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Water: A key resource in energy production

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ABSTRACT

Water and energy are the key resources required for both economic and population growth, and yet both are increasingly scarce. The distribution of water takes large amounts of energy, while the production of energy requires large amounts of water in processes such as thermal plant cooling systems or raw materials extraction. This study analyzes the water needs for energy production in Spain according to the energy source sector (electricity, transportation or domestic) and process type (extraction and refining of raw materials or thermal plant use). Current and future water needs are quantified according to energy demand and technology mix evolution. Hypothetical scenarios that simulate the risks of promoting specific energy policies are also analyzed. Results show that the combination of energy resources used in Spain is projected to be more than 25% more water consumptive in 2030 than in 2005 under ceteris paribus conditions. Renewable energies are mixed in terms of their consequences on the water supply; wind power can reduce water withdrawal, while the biofuels production is a water-intensive process.

1. Introduction

Water and energy are the key factors for economic and population growth, and both are increasingly scarce. While this is well known, the fact that they are inextricably linked is less well understood. Our ability to provide both resources is being threatened by a number of emerging issues that must be addressed. The global community has to recognize that climate change will affect freshwater availability (IPCC, 2007), and that population growth is placing strains on water (Vorosmarty et al., 2000) and energy supplies (International Energy Agency, 2008). The distribution of water takes large amounts of energy, and the production of energy requires large amounts of water (King et al., 2008). Increasing energy security and reducing climate change are conflicting objectives that require tradeoffs. If the quality, quantity and accessibility of water resources is declining, the promotion of a diverse supply of reliable, affordable and sustainable energy is also at stake. Therefore, water security is an additional dimension that must be taken into account when planning future energy systems.

Water resources are under pressure in many parts of the world, including Spain. Analysis of whether the water reserves of a region can support energy production processes will be a critical issue in the near future. Water is used mainly for agriculture, drinking water and power production (Climate Institute, 2005). The power sector is one of the biggest water users in the world (Hightower and Pierce, 2008). Water is used at various stages of the power generation cycle, including fuel extraction (mining and refining, oil, gas, uranium and coal processing, coal and gas liquefaction and gasification, carbon sequestration) and generation (coal, gas, oil, nuclear and biomass power plants) (US Department of Energy, 2006). In addition, the rising use of biomass-based biofuels should also be taken into consideration, as biomass production (energy crops production) and processing (thermal biomass in power plants, ethanol production for transport fuels) also require huge volumes of water (King et al., 2008).

This study is focused on the quantification of both the water withdrawal and the water consumption for energy purposes, including any process used to produce thermal energy, electricity or transportation fuels. Water withdrawal is defined as the removal of water from any source or reservoir for human use. The water withdrawal constitutes the conveyance losses, consumptive use and return flow (AQUASTAT, 1998). If not consumed, the water is later returned to the same or another reservoir. When the withdrawn water is returned to the system, it may not be reusable for the same purpose; for instance, it may be returned at a different temperature or at a different sea level. Water consumption is defined as the amount of water extracted from a source that is no longer available for use, because it has evaporated, transpired, been incorporated into products and crops, consumed by man or livestock, ejected into the sea, or otherwise removed from freshwater resources (Eurostat, 2002). Water withdrawal and consumption provide a measure of overall risk with respect to changing water patterns and/or availability as a consequence of climate change.

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In Spain, the agricultural sector is the main water user followed by the thermo-electrical sector (Spanish National Institute of Statistics, 2008). However, water demand of the latter has increased more than 1/3 between 2001 and 2006, and these values are projected to continue rising as a result of projected increases in energy demands (Spanish National Institute of Statistics, 2008). At the same time, the introduction of local biofuels production increases competition with food and electricity production for limited water resources, particularly in regions where water is scarce. Overall, there are enough freshwater resources to match Spain's water needs, but water availability remains a region-specific problem (International Water Management Institute, 2007).

Hence, there is a need for the integration of water and energy resource planning. As freshwater resources will likely become more constrained in the future, thereby limiting electricity and energy supply, water efficiency must be considered in energy planning. This study, which is based on the creation of a model, points out the importance of the water-energy relations and sets the seed for modelling water needs in the energy production at a regional level. The model focuses on very different phases of energy production, carried out locally, and analyses their impact as a whole. Unifying all water-intensive energy processes for different final applications in a single model offers an integrated accounting framework to assess global water and energy policy making. The study enables comparing the large amount of water use in the energy production sector and the quantification of current and future water requirements according to energy demand by analyzing several scenarios. The model will help to evaluate the impacts of promoting specific energy policies. This quantitative approach assesses water security analysis and supports integrated planning between energy and water utilities.

