

The Castelnou thermal power plant would, again, guarantee additional water savings, due to its air-cooling system. Therefore, the combinations below (see Table 8) represent the best water-saving options. In this scenario, combinations of water withdrawals are around 1% of withdrawals from nuclear power plants, and water consumption is between 40–50% of nuclear power stations (around 7–9 $hm^3$ compared to 16.9 $hm^3$).

**Table 8.** Set of combinations in Scenario 4.

| Power Plants | Maximum Output (GWh) | Maximum Water Withdrawal (hm$^3$) | Maximum Water Consumption (hm$^3$) |
|---|---|---|---|
| C.1 (Escatrón Peaker, Escatrón, Castelnou) | 16,292 | 9.4 | 7.5 |
| C.2 (Castejón 1, Castejón 3, Escatrón Peaker, Castelnou) | 16,344 | 12.7 | 9 |
| C.3 (Castejón 2, Arrúbal, Castelnou) | 16,910 | 17.7 | 7.3 |

The scenarios presented above do not refer to any particular time horizon. The scenarios merely aim to demonstrate that it is possible to produce almost similar energy outputs while saving large amounts of water under a hypothetical future without nuclear power plants in the Ebro river basin. However, these water savings would be achieved at the expense of higher $CO_2$ emissions. Likewise, the estimated maximum water withdrawals (See Table 4) would satisfy the concessions originally imposed by the Ebro Hydrographic Confederation, except for the Andorra thermal power station. This thermal power plant would exceed 2 hm$^3$—its original concession.

## 5. Discussion

This article quantifies the volume of water used in the cooling processes of the thermoelectric plants in the Ebro River basin. However, issues related to the qualitative aspects of water have been largely set aside. The increase in river temperatures is attracting the most research attention [55,56]. For example, increases in river temperatures due to climate change might affect the cooling capacity of conventional and nuclear power plants. In other words, high temperatures might force the plants to reduce their capacity due to the decrease in cooling flow. At the same time, water discharges from thermal power stations could also pose a risk to the environment by increasing water temperatures and affecting water ecosystems. These issues will need future research: the assessment of qualitative impacts on water requires different research strategies.

There are geographical differences within the river basin; the distribution of freshwater resources among competing users is already posing a problem in specific areas with water scarcity problems. Thus, according the Hydrological Plan of the Ebro Hydrographic Demarcation 2015–2021 (for the complete Hydrological Plan, see [57]), water scarcity in the area of the Andorra coal-fired power, with its demand of 18 hm$^3$/year, has required agreements to be reached to balance the needs of energy and irrigation. Therefore, future research on this matter at a lower level of disaggregation could be interesting, given the geographical differences within the Ebro River basin itself.

The collection of real data for most power plants has made it possible to carry out a comparative analysis in terms of water factors among the facilities, different types of technologies, and cooling systems (see Table 2). Thermal generating technology nuclear power plants require the greatest water withdrawals and consumption. Similarly, open-loop systems require greater water withdrawals, and cooling towers entail higher water consumption (i.e., water evaporation losses). In this regard, the data on the water consumption of the Ascó nuclear power plant seems very questionable if compared to the technical water factors discussed in the international literature for the same type of technologies and cooling systems. Therefore, although real data are available for this nuclear power plant, this water consumption factor should probably be greater to be in line with other research. Finally, this refinement of the database has led to a substantial improvement in the results related to Spanish nuclear power plants published in previous studies [39]. Thus, this study confirms that water cooling demands in the Ebro River basin do not exceed the maximum threshold stipulated by the Ebro Hydrographic Confederation in its original concessions (i.e., 3340 hm$^3$).

As mentioned previously, thermoelectric generation in the Ebro River basin multiplied almost 30 times from 1969 to 2000. The results show that, during the period, water withdrawals and water consumption multiplied approximately 24 and 22 times, respectively, which suggests some efficiency in water use. More extensive analysis on technological water intensity was carried out for the period.

Thus, the improvement of existing cooling systems or, even the replacement of cooling systems that have high water demands by lower demand systems, could be alternatives if additional reductions in the demand for water are necessary. In any case, the demand for water for cooling is not expected to significantly increase in the Ebro River basin in the short term. According to the last Hydrological Plan for 2015–2021, there is little likelihood that new coal-fired power plants will be installed in the Ebro River basin in the coming years, as this would be limited by $CO_2$ capture and storage technologies, the development of $CO_2$ transport, and the establishment of gas storage facilities. Similarly, no more nuclear power plants will be installed in the river basin, mainly due to the low acceptance of nuclear energy by the Spanish population. Lastly, the installation of new combined-cycles plants in the region is unlikely due to low electricity demands and the underutilization of existing combined-cycle plants. Therefore, water concessions for cooling are unlikely to increase in the near future and, therefore, neither will water consumption.

To sum up, these findings contribute to a better understanding of the energy-water nexus in Spain, the most arid country in Europe. However, detailed data about thermal power facilities' water withdrawals and consumption are still barely accessible. This creates significant difficulties in assessing the water-energy nexus and in making integrated decisions in the water and energy sectors. Therefore, advances in the publication of public and open data in Spanish official information sources will be necessary to improve research in this area. This is demonstrated by research on the lack of open data on water use and the inconsistencies among the different information sources on the Spanish water-energy nexus [40,58].

## 6. Conclusions

This study estimates the water needs for thermoelectric power generation in the Ebro River basin through an analysis based on the calculation of technical water factors. The difference between water withdrawals and consumption is considerable. Thus, although the value of thermoelectric water consumption seems to be of little importance, it equals the amount of water taken for industrial use. The quantities of water withdrawals should not be overlooked, as in times of drought, these amounts of water could affect the water demands of the other water users in the basin. This point is reinforced when a sector ranking is carried out. For example, thermoelectricity generation is second in water demand only behind agriculture. Moreover, this paper shows that water intensity in consumption and withdrawals for thermoelectricity has declined slightly over the years. Finally, the results show that similar quantities of electricity can be generated using less water. Given the different water requirements of each type of generation technology and cooling system, significant water savings could be achieved if we face a future without nuclear power plants in the Ebro River basin. More water will be saved by using combinations of natural gas combined-cycle plants, including the Castelnou power plant.

**Supplementary Materials:** The following are available online at http://www.mdpi.com/2073-4441/11/3/441/s1, Data File S1: water withdrawals, water consumption, and water intensity.

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## Appendix A

The following sources of information complete the extensive data search from Table 2:

ENDESA S.A. environmental reports for Andorra's thermal power station from 2011: available at [59]. IBERDROLA S.A. and EDP HC Energía environmental reports for the Castejón generating units 1, 2, and 3, from 2005 up to now: available at [60,61]. More data on the theoretical water flows rates, removals and consumption of the Castejón combined cycle thermal power plant can be found in the environmental impact study published in 2003 by ELEREBRO (now EDP HC Energía), available at [47].

Periodical publications from the Spanish official gazette and some Autonomous Communities containing water data: BOE 289. 3 December 2002, pp. 42230–42243; BOA 102. 28 May 2013, pp. 11969–11996; BOR 54. 1 May 2003, Section III.B.43; BOE 309. 24 December 2009, Section III, pp. 109653–10967; BOE 101. 27 April 2000, pp. 16395–16412; BOE 129. 31 May 2005, pp. 18317–18329; BOE 136. June 7, 2000, pp. 7596–7597; BOE 248. October 14, 2009, pp. 86859-86883; BOE 244. October 11, 2001, pp. 37509–37519; BOE 240. 7 October 2005, pp. 33034–33047; BOE 284. 25 November 2004, pp. 39076–39089; BOE 49. 26 February 2015, pp. 18618–18623.

The Ebro Hydrographic Confederation [53] presents theoretical maximum volumes of water withdrawals for Ascó (2270 $hm^3$/year), Santa María de Garoña (766 $hm^3$/year), and Teruel conventional power station (18 $hm^3$/year). No figures are given for all those power plants located in Arrúbal, Castejón, and Escatrón.

Theoretical data on water volumes for the Andorra power plant can be seen at [62].

This table shows average factors for water withdrawals and consumption, but the analysis has been carried out using more precise water factors for most power plants, obtained directly from the operators. However, due to confidentiality agreements, the specific factor cannot be shown.

## References

1. IEA (International Energy Agency). Water Energy Nexus. In *World Energy Outlook 2016*; OECD/IEA: Paris, France, 2016. Available online: https://www.iea.org/publications/freepublications/publication/WorldEnergyOutlook2016ExcerptWaterEnergyNexus.pdf (accessed on 17 December 2018).
2. Scott, C.A.; Pierce, S.A.; Pasqualetti, M.J.; Jones, A.L.; Montz, B.E.; Hoover, J.H. Policy and institutional dimensions of the water–energy nexus. *Energy Policy* **2011**, *39*, 6622–6630. [CrossRef]
3. Hussey, K.; Pittock, J. The Energy–Water Nexus: Managing the Links between Energy and Water for a Sustainable Future. *Ecol. Soc.* **2012**, *17*, 31. [CrossRef]
4. Ackerman, F.; Fisher, J. Is there a water–energy nexus in electricity generation? Long-term scenarios for the western United States. *Energy Policy* **2013**, *59*, 235–241. [CrossRef]
5. Hamiche, A.M.; Stambouli, A.B.; Flazi, S. A review of the water-energy nexus. *Renew. Sustain. Energy Rev.* **2016**, *65*, 319–331. [CrossRef]
6. Miglietta, P.; Morrone, D.; De Leo, F. The Water Footprint Assessment of Electricity Production: An Overview of the Economic-Water-Energy Nexus in Italy. *Sustainability* **2018**, *10*, 228. [CrossRef]
7. Lofman, D.; Petersen, M.; Bower, A. Water, Energy and Environment Nexus: The California Experience. *Int. J. Water Resour. Dev.* **2002**, *18*, 73–85. [CrossRef]
8. Siddiqi, A.; Anadon, L.D. The water–energy nexus in Middle East and North Africa. *Energy Policy* **2011**, *39*, 4529–4540. [CrossRef]
9. Stillwell, A.S.; King, C.W.; Webber, M.E.; Duncan, I.J.; Hardberger, A. The energy-water nexus in Texas. *Ecol. Soc.* **2011**, *16*, 2. [CrossRef]
10. Scanlon, B.R.; Duncan, I.; Reedy, R.C. Drought and the water–energy nexus in Texas. *Environ. Res. Lett.* **2013**, *8*, 045033. [CrossRef]