2. Water-energy modeling and model structure

The model estimates the total water needs associated with energy production in different sectors for different purposes. This linear structured model provides the water uses for different sources of energy (coal, oil, nuclear, hydropower, natural gas and renewables) regarding technology available and regional energy demand. This model has been obtained by the creation and calibration of a technology matrix and a regional vector.

The model represents the current water-energy existing fleet, simulates projected scenarios and suggests improvements on water management in the energy production. Initially, a detailed study of the role of water consumption and withdrawal in the energy sector provided a list of the most water-consumptive energy processes carried out in Spain. Data was collected for total average water withdrawal and consumption, and energy production, per technology process to determine a technology data matrix. The model is disaggregated according to the energy source, technology process and economic sector. Finally, several scenarios are analyzed according to an energy scenario data vector. The model provides final results to assess the regional and national impacts on water withdrawal and consumption. (For more information about the methodology of the study step by step, see Appendix A)

Each source of energy will be processed differently depending on its final use in different sectors. Three sector categories will be considered: electricity, transportation and other sectors. The other sectors comprise the domestic, agriculture and industrial sectors. An energy carrier will pass through three different phases before its final use: production or extraction, refining, and transformation of raw materials (coal, gas, biomass) into final energy (electricity, thermal power or transportation fuels).

The electricity sector consists of three parts: electricity generation, extraction or production of raw materials, and refining raw materials.

- Electricity generation includes thermal plants (primarily conventional and combined-cycle) from coal, oil, gas, biomass and other residuum, nuclear plants, and renewable energies such as solar and wind. The extraction or production of raw material includes the extraction processes of coal, oil, natural gas and uranium and the acquisition or production of biomass. Refining of raw materials includes coal transformation and oil refining processes.
- The transportation sector consists of the production and refining processes of oil and the cultivation and production of biomass to produce bioethanol, biodiesel and biogas.
- Finally, the other sectors consider the production and extraction of oil and thermal biomass for energy purposes in the domestic, agriculture and industrial sectors.

The model has a linear structure as shown in Fig. 1.

The model inputs include the technology data matrix and the regional scenario data vector. The technology matrix contains water withdrawal or consumption data in liters per kilowatt hour (kwh) or kiloton oil equivalent (ktoe) of energy obtained. The matrix is sorted according to the energy type, economic sector and process type described above. The energy types are coal, oil, gas, nuclear, hydropower, solar energy, wind energy, electric biomass, other residuum, thermal biomass, bioethanol, biodiesel and biogas. The economic sectors are electricity generation, transportation and other sectors which includes agriculture, domestic and industrial sectors. The processes include production or extraction, refining, and transformation of raw materials into useful energy (electricity, thermal power or transportation fuels). For more information about the technology data matrix, see Appendix B.

The regional scenario vector consists of the total energy demand of a given country in kwh or ktoe. The geographic scale of the information depends on the source of energy, type of system and the source of information. While the water use data is mainly collected according to river basins, the energy data is gathered per autonomous region. Consequently, to gather all data in a common framework and to get to conclusions at a national level, the geographic scale of the regional vector is reduced to a country level. This regional linear model produces the water requirements sorted by energy source, economic sector and process type, and is applied to hypothetical scenarios in Spain. What distinguishes a Regional Model from a LCA Model is that the LCA Model examines the impact of a product on the environment from the beginning to the end of its lifetime while the Regional Model only analyses the processes, in the lifetime of the product,

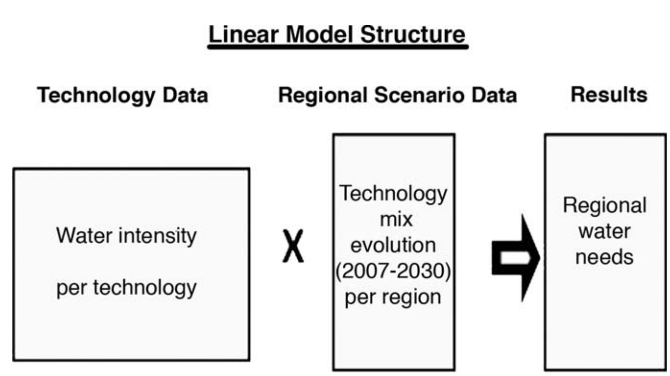

Fig. 1. Model structure.

which are carried out in a specific region. See Appendix Cfor more information about the regional scenario data vector.

Water requirements of energy-generation systems differ depending on the energy source. Thermal plants use fossil fuels to generate electricity or heat, and their water needs can vary drastically depending on the type of plant, type of refrigeration system, type of fuel and region (Electric Power Research Institute, 2002). The water demands of nuclear plants also depend on the cooling system; however, in current practice, nuclear plants often have lower thermal efficiency than thermal plants of similar age, according to the World Nuclear Association.