11. Erensu, S. Abundance and scarcity amidst the crisis of 'modern water': The changing water–energy nexus in Turkey. In *Contemporary Water Governance in the Global South*; Routledge: London, UK, 2015; pp. 61–78.
12. Lubega, W.N.; Stillwell, A.S. Maintaining electric grid reliability under hydrologic drought and heat wave conditions. *Appl. Energy* **2018**, *210*, 538–549. [CrossRef]
13. Kahrl, F.; Roland-Holst, D. China's water–energy nexus. *Water Policy* **2008**, *10*, 51–65. [CrossRef]
14. Eyre, N.; Hall, J.W.; Liao, X. Water for energy in China. In *Food, Energy and Water Sustainability*; Routledge: London, UK, 2017; pp. 67–87.
15. Zhang, X.; Liu, J.; Tang, Y.; Zhao, X.; Yang, H.; Gerbens-Leenes, P.; Van Vliet, M.T.; Yan, J. China's coal-fired power plants impose pressure on water resources. *J. Clean. Prod.* **2017**, *161*, 1171–1179. [CrossRef]
16. Liu, L.; Hejazi, M.; Patel, P.; Kyle, P.; Davies, E.; Zhou, Y.; Clarke, L.; Edmonds, J. Water demands for electricity generation in the U.S.: Modeling different scenarios for the water–energy nexus. *Technol. Forecast. Soc. Chang.* **2015**, *94*, 318–334. [CrossRef]
17. Eyer, J.; Wichman, C.J. Does water scarcity shift the electricity generation mix toward fossil fuels? Empirical evidence from the United States. *J. Environ. Econ. Manag.* **2018**, *87*, 224–241. [CrossRef]
18. Zhou, Q.; Hanasaki, N.; Fujimori, S.; Yoshikawa, S.; Kanae, S.; Okadera, T. Cooling Water Sufficiency in a Warming World: Projection Using an Integrated Assessment Model and a Global Hydrological Model. *Water* **2018**, *10*, 872. [CrossRef]
19. Mazdiyasni, O.; AghaKouchak, A. Substantial increase in concurrent droughts and heatwaves in the United States. *Proc. Natl. Acad. Sci. USA* **2015**, *112*, 11484–11489. [CrossRef] [PubMed]
20. Rodriguez, D.J.; Delgado, A.; DeLaquil, P.; Sohns, A. Thirsty energy. In *Water Papers*; World Bank: Washington, DC, USA, 2013; Available online: https://openknowledge.worldbank.org/handle/10986/16536 (accessed on 18 December 2018).
21. International Energy Agency. World Energy Outlook. Available online: https://www.iea.org/weo (accessed on 18 December 2018).
22. World Bank Group. Thirsty Energy. Available online: http://www.bancomundial.org/es/topic/sustainabledevelopment/brief/water-energy-nexus (accessed on 18 December 2018).
23. Delgado, A.; Rodríguez, D.J.; Sohns, A.A. Thirsty Energy: Understanding the Linkages between Energy and Water. 2015. Available online: http://documents.worldbank.org/curated/en/944141468329076361/Thirsty-energy-understanding-the-linkages-between-energy-and-water (accessed on 28 February 2019).
24. Glassman, D.; Wucker, M.; Isaacman, T.; Champilou, C. *The Water-Energy Nexus: Adding to the Energy Agenda. World Policy Paper*; World Policy Institute: New York, NY, USA, 2011. Available online: https://worldpolicy.org/2011/03/18/the-water-energy-nexus/ (accessed on 18 December 2018).
25. Bauer, D.; Philbrick, M.; Vallario, B.; Battey, H.; Clement, Z.; Fields, F. *The Water-Energy Nexus: Challenges and Opportunities*; US Department of Energy: Washington, DC, USA, 2014. Available online: http://sameoc.org/FD/2015/CPEN/Bauer-SAME-CPEN-Day-2015-06-18-updated.pdf (accessed on 18 December 2018).
26. Kenny, J.F.; Barber, N.L.; Hutson, S.S.; Linsey, K.S.; Lovelace, J.K.; Maupin, M.A. *Estimated Use of Water in the United States in 2005*; U.S. Geological Survey Circular 1344: Reston, VA, USA.
27. IEA (International Energy Agency). Water for Energy: Is energy becoming a thirstier resource. In *World Energy Outlook 2012*; OECD/IEA: Paris, France, 2012. Available online: https://www.iea.org/media/publications/weo/WEO_2012_Water_Excerpt.pdf (accessed on 18 December 2018).
28. Feeley, T.J.; Skone, T.J.; Stiegel, G.J.; McNemar, A.; Nemeth, M.; Schimmoller, B.; Murphy, J.T.; Manfredo, L. Water: A critical resource in the thermoelectric power industry. *Energy* **2008**, *33*, 1–11. [CrossRef]
29. Chapagain, A.K.; Hoekstra, A.Y. *Water Footprints of Nations*; Value of Water Research Report Series No. 16; UNESCO-IHE: Delft, The Netherlands, 2004. Available online: http://www.waterfootprint.org/Reports/Report16.pdf (accessed on 18 December 2018).
30. Gerbens-Leenes, W.; Hoekstra, A.Y.; Van Der Meer, T.H. The water footprint of bioenergy. *Proc. Natl. Acad. Sci. USA* **2009**, *106*, 10219–10223. [CrossRef] [PubMed]
31. Mekonnen, M.M.; Hoekstra, A.Y. The green, blue and grey water footprint of crops and derived crop products. *Hydrol. Earth Syst. Sci.* **2011**, *15*, 1577–1600. [CrossRef]
32. Hoekstra, A.Y.; Mekonnen, M.M. The water footprint of humanity. *Proc. Natl. Acad. Sci.* **2012**, *109*, 3232–3237. [CrossRef] [PubMed]
33. Egan, M. The Water Footprint Assessment Manual. Setting the Global Standard. *Soc. Environ. Account. J.* **2011**, *31*, 181–182. [CrossRef]

34. Mekonnen, M.M.; Hoekstra, A.Y. The blue water footprint of electricity from hydropower. *Hydrol. Earth Syst. Sci.* **2012**, *16*, 179–187. [CrossRef]
35. Mekonnen, M.M.; Gerbens-Leenes, P.W.; Hoekstra, A.Y. The consumptive water footprint of electricity and heat: A global assessment. *Environ. Sci. Water Res. Technol.* **2015**, *1*, 285–297. [CrossRef]
36. Chini, C.M.; Djehdian, L.A.; Lubega, W.N.; Stillwell, A.S. Virtual water transfers of the US electric grid. *Nat. Energy* **2018**, *3*, 1115–1123. [CrossRef]
37. Carrillo, A.M.R.; Frei, C. Water: A key resource in energy production. *Energy Policy* **2009**, *37*, 4303–4312. [CrossRef]
38. Hardy, L.; Garrido, A.; Juana, L. Evaluation of Spain's Water-Energy Nexus. *Int. J. Water Resour. Dev.* **2012**, *28*, 151–170. [CrossRef]
39. Martín, D.S.; Rubio-Varas, M.D.M. Freshwater for Cooling Needs: A Long-Run Approach to the Nuclear Water Footprint in Spain. *Ecol. Econ.* **2017**, *140*, 146–156. [CrossRef]
40. Sesma-Martín, D.; Rubio-Varas, M.D.M. The weak data on the water–energy nexus in Spain. *Water Policy* **2019**. [CrossRef]
41. Spanish Government; Ministerio de Medio AmbienteSecretaria de Estado de Aguas y Costas; Dirección General de Obras Hidráulicas y Calidad de Aguas. *Libro Blanco del Agua*; Centro de Publicaciones Secretaria General Técnica Ministerio de Medio Ambiente: Madrid, Spain, 2000; ISBN 84-8320-128-3. Available online: http://hispagua.cedex.es/node/66958 (accessed on 27 February 2019).
42. Pinilla, V. Gestión y usos del agua en el siglo XX. Un estudio de caso: la Cuenca del Ebro. In *Gestión y usos del agua en la Cuenca del Ebro en el siglo XX*; Prensas Universitarias de Zaragoza: Zaragoza, Spain, 2008; pp. 39–96. ISBN 978-84-7733-997-7.
43. Benlloch, P.I.; Pérez, F.; Rabanaque, I.; Rodrigo, V. Condicionantes ecológicos para el desarrollo de la agricultura. In *Gestión y usos del agua en la cuenca del Ebro en el siglo XX*; Prensas Universitarias de Zaragoza: Zaragoza, Spain, 2008; ISBN 978-84-7733-997-7.
44. Barceló, D.; Petrovic, M. The Ebro River Basin. In *The Handbook of Environmental Chemistry*; Springer Verlag: Berlin, Germany, 2011; Volume 13, p. 434.
45. Boneta Carrera, M. El desarrollo de las infraestructuras hidráulicas en la cuenca catalana del Ebro durante el siglo XX. La hidroelectricidad. In *Gestión y Usos del Agua en la Cuenca del Ebro en el Siglo XX*; Prensas Universitarias de Zaragoza: Zaragoza, Spain, 2008; pp. 265–274. ISBN 978-84-7733-997-7.
46. Miana Escabosa, A.; Valero Ruiz, C. *La Minería del Carbón en Aragón: su Historia, Métodos de Trabajo y Evolución Tecnológica*; Tierra AC: Zaragoza, Spain, 2003; pp. 240–248. ISBN 84-932408-5-0.
47. ELEREBRO, Environmental Report. Available online: http://siun.navarra.es/documentosPDF/MPSIS/104084/104084_009.pdf (accessed on 18 December 2018).
48. Spanish Ministry of Industry and Energy. Study on the use of lignite in Teruel and Catalonia. Available online: http://info.igme.es/SidPDF%5C006000%5C256%5CTomo%20I%5C6256_0001.pdf. (accessed on 18 December 2018).
49. Macknick, J.; Newmark, R.; Heath, G.; Hallett, K.C. *Review of Operational Water Consumption and Withdrawal Factors for Electricity Generating Technologies*; National Renewable Energy Lab (NREL): Golden, CO, USA, 2011.
50. Macknick, J.; Newmark, R.; Hallett, K.C.; Heath, G. Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature. *Environ. Res. Lett.* **2012**, *7*, 045802. [CrossRef]
51. Nettles-Anderson, S.; Macknick, J.; Meldrum, J.; Heath, G. Life cycle water use for electricity generation: a review and harmonization of literature estimates. *Environ. Res. Lett.* **2013**, *8*, 015031.
52. Spang, E.S.; Moomaw, W.R.; Gallagher, K.S.; Kirshen, P.H.; Marks, D.H. The water consumption of energy production: an international comparison. *Environ. Res. Lett.* **2014**, *9*, 105002. [CrossRef]
53. Confederación Hidrográfica del Ebro. Available online: http://http://www.chebro.es (accessed on 18 December 2018).
54. Moomaw, W.R.; Gallagher, K.S.; Kirshen, P.H.; Marks, D.H.; Spang, E.S. Multiple metrics for quantifying the intensity of water consumption of energy production. *Environ. Res. Lett.* **2014**, *9*, 105003.
55. Van Vliet, M.T.; Franssen, W.H.; Yearsley, J.R.; Ludwig, F.; Haddeland, I.; Lettenmaier, D.P.; Kabat, P. Global river discharge and water temperature under climate change. *Glob. Environ. Chang.* **2013**, *23*, 450–464. [CrossRef]

56. Kaushal, S.S.; Likens, G.E.; Jaworski, N.A.; Pace, M.L.; Sides, A.M.; Seekell, D.; Belt, K.T.; Secor, D.H.; Wingate, R.L. Rising stream and river temperatures in the United States. *Front. Ecol. Environ.* **2010**, *8*, 461–466. [CrossRef]
57. Confederación Hidrográfica del Ebro. Plan Hidrológico del Ebro 2015-2021. Available online: http://www.chebro.es/contenido.visualizar.do?idContenido=34057&idMenu=4281 (accessed on 18 December 2018).
58. De Stefano, L.; Hernández-Mora, N.; Cabello, V. Informe sobredatos abiertos en el sector del aguaFundación Botín, Observatorio Del Agua, Santanderp. 27. 2018, p. 27. Available online: https://www.fundacionbotin.org/89dguuytdfr276ed_uploads/Observatorio%20Tendencias/PUBLICACIONES/MONOGRAFIAS/Datos_Abiertos_2018.pdf (accessed on 18 December 2018).
59. ENDESA, Environmental Reports. Available online: https://www.endesa.com/es/sostenibilidad/a201610-gestion-ambiental.html (accessed on 18 December 2018).
60. IBERDROLA. Environmental Reports. Available online: https://www.iberdrola.com/sostenibilidad/medio-ambiente/gestion-medioambiental/certificaciones-verificaciones (accessed on 18 December 2018).
61. EDP HC Energía, Environmental Reports. Available online: https://www.sostenibilidadedp.es/publicaciones/index_for_categoria/174 (accessed on 18 December 2018).
62. Galve Dolz, M. La Central térmica de Teruel. In *El Agua, Vida y Paisaje en las Comarcas de Andorra-Sierra de Arcos y del Bajo Martín*; CELAN, CEBM, Comarca de Andorra-Sierra de Arcos y Comarca del Bajo Martín: Teruel, Spain, 2007; p. 236.

# 5. Conclusions

This thesis has deepened the study on the water-energy nexus in Spain and, more specifically, on the water-thermoelectricity nexus. The results derived from this thesis represent a first approach to the freshwater needs of the Spanish thermoelectric power plants for the period 1969-2015. Several conclusions can be drawn from this research.

The lack of studies on the water-energy nexus in Spain is clearly evident. Similarly, the statistics available to make a proper estimate of the water needed for cooling are insufficient and, in most cases, contradictory. Furthermore, some sources of information do not make adequate use of the terms referring to water uses. Water constraints can translate into energy constraints. In Spain, almost two thirds of the national electricity generation could be altered in the absence of an adequate water supply (REE, 2017). Therefore, the improvement of these indicators seems to be an indispensable issue for a better understanding of the nexus and efficient management of water resources in the future, precisely in the most arid country in Europe.

The Spanish blue water footprint of plant operations is insignificant in comparison with the water footprint of other activities (i.e., agriculture and irrigation). However, water withdrawals for thermoelectric power generation appears as the second thirstiest sector, just behind agriculture. Water withdrawals are critical for power generation because if the quantity demanded is not available, plants might be forced to shut down or limit their operations. Furthermore, all these volumes could have significant effects on the overall water supply putting at risk the use of the resource for other alternative activities in areas with water availability problems. Increases in the magnitude and duration of droughts and heat waves due to climate change could worsen the situation even further. Consequently, the location of the plants on the territory should be an important factor to analyze. The diversity of the Spanish geography, the consideration of a semi-arid country and the imbalances in rainfall in each region make it necessary to keep in mind the territorial component.

When comparing by thermoelectric technologies, nuclear power plants appear as the major water users followed by conventional coal-fired power plants and, finally, combined cycle power plants. The long-term evolution of water withdrawals and consumption by technology evidences this point. However, this sign does not seem so clear when we look individually at the water factors of each power plant. For example, for a given type of cooling system, the coal-fired plants located in Aliaga and Escatrón show higher water consumption factors than the two generating units of the Ascó nuclear power plant. Additionally, Mekonnen et al. (2015) find an operational water footprint range for gas fired power plants of 74 to 1200 m3/TJe and for nuclear of 0 to 936 m3/TJe. This does not mean that nuclear has a larger operation water footprint than gas fired power plants. In this way, apart from the technical characteristics, both the location of a plant and its corresponding climatic conditions can affect the overall efficiency and thus its water use coefficient (Macknick et al., 2012a).

Finally, a shift in fuel from nuclear to coal and natural gas could decrease water consumptions and withdrawals considerably. Similarly, a shift from wet cooling to dry cooling systems would result in additional water savings. Others studies focused on the United States find that a shift from coal-generated to natural gas-generated electricity could decrease water consumption and withdrawal by an average of 32% and 37% respectively. Additionally, a shift from open-loop systems to cooling towers could decrease water withdrawals by an average of 96%, while water consumption would increase by 58% (DeNooyer et al., 2016). In the same line, Scanlon et al. (2013) prove that increases in natural gas power generation can have important implications for drought resilience, understood as the ability of a power plant to recover from drought stress. All these results represent potential measures in the face of future water scarcity scenarios.

## 5.1. Recommendations for further research.

Despite these advances, additional steps are needed in future research in order to better understand the water-energy nexus in Spain.

Additional progress is needed to have a fully comprehensive picture of the freshwater needs for the country as a whole, since the remaining Spanish river basins contain more than twenty additional thermoelectric power plants to be analyzed. Moreover, renewable energy technologies generally have lower water needs than fossil fuels (PV technologies and wind turbines). Conversely, there are other renewable energy sources requiring large amounts of water. For instance, water consumption factors of hydropower plants can range from 4491 gallon/MWh to 18000 gallon/MWh, while concentrating solar power plants may vary from 906 gallon/MWh to 1109 gallon/MWh (Macknick et al., 2012a). The quantification of the water needs of renewable technologies represents a potential avenue of research for the future.

This study makes annual analysis. Nevertheless, restrictions on the availability of water in specific months throughout a year could have significant negative impacts on the operation of the plants, forcing the plants to close down or curtail their operation. Analysis on a monthly basis could provide additional conclusions to this research. Another alternative is to analyse water consumption and withdrawals taking into account the hydrological year (instead of calendar year), so that the water needs of the power plants can be compared with the volume of rainfall each month.

All the figures provided refer to quantitative aspects of water (i.e., the amounts of water withdrawals and consumption for cooling) leaving aside all those issue related to the qualitative aspects of water. For example, water discharges from once-through cooling systems transfer waste heat from the power plant to the discharge water body, causing an increase in the local temperature. Furthermore, temperature increases produced by power plant discharges may have adverse impacts on aquatic ecosystems (De Vries et al., 2008). Therefore, the analysis of these issues related to the qualitative aspects of water represents another possible extension for research.

Lastly, this thesis covers the 'water for energy' way, focusing on the operating stage of the plants. From this side of the nexus, there are, however, other processes that need to be analyzed (namely, fuel supply or construction of power plant). But to have a complete perspective it is also necessary to analyze the other directionality of the nexus, 'energy for water'.

# Conclusiones

Esta tesis ha profundizado en el estudio del nexo agua-energía en España y, más concretamente, del nexo agua-termoelectricidad. Los resultados de esta tesis representan una primera aproximación a las necesidades de agua dulce de las centrales termoeléctricas españolas para el periodo 1969-2015. Se pueden extraer varias conclusiones de esta investigación.

La falta de estudios sobre el nexo agua-energía en España es evidente. Las estadísticas disponibles para estimar correctamente el agua de refrigeración de las centrales térmicas son insuficientes , en algunos casos, contradictorias. Del mismo modo, existen fuentes de información que no definen correctamente los términos que hacen referencia a los usos del agua. Las restricciones de agua pueden traducirse en restricciones energéticas. En España, casi dos tercios de la producción eléctrica nacional podrían verse alterados en ausencia de un suministro adecuado de agua (REE, 2017). Por lo tanto, la mejora de estos indicadores es indispensable para una mejor comprensión del nexo y una gestión eficaz de los recursos hídricos en el futuro, precisamente en el país más árido de Europa.

En España, la huella hídrica azul (agua consumida) resultante del funcionamiento de las centrales termoeléctricas es insignificante en comparación con el impacto de otras actividades (por ejemplo, la agricultura y el riego). Sin embargo, la generación de energía termoeléctrica representa la segunda actividad más sedienta en términos de extracciones de agua, justo por detrás de los usos agrícolas. Estos volúmenes son cruciales para la generación de energía, ya que si la cantidad demandada no está disponible, las plantas podrían verse obligadas limitar sus operaciones e incluso a cerrar. Asimismo, todas estas captaciones podrían tener efectos significativos en el suministro general de agua, poniendo en riesgo el uso del recurso para otras actividades alternativas en áreas con problemas de disponibilidad de agua. El incremento en la magnitud y la duración de las sequías, y las olas de calor debidas al cambio climático podría empeorar aún más la situación. En consecuencia, la ubicación de las centrales en el territorio debe ser un factor importante a analizar. La diversidad de la geografía española, la consideración de país semiárido y los desequilibrios pluviométricos entre las regiones hacen necesario tener en cuenta el componente territorial.

Comparando las diferentes tecnologías termoeléctricas, las centrales nucleares aparecen como las principales usuarias de agua, seguidas de las centrales térmicas convencionales de carbón y, por último, las de ciclo combinado. La evolución a largo plazo de las extracciones de agua y del consumo por tipo de tecnología así lo confirma. Sin embargo, esta afirmación no parece tan evidente cuando analizamos individualmente los factores del agua de cada central eléctrica. Por ejemplo, para un determinado tipo de sistema de refrigeración, las centrales de carbón ubicadas en Aliaga y Escatrón presentan un mayor consumo de agua que las dos unidades generadoras de la central nuclear de Ascó. Por su parte, Mekonnen et al. (2015) muestran que huella hídrica correspondiente al funcionamiento de las centrales de gas oscila entre 74 y 1200 m3/TJe. En el caso de las centrales nucleares, el rango varía entre 0 y 936 m3/TJe. Esto no significa que las centrales nucleares tengan mayor huella hídrica que las centrales de gas. En este sentido, además de sus características técnicas, la ubicación de las centrales y las condiciones climáticas correspondientes podrían afectar a la eficiencia global de las centrales y, en consecuencia, a sus coeficientes de uso del agua (Macknick et al., 2012a).

Por último, la transición del combustible nuclear al carbón y gas natural podría reducir considerablemente los consumo y las extracciones de agua. Asimismo, la transición de sistemas de refrigeración de tipo húmedo a sistemas de tipo seco supondría ahorros adicionales de agua. Otros estudios centrados en los Estados Unidos encuentran que un cambio de la electricidad generada con carbón a la generada con gas natural podría reducir el consumo y la extracción de agua de media un 32% y 37%, respectivamente. Además, la transición de sistemas de ciclo abierto a torres de refrigeración podría reducir la extracción de agua de las centrales en un 96%, aumentando el consumo en un 58% (DeNooyer et al., 2016). En esta misma línea, Scanlon et al. (2013) demuestran que el aumento en la producción de energía eléctrica a partir de gas natural representa una importante medida de resiliencia a la sequía, entendida ésta como la capacidad de una central para recuperarse del estrés hídrico. Todos estos resultados representan medidas potenciales frente a futuros escenarios de escasez de agua.

## Recomendaciones para futuras investigaciones

A pesar de estos avances, se necesitan pasos adicionales en la investigación futura para entender mejor el nexo agua-energía en España.

Avances adicionales son necesarios para tener una visión completa de las necesidades de agua dulce para el conjunto del país. Por ejemplo, el resto de cuencas hidrográficas españolas albergan al menos una veintena de centrales termoeléctricas adicionales que deben analizadas. En general, las tecnologías basadas en energías renovables suelen necesitar menos agua que los combustibles fósiles (tecnologías fotovoltaicas y turbinas eólicas). Sin embargo, existen algunas excepciones. Por ejemplo, los factores de consumo de agua de las centrales hidroeléctricas pueden variar de 4491 galones/MWh a 18000 galones/MWh, mientras que las centrales de energía solar por concentración pueden variar de 906 galones/MWh a 1109 galones/MWh (Macknick et al., 2012a). Cuantificar las necesidades hídricas de las tecnologías renovables representa una vía potencial de investigación para el futuro.

Este estudio realiza un análisis anual. Sin embargo, las restricciones en la disponibilidad de agua en algunos meses concretos a lo largo del año podrían tener impactos negativos significativos en la operación de las plantas, obligando a las centrales a cerrar o restringir su operación. Un análisis con una periodicidad mensual podría arrojar conclusiones adicionales a esta investigación. Otra alternativa se basa en analizar las captaciones y consumos de agua teniendo en cuenta el año hidrológico (en lugar del calendario natural), de modo que las necesidades hídricas de las instalaciones puedan compararse con el volumen de precipitaciones mensuales.

Todas las magnitudes que aquí se presentan se refieren a aspectos cuantitativos del agua (esto es, volúmenes sobre captaciones y consumos de agua para refrigeración), dejando de lado todas las cuestiones relacionadas con los aspectos cualitativos del agua. Por ejemplo, las descargas de agua de los sistemas de refrigeración de ciclo abierto transfieren el calor residual de la central térmica a la masa de agua de descarga, lo que provoca un aumento de la temperatura local. Además, los aumentos de temperatura producidos por las descargas de estas centrales pueden tener efectos negativos en los ecosistemas acuáticos (De Vries et al., 2008). Por lo tanto, el análisis de estas cuestiones relacionadas con los aspectos cualitativos del agua representa otra posible extensión de la investigación.

Por último, esta tesis estudia relación 'agua para la energía', centrándose en la fase de operación de las centrales. Desde este lado del nexo, hay, sin embargo, otros procesos que necesitan ser analizados (por ejemplo, los que tienen que ver con el suministro de combustible o la construcción de la central). Pero para tener una perspectiva completa también es necesario analizar la otra direccionalidad del nexo: 'energía para el agua'.

## Supplementary Material

This section collects the supplementary material from published papers. Likewise, additional unpublished material on the historical time series used to elaborate various figures is also collected for those cases where data can be displayed.

1. **Supplementary material** published in Sesma-Martín, D., & Rubio-Varas, M.d.M (2017). Freshwater for cooling needs: A long-run approach to the nuclear water footprint in Spain. *Ecological Economics*, *140*, 146-156.

*Individual Reactor Published Data Available*

Cofrentes data have been compared with official statistics appearing in the Cofrentes webpage and some research papers. For example, Asensio et al., (2000) state that water consumption is around 21 $hm^3$/year. Likewise, Cofrentes website provides information about its flow rate (i.e. maximum total consumption volume of 20 $hm^3$/year and an amount of water catchment of 34.7 authorized $hm^3$/year). Finally, the Boletín Oficial del Estado establish a water withdrawal flow of 23.65 $hm^3$/year, coinciding with the figure of maximum withdrawals granted.

Data for Trillo, Almaraz, and Zorita have been contrasted with data from Greenpeace environmental reports and Tajo Hydrographic Confederation. First, Greenpeace states that Trillo´s water consumption is 21 $hm^3$/year, whereas Nuclear Jose Cabrera (Zorita, as known) consumes 15 $hm^3$/year and Almaraz 16 $hm^3$/year. On the other hand, the Tajo´s Hydrographic Confederation speaks that water withdrawals for Trillo are around 37.8 $hm^3$/year and its consumptive use is around 20.50 $hm^3$/year. For Almaraz the same source offers 436 $hm^3$/year for withdrawals and 46.30 $hm^3$/year for consumption. Additionally, other sources provide data for water withdrawals from these plants. Water withdrawals data for Trillo from BOE coincides with the maximum water flow of the River Basin (45 $hm^3$/year). The Consejo de Seguridad Nuclear (CSN) estimates in 210 $hm^3$/year the water withdrawals for Zorita. Other figures for this nuclear power plant are 362.66 $hm^3$/year (maximum water flows) and 224 $hm^3$/year (BOE). Finally, Almaraz data for water withdrawals vary from 583 $hm^3$/year (BOE and Libro Blanco del Agua), 1,461 $hm^3$/year (CSN), and 2,522 $hm^3$/year (max. water flows).

Similarly, Greenpeace environmental reports and Ebro´s Hydrographic Confederation provide some data about Ascó and Santa María de Garoña. In this way, the Ebro River Basin states that the data on freshwater demands for cooling for Ascó (units I and II) and Garoña are 2,270 $hm^3$/year and 766 $hm^3$/year (these figures also coincides with data from Libro Blanco del Agua for both cases), respectively. On the other hand, Greenpeace estimates that Garoña employs 720 $hm^3$/year for cooling. Data for Garoña and Ascó (units I and II) from the CSN are 756 $hm^3$/year and 1,140 $hm^3$/year. In case of Ascó the BOE states around 2,324 $hm^3$/year (equal to maximum flows) and for Garoña, around 767 $hm^3$/year.

We have assumed that nuclear power plants run 24 hours 365 days a year to transform the available data to cubic meter per year ($m^3$/year).

As shown above, the few cases where some figures are provided, the available data cover either water withdrawals or water consumption but not both. In other occasions the sources obviate to define whether the figure provided refers to withdrawals or consumptions or to differentiate between cooling technologies or individual facilities. As explicit data for each nuclear power plant are lacking for most Spanish reactors, we resorted to estimations based on the international literature. In this way, we compare the different WW and WC factors for each of the Spanish nuclear reactors resulting from homogenizing as much as possible the available published data on water needs and contrast them with the estimations of the water factors of the different cooling technologies by the international literature.

***Note**: These previous data were also used for the elaboration of Figures 3 and 4 from Sesma-Martín, D., & Rubio-Varas, M. (2019). The weak data on the water–energy nexus in Spain. *Water Policy*, *21*(2), 382-393.

2. **Unpublished historical time series** used for the elaboration of figures from Sesma-Martín, D., & Rubio-Varas, M.d.M (2017). Freshwater for cooling needs: A long-run approach to the nuclear water footprint in Spain. *Ecological Economics*, *140*, 146-156.

- Data for the preparation of Fig. 2_Evolution of total water withdrawals of Spanish nuclear power plants (1969-2014), by using literature factors.

| Year | Water Withdrawal ($hm^3$/year) | | |
|---|---|---|---|
| | **Minimum** | **Median** | **Maximum** |
| **1969** | 78.49 | 139.25 | 188.38 |
| **1970** | 87.34 | 154.94 | 209.61 |
| **1971** | 238.74 | 423.52 | 572.97 |
| **1972** | 337.41 | 598.57 | 809.79 |
| **1973** | 321.58 | 570.49 | 771.80 |
| **1974** | 326.91 | 579.94 | 784.59 |
| **1975** | 382.10 | 677.84 | 917.03 |
| **1976** | 390.90 | 693.46 | 938.17 |
| **1977** | 295.13 | 523.56 | 708.32 |
| **1978** | 413.05 | 732.76 | 991.33 |
| **1979** | 330.21 | 585.79 | 792.50 |
| **1980** | 169.08 | 299.94 | 405.79 |
| **1981** | 615.58 | 1,092.04 | 1,477.39 |

| | | | |
|---|---|---|---|
| **1982** | 530.45 | 941.02 | 1,273.08 |
| **1983** | 671.98 | 1,191.57 | 1,613.89 |
| **1984** | 1,476.11 | 2,613.02 | 3,554.61 |
| **1985** | 1,328.52 | 2,343.15 | 3,217.63 |
| **1986** | 1,610.90 | 2,836.14 | 3,912.32 |
| **1987** | 1,767.59 | 3,111.56 | 4,293.81 |
| **1988** | 1,706.45 | 2,997.62 | 4,158.76 |
| **1989** | 1,838.79 | 3,227.15 | 4,487.62 |
| **1990** | 1,821.37 | 3,197.07 | 4,444.01 |
| **1991** | 1,954.07 | 3,432.40 | 4,762.69 |
| **1992** | 1,780.01 | 3,120.47 | 4,351.68 |
| **1993** | 1,950.35 | 3,424.80 | 4,755.90 |
| **1994** | 1,766.44 | 3,097.43 | 4,316.91 |
| **1995** | 1,817.53 | 3,189.00 | 4,437.49 |
| **1996** | 1,794.52 | 3,146.73 | 4,385.40 |
| **1997** | 1,746.40 | 3,061.68 | 4,269.24 |
| **1998** | 1,936.69 | 3,398.58 | 4,727.35 |
| **1999** | 2,015.50 | 3,538.14 | 4,917.05 |
| **2000** | 2,054.73 | 3,605.04 | 5,016.96 |
| **2001** | 2,091.85 | 3,670.85 | 5,106.15 |
| **2002** | 2,108.06 | 3,699.36 | 5,145.54 |
| **2003** | 1,953.25 | 3,424.39 | 4,774.75 |
| **2004** | 2,148.49 | 3,771.68 | 5,241.32 |
| **2005** | 2,101.40 | 3,690.00 | 5,124.30 |
| **2006** | 1,918.13 | 3,362.27 | 4,690.02 |
| **2007** | 1,930.13 | 3,387.75 | 4,709.90 |
| **2008** | 1,999.26 | 3,508.59 | 4,879.61 |

| | | | |
|---|---|---|---|
| **2009** | 1,770.49 | 3,105.18 | 4,325.39 |
| **2010** | 1,927.95 | 3,379.44 | 4,714.15 |
| **2011** | 1,947.99 | 3,418.65 | 4,754.41 |
| **2012** | 1,948.51 | 3,415.91 | 4,763.53 |
| **2013** | 1,585.32 | 2,772.65 | 3,889.62 |
| **2014** | 1,592.72 | 2,786.56 | 3,905.71 |

- Data for the preparation of Fig. 3_Evolution of total water consumption of Spanish nuclear power plants (1969-2014), by using literature factors.

| | **Water Consumption ($hm^3$/year)** | | |
|---|---|---|---|
| **Year** | **Minimum** | **Median** | **Maximum** |
| **1969** | 0.31 | 0.84 | 1.26 |
| **1970** | 0.35 | 0.94 | 1.40 |
| **1971** | 0.95 | 2.57 | 3.82 |
| **1972** | 1.35 | 3.63 | 5.40 |
| **1973** | 1.29 | 3.46 | 5.15 |
| **1974** | 1.31 | 3.52 | 5.23 |
| **1975** | 1.53 | 4.11 | 6.11 |
| **1976** | 1.56 | 4.21 | 6.25 |
| **1977** | 1.18 | 3.18 | 4.72 |
| **1978** | 1.65 | 4.44 | 6.61 |
| **1979** | 1.32 | 3.55 | 5.28 |
| **1980** | 0.68 | 1.82 | 2.71 |
| **1981** | 2.46 | 6.62 | 9.85 |
| **1982** | 2.12 | 5.71 | 8.49 |
| **1983** | 3.65 | 8.33 | 12.13 |
| **1984** | 16.06 | 27.54 | 38.25 |

| | | | |
|---|---|---|---|
| **1985** | 30.10 | 42.76 | 56.96 |
| **1986** | 45.66 | 62.36 | 82.26 |
| **1987** | 50.91 | 69.35 | 91.42 |
| **1988** | 60.60 | 80.11 | 104.76 |
| **1989** | 70.67 | 92.48 | 120.61 |
| **1990** | 69.09 | 90.55 | 118.15 |
| **1991** | 69.77 | 92.16 | 120.50 |
| **1992** | 74.80 | 96.86 | 125.96 |
| **1993** | 71.58 | 94.21 | 123.07 |
| **1994** | 72.87 | 94.56 | 123.04 |
| **1995** | 71.36 | 93.14 | 121.39 |
| **1996** | 73.92 | 95.94 | 124.84 |
| **1997** | 73.15 | 94.76 | 123.24 |
| **1998** | 75.13 | 98.20 | 128.03 |
| **1999** | 75.90 | 99.58 | 129.96 |
| **2000** | 80.95 | 105.62 | 137.63 |
| **2001** | 81.19 | 106.11 | 138.35 |
| **2002** | 81.68 | 106.78 | 139.22 |
| **2003** | 81.69 | 105.83 | 137.65 |
| **2004** | 80.76 | 105.98 | 138.32 |
| **2005** | 77.18 | 101.58 | 132.68 |
| **2006** | 81.19 | 105.05 | 136.58 |
| **2007** | 73.64 | 96.46 | 125.83 |
| **2008** | 77.16 | 100.92 | 131.60 |
| **2009** | 71.85 | 93.41 | 121.61 |
| **2010** | 81.70 | 105.69 | 137.41 |
| **2011** | 75.13 | 98.27 | 128.15 |

| | | | |
|---|---|---|---|
| **2012** | 81.80 | 105.93 | 137.76 |
| **2013** | 78.44 | 99.84 | 129.21 |
| **2014** | 77.05 | 98.29 | 127.28 |

- Data for the elaboration of Fig. 4 and 5_Evolution of total Water Withdrawals and Consumption of Spanish Nuclear Power Plants (1969-2014), by using adjusted factors.

| **Year** | **Spanish Nuclear Power Plants** | |
|---|---|---|
| | **Water Withdrawals ($hm^3$/year)** | **Water Consumption ($hm^3$/year)** |
| **1969** | 175 | 0.84 |
| **1970** | 195 | 0.94 |
| **1971** | 739 | 2.57 |
| **1972** | 1,116 | 3.63 |
| **1973** | 1,055 | 3.46 |
| **1974** | 1,053 | 3.52 |
| **1975** | 1,247 | 4.11 |
| **1976** | 1,283 | 4.21 |
| **1977** | 920 | 3.18 |
| **1978** | 1,370 | 4.44 |
| **1979** | 1,076 | 3.55 |
| **1980** | 489 | 1.82 |
| **1981** | 1,472 | 11.20 |
| **1982** | 1,030 | 11.47 |
| **1983** | 1,083 | 18.97 |
| **1984** | 2,476 | 53.50 |
| **1985** | 2,034 | 69.99 |
| **1986** | 3,841 | 90.13 |

| | | |
|---|---|---|
| **1987** | 3,970 | 102.70 |
| **1988** | 4,213 | 111.63 |
| **1989** | 4,537 | 125.51 |
| **1990** | 4,200 | 126.96 |
| **1991** | 4,641 | 128.75 |
| **1992** | 4,333 | 131.54 |
| **1993** | 4,593 | 131.24 |
| **1994** | 4,249 | 130.42 |
| **1995** | 4,272 | 127.94 |
| **1996** | 4,512 | 130.08 |
| **1997** | 4,526 | 127.55 |
| **1998** | 4,895 | 133.81 |
| **1999** | 4,912 | 138.43 |
| **2000** | 5,221 | 144.09 |
| **2001** | 5,001 | 146.71 |
| **2002** | 5,252 | 147.05 |
| **2003** | 5,089 | 142.48 |
| **2004** | 5,035 | 146.67 |
| **2005** | 4,953 | 142.19 |
| **2006** | 4,868 | 142.41 |
| **2007** | 4,554 | 135.89 |
| **2008** | 4,714 | 141.01 |
| **2009** | 4,215 | 128.80 |
| **2010** | 4,794 | 144.25 |
| **2011** | 4,477 | 137.72 |
| **2012** | 4,786 | 144.99 |
| **2013** | 3,588 | 138.86 |

| | | |
|---|---|---|
| **2014** | 3,201 | 137.76 |

- Data for the elaboration of Fig. 6_Evolution of total Water Withdrawals ($hm^3$/year) of Spanish nuclear power plants by river basins.

| Year | River Basins | | |
|---|---|---|---|
| | Ebro | Tagus | Jucar |
| **1969** | 0 | 175 | 0 |
| **1970** | 0 | 195 | 0 |
| **1971** | 526 | 212 | 0 |
| **1972** | 927 | 189 | 0 |
| **1973** | 861 | 194 | 0 |
| **1974** | 826 | 227 | 0 |
| **1975** | 1,008 | 239 | 0 |
| **1976** | 1,049 | 234 | 0 |
| **1977** | 669 | 252 | 0 |
| **1978** | 1,146 | 225 | 0 |
| **1979** | 865 | 210 | 0 |
| **1980** | 286 | 203 | 0 |
| **1981** | 1,166 | 306 | 0 |
| **1982** | 760 | 270 | 0 |
| **1983** | 936 | 147 | 0 |
| **1984** | 1,880 | 594 | 2 |
| **1985** | 1,584 | 420 | 29 |
| **1986** | 3,212 | 597 | 32 |
| **1987** | 3,254 | 683 | 33 |
| **1988** | 3,501 | 678 | 34 |
| **1989** | 3,792 | 711 | 34 |

| | | | |
|---|---|---|---|
| **1990** | 3,454 | 713 | 34 |
| **1991** | 3,871 | 737 | 33 |
| **1992** | 3,564 | 732 | 37 |
| **1993** | 3,841 | 718 | 33 |
| **1994** | 3,711 | 504 | 33 |
| **1995** | 3,671 | 562 | 39 |
| **1996** | 3,780 | 695 | 37 |
| **1997** | 3,852 | 641 | 33 |
| **1998** | 4,121 | 736 | 39 |
| **1999** | 4,093 | 783 | 36 |
| **2000** | 4,404 | 781 | 35 |
| **2001** | 4,163 | 799 | 39 |
| **2002** | 4,445 | 770 | 38 |
| **2003** | 4,302 | 750 | 38 |
| **2004** | 4,168 | 825 | 42 |
| **2005** | 4,112 | 809 | 32 |
| **2006** | 4,222 | 604 | 42 |
| **2007** | 3,976 | 549 | 29 |
| **2008** | 4,123 | 554 | 37 |
| **2009** | 3,688 | 490 | 37 |
| **2010** | 4,218 | 532 | 44 |
| **2011** | 3,894 | 546 | 36 |
| **2012** | 4,204 | 540 | 43 |
| **2013** | 3,011 | 539 | 38 |
| **2014** | 2,613 | 544 | 43 |

- Data for the elaboration of Fig. 7_Evolution of total Water Consumption ($hm^3$/year) of Spanish nuclear power plants by river basins.

| | River Basins | | |
|---|---|---|---|
| **Year** | **Ebro** | **Tagus** | **Jucar** |
| **1969** | 0.00 | 0.84 | 0.00 |
| **1970** | 0.00 | 0.94 | 0.00 |
| **1971** | 1.54 | 1.03 | 0.00 |
| **1972** | 2.72 | 0.91 | 0.00 |
| **1973** | 2.53 | 0.93 | 0.00 |
| **1974** | 2.42 | 1.10 | 0.00 |
| **1975** | 2.96 | 1.16 | 0.00 |
| **1976** | 3.08 | 1.13 | 0.00 |
| **1977** | 1.96 | 1.21 | 0.00 |
| **1978** | 3.36 | 1.08 | 0.00 |
| **1979** | 2.54 | 1.02 | 0.00 |
| **1980** | 0.84 | 0.98 | 0.00 |
| **1981** | 3.42 | 7.78 | 0.00 |
| **1982** | 2.23 | 9.24 | 0.00 |
| **1983** | 3.61 | 15.36 | 0.00 |
| **1984** | 13.91 | 38.58 | 1.02 |
| **1985** | 14.41 | 38.69 | 16.89 |
| **1986** | 31.63 | 40.20 | 18.29 |
| **1987** | 35.49 | 48.28 | 18.93 |
| **1988** | 38.60 | 53.44 | 19.59 |
| **1989** | 39.35 | 66.86 | 19.31 |
| **1990** | 38.54 | 69.06 | 19.37 |
| **1991** | 39.82 | 69.72 | 19.21 |

| | | | |
|---|---|---|---|
| **1992** | 39.60 | 70.74 | 21.19 |
| **1993** | 39.54 | 72.51 | 19.18 |
| **1994** | 39.87 | 71.38 | 19.17 |
| **1995** | 36.73 | 68.81 | 22.40 |
| **1996** | 40.08 | 68.95 | 21.04 |
| **1997** | 41.24 | 67.40 | 18.91 |
| **1998** | 42.99 | 68.45 | 22.37 |
| **1999** | 44.20 | 73.71 | 20.52 |
| **2000** | 46.86 | 76.87 | 20.37 |
| **2001** | 45.05 | 78.99 | 22.67 |
| **2002** | 47.20 | 78.24 | 21.62 |
| **2003** | 46.58 | 74.00 | 21.89 |
| **2004** | 43.08 | 79.44 | 24.15 |
| **2005** | 43.86 | 79.77 | 18.56 |
| **2006** | 44.99 | 73.08 | 24.34 |
| **2007** | 42.68 | 76.74 | 16.48 |
| **2008** | 42.71 | 76.77 | 21.53 |
| **2009** | 38.87 | 68.68 | 21.25 |
| **2010** | 44.69 | 74.36 | 25.21 |
| **2011** | 40.70 | 76.16 | 20.86 |
| **2012** | 44.54 | 75.70 | 24.76 |
| **2013** | 42.35 | 74.53 | 21.98 |
| **2014** | 36.98 | 75.78 | 25.00 |

3. **Historical time series** published as supplementary material in Sesma-Martín, D. (2019). The River's Light: Water Needs for Thermoelectric Power Generation in the Ebro River Basin, 1969–2015. *Water*, *11*(3), 441.

- Data for the elaboration of Fig. 4(a)_Evolution of total water withdrawals by type of technology in the Ebro River basin, 1969-2015.

*WATER WITHDRAWALS* $(hm^3/year)$

| Year | Technology | | | Total |
|---|---|---|---|---|
| | Coal | Nuclear | Natural Gas CC | |
| **1969** | 100.56 | 0.00 | 0.00 | 100.56 |
| **1970** | 131.81 | 0.00 | 0.00 | 131.81 |
| **1971** | 140.95 | 233.65 | 0.00 | 374.60 |
| **1972** | 139.55 | 411.36 | 0.00 | 550.91 |
| **1973** | 135.86 | 382.34 | 0.00 | 518.20 |
| **1974** | 131.87 | 366.62 | 0.00 | 498.49 |
| **1975** | 159.81 | 447.42 | 0.00 | 607.22 |
| **1976** | 151.27 | 465.58 | 0.00 | 616.86 |
| **1977** | 149.69 | 296.83 | 0.00 | 446.52 |
| **1978** | 77.32 | 508.57 | 0.00 | 585.89 |
| **1979** | 53.71 | 384.10 | 0.00 | 437.81 |
| **1980** | 73.54 | 126.98 | 0.00 | 200.52 |
| **1981** | 73.20 | 517.55 | 0.00 | 590.75 |
| **1982** | 79.37 | 337.52 | 0.00 | 416.89 |
| **1983** | 77.09 | 421.68 | 0.00 | 498.77 |
| **1984** | 75.81 | 892.99 | 0.00 | 968.80 |
| **1985** | 50.77 | 775.32 | 0.00 | 826.09 |
| **1986** | 45.32 | 1,654.61 | 0.00 | 1,699.93 |
| **1987** | 34.97 | 1,706.55 | 0.00 | 1,741.52 |
| **1988** | 11.10 | 1,845.12 | 0.00 | 1,856.22 |
| **1989** | 15.71 | 1,971.83 | 0.00 | 1,987.54 |
| **1990** | 15.06 | 1,825.51 | 0.00 | 1,840.56 |
| **1991** | 15.24 | 2,009.20 | 0.00 | 2,024.43 |
| **1992** | 16.69 | 1,881.22 | 0.00 | 1,897.91 |

| | | | | |
|---|---|---|---|---|
| **1993** | 16.67 | 1,997.22 | 0.00 | 2,013.89 |
| **1994** | 18.01 | 1,945.02 | 0.00 | 1,963.04 |
| **1995** | 18.34 | 1,902.83 | 0.00 | 1,921.17 |
| **1996** | 14.86 | 1,961.23 | 0.00 | 1,976.08 |
| **1997** | 18.25 | 2,025.73 | 0.00 | 2,043.98 |
| **1998** | 11.77 | 2,418.12 | 0.00 | 2,429.89 |
| **1999** | 13.22 | 2,215.00 | 0.00 | 2,228.22 |
| **2000** | 16.69 | 2,406.70 | 0.00 | 2,423.39 |
| **2001** | 12.06 | 2,193.18 | 0.00 | 2,205.24 |
| **2002** | 16.37 | 2,065.94 | 0.61 | 2,082.93 |
| **2003** | 15.62 | 2,605.44 | 2.16 | 2,623.22 |
| **2004** | 15.09 | 2,388.16 | 6.32 | 2,409.57 |
| **2005** | 16.76 | 2,193.34 | 11.27 | 2,221.37 |
| **2006** | 14.79 | 1,916.44 | 11.67 | 1,942.90 |
| **2007** | 16.14 | 2,028.27 | 10.95 | 2,055.36 |
| **2008** | 11.87 | 2,075.24 | 13.27 | 2,100.39 |
| **2009** | 7.20 | 2,182.68 | 12.80 | 2,202.68 |
| **2010** | 4.05 | 2,219.33 | 11.21 | 2,234.60 |
| **2011** | 14.34 | 1,802.88 | 5.77 | 1,822.99 |
| **2012** | 10.98 | 1,532.22 | 5.91 | 1,549.11 |
| **2013** | 8.53 | 2,203.16 | 2.35 | 2,214.03 |
| **2014** | 11.29 | 1,698.21 | 1.73 | 1,711.23 |
| **2015** | 10.86 | 1,632.70 | 3.36 | 1,646.92 |

- Data for the elaboration of Fig. 4(b)_Evolution of total water consumption by type of technology in the Ebro River basin, 1969-2015.

***WATER CONSUMPTION*** $(hm^3/year)$

| Year | Technology | | | Total |
|---|---|---|---|---|
| | **Coal** | **Nuclear** | **Natural Gas CC** | |
| **1969** | 1.37 | 0.00 | 0.00 | 1.37 |
| **1970** | 1.49 | 0.00 | 0.00 | 1.49 |
| **1971** | 1.44 | 1.54 | 0.00 | 2.99 |
| **1972** | 1.49 | 2.72 | 0.00 | 4.21 |
| **1973** | 1.42 | 2.53 | 0.00 | 3.94 |
| **1974** | 1.18 | 2.42 | 0.00 | 3.60 |
| **1975** | 1.37 | 2.96 | 0.00 | 4.33 |
| **1976** | 1.37 | 3.08 | 0.00 | 4.45 |
| **1977** | 1.60 | 1.96 | 0.00 | 3.56 |
| **1978** | 0.96 | 3.36 | 0.00 | 4.32 |
| **1979** | 1.30 | 2.54 | 0.00 | 3.84 |
| **1980** | 6.30 | 0.84 | 0.00 | 7.14 |
| **1981** | 8.08 | 3.42 | 0.00 | 11.50 |
| **1982** | 8.48 | 2.23 | 0.00 | 10.71 |
| **1983** | 8.68 | 2.96 | 0.00 | 11.64 |
| **1984** | 8.58 | 7.63 | 0.00 | 16.21 |
| **1985** | 9.21 | 7.12 | 0.00 | 16.34 |
| **1986** | 8.07 | 15.39 | 0.00 | 23.46 |
| **1987** | 8.08 | 16.49 | 0.00 | 24.58 |
| **1988** | 5.04 | 17.88 | 0.00 | 22.93 |
| **1989** | 7.56 | 18.70 | 0.00 | 26.27 |
| **1990** | 7.26 | 17.77 | 0.00 | 25.03 |

| | | | | |
|---|---|---|---|---|
| **1991** | 7.27 | 19.00 | 0.00 | 26.27 |
| **1992** | 8.19 | 18.29 | 0.00 | 26.47 |
| **1993** | 8.41 | 18.88 | 0.00 | 27.28 |
| **1994** | 9.72 | 18.68 | 0.00 | 28.40 |
| **1995** | 9.48 | 17.78 | 0.00 | 27.26 |
| **1996** | 7.39 | 18.80 | 0.00 | 26.19 |
| **1997** | 8.55 | 19.39 | 0.00 | 27.94 |
| **1998** | 5.83 | 22.11 | 0.00 | 27.94 |
| **1999** | 6.77 | 19.87 | 0.00 | 26.64 |
| **2000** | 7.99 | 22.81 | 0.00 | 30.80 |
| **2001** | 5.74 | 21.69 | 0.00 | 27.43 |
| **2002** | 7.53 | 18.95 | 0.44 | 26.92 |
| **2003** | 7.49 | 23.44 | 1.55 | 32.48 |
| **2004** | 6.45 | 22.18 | 3.21 | 31.84 |
| **2005** | 7.48 | 19.62 | 5.66 | 32.75 |
| **2006** | 6.94 | 17.60 | 5.68 | 30.22 |
| **2007** | 7.59 | 18.03 | 5.34 | 30.97 |
| **2008** | 6.06 | 19.30 | 7.55 | 32.91 |
| **2009** | 3.94 | 19.33 | 7.83 | 31.10 |
| **2010** | 1.90 | 20.12 | 6.36 | 28.38 |
| **2011** | 6.83 | 16.22 | 3.85 | 26.90 |
| **2012** | 5.15 | 13.40 | 4.37 | 22.92 |
| **2013** | 4.00 | 16.36 | 0.67 | 21.03 |
| **2014** | 5.29 | 16.82 | 0.94 | 23.06 |
| **2015** | 5.09 | 16.19 | 1.34 | 22.62 |

- Data for the elaboration of Fig. 5_Evolution of technological water intensity in terms of water withdrawals and water consumption of thermal power stations in the Ebro River basin, 1969-2015.

***TECHNOLOGICAL WATER INTENSITY*** **$(m^3/MWh)$**

| **Year** | **Water Withdrawals** | **Water Consumption** |
|---|---|---|
| **1969** | 101.72 | 1.39 |
| **1970** | 111.95 | 1.26 |
| **1971** | 137.74 | 1.10 |
| **1972** | 141.82 | 1.08 |
| **1973** | 141.95 | 1.08 |
| **1974** | 144.95 | 1.05 |
| **1975** | 145.73 | 1.04 |
| **1976** | 145.28 | 1.05 |
| **1977** | 138.29 | 1.10 |
| **1978** | 145.60 | 1.07 |
| **1979** | 120.45 | 1.06 |
| **1980** | 29.87 | 1.06 |
| **1981** | 53.61 | 1.04 |
| **1982** | 40.67 | 1.04 |
| **1983** | 44.79 | 1.05 |
| **1984** | 62.76 | 1.05 |
| **1985** | 58.58 | 1.16 |
| **1986** | 78.45 | 1.08 |
| **1987** | 77.50 | 1.09 |
| **1988** | 84.66 | 1.05 |
| **1989** | 81.22 | 1.07 |
| **1990** | 79.13 | 1.08 |

| | | |
|---|---|---|
| **1991** | 82.29 | 1.07 |
| **1992** | 77.99 | 1.09 |
| **1993** | 81.44 | 1.10 |
| **1994** | 79.97 | 1.16 |
| **1995** | 79.36 | 1.13 |
| **1996** | 82.40 | 1.09 |
| **1997** | 77.43 | 1.06 |
| **1998** | 100.31 | 1.15 |
| **1999** | 89.70 | 1.07 |
| **2000** | 86.27 | 1.10 |
| **2001** | 87.78 | 1.09 |
| **2002** | 72.36 | 0.94 |
| **2003** | 87.96 | 1.09 |
| **2004** | 77.58 | 1.03 |
| **2005** | 63.90 | 0.94 |
| **2006** | 56.76 | 0.88 |
| **2007** | 62.01 | 0.93 |
| **2008** | 61.81 | 0.97 |
| **2009** | 72.50 | 1.02 |
| **2010** | 74.70 | 0.95 |
| **2011** | 65.41 | 0.97 |
| **2012** | 58.52 | 0.87 |
| **2013** | 104.32 | 0.99 |
| **2014** | 85.85 | 1.16 |
| **2015** | 74.42 | 1.02 |

# Appendix

The impact factor and subject categories corresponding to the publications included in this thesis are detailed below. The doctoral candidate's contribution to co-authored publications is also specified.

1. Sesma-Martín, D., & Rubio-Varas, M. (2019). The weak data on the water–energy nexus in Spain. *Water Policy*, *21*(2), 382-393. doi: https://doi.org/10.2166/wp.2019.081

**Impact factor**: 0.838 (Q4); **Subject Category**: Water Resources.

**Doctoral candidate's contribution**: Literature review, data collection, performing the analysis and manuscript writing. Corresponding author.

2. Sesma Martín, D., & Rubio-Varas, M.d.M (2017). Freshwater for cooling needs: A long-run approach to the nuclear water footprint in Spain. *Ecological Economics*, 140, 146-156. doi: https://doi.org/10.1016/j.ecolecon.2017.04.032

**Impact Factor**: 3.895 (Q1); **Subject Category**: Economics.

**Doctoral candidate's contribution**: Literature review, data collection, estimation of technical water coefficients, performing the analysis and manuscript writing. Corresponding author.

3. Sesma-Martín, D. (2019). The River's Light: Water Needs for Thermoelectric Power Generation in the Ebro River Basin, 1969–2015. *Water*, *11*(3), 441. doi:

https://doi.org/10.3390/w11030441

**Impact Factor**: 2.069 (Q2); **Subject Category**: Water Resources.

## References


Ackerman, F., & Fisher, J. (2013). Is there a water–energy nexus in electricity generation? Long-term scenarios for the western United States. *Energy Policy*, *59*, 235-241.

AEMET (Agencia Estatal de Meteorología); Instituto de Meteorologia. (2011). Iberian Climate Atlas Gobierno de España; Ministerio de Medio Ambiente y Medio Rural y Marino: Madrid, Spain; Instituto de Meteorologia de Portugal: Lisbon, Portugal.

Aldaya, M. M., Martínez-Santos, P., & Llamas, M. R. (2010). Incorporating the water footprint and virtual water into policy: Reflections from the Mancha Occidental Region, Spain. *Water Resources Management*, *24*(5), 941-958.

Averyt, K., Macknick, J., Rogers, J., Madden, N., Fisher, J., Meldrum, J., & Newmark, R. (2013). Water use for electricity in the United States: an analysis of reported and calculated water use information for 2008. *Environmental Research Letters*, *8*(1), 015001.

Bazilian, M., Rogner, H., Howells, M., Hermann, S., Arent, D., Gielen, D., ... & Yumkella, K. K. (2011). Considering the energy, water and food nexus: Towards an integrated modelling approach. *Energy policy*, *39*(12), 7896-7906.

Bartos, M. D., & Chester, M. V. (2015). Impacts of climate change on electric power supply in the Western United States. *Nature Climate Change*, *5*(8), 748.

Biggs, E. M., Bruce, E., Boruff, B., Duncan, J. M., Horsley, J., Pauli, N., ... & Haworth, B. (2015). Sustainable development and the water–energy–food nexus: A perspective on livelihoods. *Environmental Science & Policy*, *54*, 389-397.

Bizikova, L., Roy, D., Swanson, D., Venema, H. D., & McCandless, M. (2013). *The water-energy-food security nexus: Towards a practical planning and decision-support framework for landscape investment and risk management*. Winnipeg, Manitoba: International Institute for Sustainable Development.

Brundtland, G., Khalid, M., Agnelli, S., Al-Athel, S., Chidzero, B., Fadika, L., ... Singh,M., (1987). Our Common Future (\'Brundtland report\'). UN.

Byers, E. A., Hall, J. W., & Amezaga, J. M. (2014). Electricity generation and cooling water use: UK pathways to 2050. *Global Environmental Change*, *25*, 16-30.

Carrillo, A. M. R., & Frei, C. (2009). Water: A key resource in energy production. *Energy Policy*, *37*(11), 4303-4312.

Cazcarro, I., Hoekstra, A. Y., & Chóliz, J. S. (2014). The water footprint of tourism in Spain. *Tourism Management*, *40*, 90-101.

Cazcarro, I., Duarte, R., Martín-Retortillo, M., Pinilla, V., & Serrano, A. (2015). How sustainable is the increase in the water footprint of the Spanish agricultural sector? A Provincial Analysis between 1955 and 2005–2010. *Sustainability*, *7*(5), 5094-5119.

Chandel, M. K., Pratson, L. F., & Jackson, R. B. (2011). The potential impacts of climate-change policy on freshwater use in thermoelectric power generation. *Energy Policy*, *39*(10), 6234-6242.

Chapagain, A. K., & Orr, S. (2009). An improved water footprint methodology linking global consumption to local water resources: A case of Spanish tomatoes. *Journal of environmental management*, *90*(2), 1219-1228.

Chini, C. M., Djehdian, L. A., Lubega, W. N., & Stillwell, A. S. (2018). Virtual water transfers of the US electric grid. *Nature Energy*, *3*(12), 1115.

De la Torre, J., & Rubio-Varas, M. D. M. (2016). Nuclear power for a dictatorship: state and business involvement in the Spanish atomic program, 1950–85. *Journal of Contemporary History*, *51*(2), 385-411.

DeNooyer, T. A., Peschel, J. M., Zhang, Z., & Stillwell, A. S. (2016). Integrating water resources and power generation: the energy–water nexus in Illinois. *Applied energy*, *162*, 363-371.

De Roo, A., Bouraoui, F., Burek, P., Bisselink, B., Vandecasteele, I., Mubareka, S., ... & Bianchi, A. (2012). Current water resources in Europe and Africa. *Matching Water Supply and Water Demand*, 1-4.

De Vries, P., Tamis, J. E., Murk, A. J., & Smit, M. G. (2008). Development and application of a species sensitivity distribution for temperature-induced mortality in the aquatic environment. *Environmental Toxicology and Chemistry*, *27*(12), 2591-2598.

Diaz, J. R., Knox, J. W., & Weatherhead, E. K. (2007). Competing demands for irrigation water: golf and agriculture in Spain. *Irrigation and Drainage: The journal of the International Commission on Irrigation and Drainage*, *56*(5), 541-549.

Duarte, R., Pinilla, V., & Serrano, A. (2014). The water footprint of the Spanish agricultural sector: 1860–2010. *Ecological Economics*, *108*, 200-207.

Duarte, R., Pinilla, V., & Serrano, A. (2016). Globalization and natural resources: the expansion of the Spanish agrifood trade and its impact on water consumption, 1965–2010. *Regional environmental change*, *16*(1), 259-272.

Endo, A., Tsurita, I., Burnett, K., & Orencio, P. M. (2017). A review of the current state of research on the water, energy, and food nexus. *Journal of Hydrology: Regional Studies*, *11*, 20-30.

Fang, D., & Chen, B. (2017). Linkage analysis for the water–energy nexus of city. *Applied energy*, *189*, 770-779.

Feeley III, T. J., Skone, T. J., Stiegel Jr, G. J., McNemar, A., Nemeth, M., Schimmoller, B., ... & Manfredo, L. (2008). Water: A critical resource in the thermoelectric power industry. *Energy*, *33*(1), 1-11.

Förster, H., & Lilliestam, J. (2010). Modeling thermoelectric power generation in view of climate change. *Regional Environmental Change*, *10*(4), 327-338.

Fthenakis, V., & Kim, H. C. (2010). Life-cycle uses of water in US electricity generation. *Renewable and Sustainable Energy Reviews*, *14*(7), 2039-2048.

García, S. M. L., Irurzun, J. G., & de Paz, M. B. (2010). Red Eléctrica de España en perspectiva histórica. In *La creación de Red Eléctrica de España: empresarios y reguladores en tensión:[1982-1985]* (pp. 59-131).

Garrués-Irurzun, J. (2016). La transición eléctrica en España: de la regulación tradicional a la regulación para el mercado, 1982-1996. *Revista de Historia Industrial*, *25*(61), 183-206.

Gaviria, M. (1977). *El Bajo Aragon expoliado: recursos naturales y autonomía regional*. Zaragoza: Deiba.

Gleick, P. H. (1994). Water and energy. *Annual Review of Energy and the environment*, *19*(1), 267-299.

Grubert, E. A., Beach, F. C., & Webber, M. E. (2012). Can switching fuels save water? A life cycle quantification of freshwater consumption for Texas coal-and natural gas-fired electricity. *Environmental Research Letters*, *7*(4), 045801.

Hardy, L., Garrido, A., & Juana, L. (2012). Evaluation of Spain's water-energy nexus. *International Journal of Water Resources Development*, *28*(1), 151-170.

Hervás-Gámez, C., & Delgado-Ramos, F. (2019). Drought Management Planning Policy: From Europe to Spain. *Sustainability*, *11*(7), 1862.

Hoekstra, A.Y. (2003) (ed) 'Virtual water trade: Proceedings of the International Expert Meeting on Virtual Water Trade' ,Value of Water Research Report Series No.12, UNESCO-IHE, Delft, Netherlands, https://waterfootprint.org/media/downloads/Report12_1.pdf

Hoekstra, A.Y., Chapagain, A.K., Aldaya, M.M. & Mekonnen, M.M. (2011) The water footprint assessment manual: Setting the global standard, Earthscan, London, UK.

Huang, W., Ma, D., & Chen, W. (2017). Connecting water and energy: Assessing the impacts of carbon and water constraints on China's power sector. *Applied energy*, *185*, 1497-1505.

IEA (International Energy Agency). (2012). Water for Energy: is energy becoming a thirstier resource?

IEA (International Energy Agency). (2013). World Energy Outlook. [available online: http://www.iea.org/publications/freepublications/publication/WEO2013.pdf.

IEA (International Energy Agency). (2016). Water Energy Nexus. In World Energy Outlook 2016; OECD/IEA: Paris, France. Available online: https://www.iea.org/publications/freepublications/publication/WorldEnergyOutlook2016ExcerptWaterEnergyNexus.pdf

Kahrl, F., & Roland-Holst, D. (2008). China's water–energy nexus. *Water Policy*, *10*(S1), 51-65.

Kenny, J. F., Barber, N. L., Hutson, S. S., Linsey, K. S., Lovelace, J. K., & Maupin, M. A. (2009). *Estimated use of water in the United States in 2005* (No. 1344). US Geological Survey.

Larsen, M. A. D., & Drews, M. (2019). Water use in electricity generation for water-energy nexus analyses: The European case. *Science of the Total Environment*, *651*, 2044-2058.

Liao, X., Hall, J. W., & Eyre, N. (2016). Water use in China's thermoelectric power sector. *Global environmental change*, *41*, 142-152.

Liu, L., Hejazi, M., Patel, P., Kyle, P., Davies, E., Zhou, Y., ... & Edmonds, J. (2015). Water demands for electricity generation in the US: Modeling different scenarios for the water–energy nexus. *Technological Forecasting and Social Change*, *94*, 318-334.

Macknick, J., Newmark, R., Heath, G., & Hallett, K. C. (2011). *Review of Operational Water Consumption and Withdrawal Factors for Electricity Generating Technologies* (No. NREL/TP-6A20-50900). National Renewable Energy Lab.(NREL), Golden, CO (United States).

Macknick, J., Newmark, R., Heath, G., & Hallett, K. C. (2012a). Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature. *Environmental Research Letters*, *7*(4), 045802.

Macknick, J., Sattler, S., Averyt, K., Clemmer, S., & Rogers, J. (2012b). The water implications of generating electricity: water use across the United States based on different electricity pathways through 2050. *Environmental Research Letters*, *7*(4), 045803.

Maupin, M. A., Kenny, J. F., Hutson, S. S., Lovelace, J. K., Barber, N. L., & Linsey, K. S. (2014). *Estimated use of water in the United States in 2010* (No. 1405). US Geological Survey.

Mazdiyasni, O.; AghaKouchak, A. Substantial increase in concurrent droughts and heatwaves in the United States. Proc. Natl. Acad. Sci. USA 2015, 112, 11484–11489.

McMahon, J. E. and Price, S. K. (2011). Water and energy interactions. Annu. Rev. Environ. Resources 36163–91.

Mekonnen, M. M., Gerbens-Leenes, P. W., & Hoekstra, A. Y. (2015). The consumptive water footprint of electricity and heat: a global assessment. *Environmental Science: Water Research & Technology*, *1*(3), 285-297.

Meldrum, J., Nettles-Anderson, S., Heath, G., & Macknick, J. (2013). Life cycle water use for electricity generation: a review and harmonization of literature estimates. *Environmental Research Letters*, *8*(1), 015031.

Micheletti, W. C., & Burns, J. M. (2002). Emerging issues and needs in power plant cooling systems. In *Proceedings of the Workshop on "Electric Utilities and Water: Emerging Issues and R&D Needs": Pittsburgh, Pennsylvania*.

Mielke E, Diaz Anadon, L. & Narayanamurti, V. (2010) Waterconsumption of energy resource extraction, processing, andconversionDiscussion Paper 2010-15(Cambridge, MA:Energy Technology Innovation Policy Research Group, BelferCenter for Science and International Affairs, Harvard KennedySchool, Harvard University).

Naredo, J. M., Gaviria, M., y Serna, J. (1978). Extremadura saqueada: recursos naturales y autonomía regional.

OECD (2012), *OECD Environmental Outlook to 2050: The Consequences of Inaction*, OECD Publishing, Paris, France.

Perrone, D., Murphy, J., & Hornberger, G. M. (2011). Gaining perspective on the water− energy nexus at the community scale.

REE (Red Eléctrica de España) (2017). The Spanish Electricity System. Preliminary report 2017. Madrid. Available online: http://www.ree.es/sites/default/files/downloadable/avance_informe_sistema_electrico_2017_eng.pdf

Rodriguez, D.J., Delgado, A., DeLaquil, P., Sohns, A. (2013). Thirsty energy. In Water Papers; World Bank: Washington, DC, USA. Available online: https://openknowledge.worldbank.org/handle/10986/16536

Salmoral, G., Aldaya, M. M., Chico, D., Garrido, A., & Llamas, R. (2011). The water footprint of olives and olive oil in Spain. *Spanish Journal of Agricultural Research*, *9*(4), 1089-1104.

Saltelli, A. (2002). Sensitivity analysis for importance assessment. *Risk analysis*, *22*(3), 579-590.

Sanders, K. T. (2014). Critical review: Uncharted waters? The future of the electricity-water nexus. *Environmental science & technology*, *49*(1), 51-66.

Scanlon, B. R., Duncan, I., & Reedy, R. C. (2013). Drought and the water–energy nexus in Texas. *Environmental Research Letters*, *8*(4), 045033.

Scott, C. A., Pierce, S. A., Pasqualetti, M. J., Jones, A. L., Montz, B. E., & Hoover, J. H. (2011). Policy and institutional dimensions of the water–energy nexus. *Energy Policy*, *39*(10), 6622-6630.

Siddiqi, A., & Anadon, L. D. (2011). The water–energy nexus in Middle East and North Africa. *Energy policy*, *39*(8), 4529-4540.

Sovacool, B. K. (2009). Running on empty: The electricity-water nexus and the US electric utility sector. *Energy LJ*, *30*, 11.

Sovacool, B. K., & Sovacool, K. E. (2009). Identifying future electricity–water tradeoffs in the United States. *Energy Policy*, *37*(7), 2763-2773.

Spang, E. S., Moomaw, W. R., Gallagher, K. S., Kirshen, P. H., & Marks, D. H. (2014). The water consumption of energy production: an international comparison. *Environmental Research Letters*, *9*(10), 105002.

Spanish National Institute of Statistics (Instituto Nacional de Estadística). (2008). Water Statistics—The National Institute of Statistics' Brochure. INE base. January, Spain.

Stillwell, A., Hoppock, D., & Webber, M. (2010). Energy recovery from wastewater treatment plants in the United States: a case study of the energy-water nexus. *Sustainability*, *2*(4), 945-962.

Stillwell, A. S., King, C. W., Webber, M. E., Duncan, I. J., & Hardberger, A. (2011). The energy-water nexus in Texas

UNESA (Asociación Española de la Industria Eléctrica). *Annual Electricity Statistical Reports*. Available at http://www.unesa.es/

Van Vliet, M. T., Yearsley, J. R., Ludwig, F., Vögele, S., Lettenmaier, D. P., & Kabat, P. (2012). Vulnerability of US and European electricity supply to climate change. *Nature Climate Change*, *2*(9), 676.

Van Vliet, M. T., Sheffield, J., Wiberg, D., & Wood, E. F. (2016). Impacts of recent drought and warm years on water resources and electricity supply worldwide. *Environmental Research Letters*, *11*(12), 124021.

Varela-Ortega, C. (2008). The Water Policies in Spain: Balancing water for food and water for nature. In *6th Rosenberg International Forum on Water Policy, Zaragoza, Spain. In: Ingram, H. and Garrido, A.(eds) Water for Food: Quantity and Quality in a Changing World. Rosenberg International Forum on Water Policy. Routledge Publisher, Taylor and Francis Group*.

Vassolo, S., & Döll, P. (2005). Global-scale gridded estimates of thermoelectric power and manufacturing water use. *Water Resources Research*, *41*(4).

Yuan, J., Lei, Q., Xiong, M., Guo, J., & Zhao, C. (2014). Scenario-based analysis on water resources implication of coal power in western China. *Sustainability*, *6*(10), 7155-7180.