Energy generated from renewable resources also requires water consumption. Hydropower, for instance, requires huge water withdrawals. The water consumed in the hydropower facilities is negligible; however, the amount of water evaporated from lakes where the hydropower generation takes places can be extremely high, depending on the region and volume of the reservoirs (US Department of Energy, 2006). On the other hand, the water consumption rate of biomass-based energy (such as ethanol) is higher than any other energy source because cultivation of dedicated crops consumes huge amounts of water (King et al., 2008). On the contrary, wind and solar energies require almost no water (American Wind Energy Association, 2007). Therefore, the mix of renewable energies in use will be a key factor when analyzing the water requirements of a renewable energy-based scenario.

The information provided by the technology data matrix for Spain is presented in Fig. 2 sorted by technology process, economic sector and energy source.

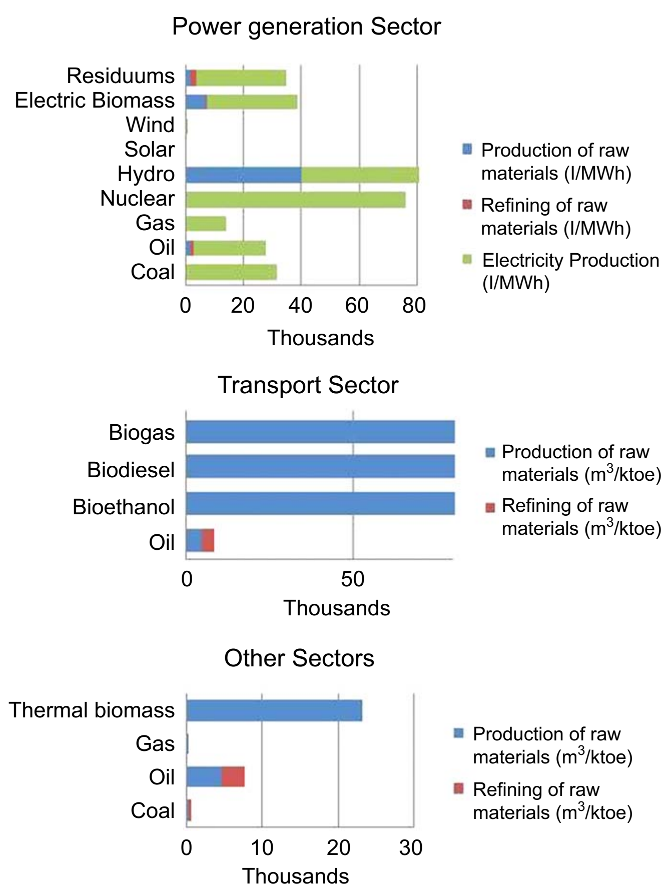

Fig. 2. Estimated water withdrawal in the Spanish Model (l/MWh = liters of water per Mwh of electricity) (m^3/toe = m^3 of water per toe of primary energy).

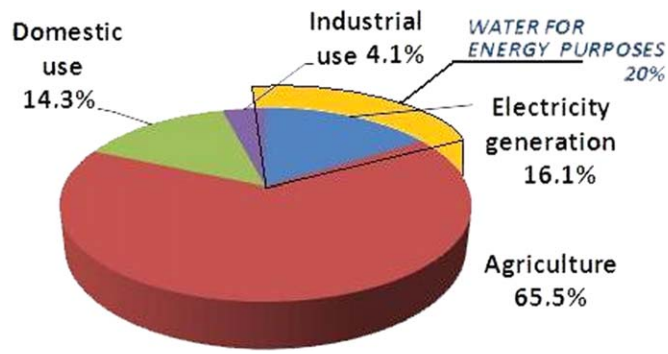

Fig. 3. 2007 Spanish freshwater withdrawal by sector (%) (Spanish Ministry of Environment, 2007).

3. Results: the Spanish model

3.1. Current freshwater uses

According to the Spanish National Institute of Statistics (2001), a total of 37.65 km^3 of freshwater was withdrawn for human use in 2001. In an ordinary year, about 60% of the total water withdrawn for human use is consumed and the rest is returned to the medium (Spanish Ministry of Environment, 2000). Water distribution by sector is shown in Fig. 3.

According to the present study, in 2005, the total water withdrawn for obtaining thermal energy, electricity and transportation fuels was around 8.5 km^3 (excluding hydropower water withdrawal).[1] Consequently, total water withdrawn and total water consumed for producing thermal energy, electricity and transportation fuels was around 20% and 3%, respectively, of the total water withdrawn for human use.

In terms of total water used by sector for energy production, electricity generation is the main withdrawer and consumer of water, followed by the transportation sector.

For the electricity generation, hydropower is the main water withdrawing source of energy. In a current hydrological year, hydropower uses more than 17 km^3 to produce energy (Spanish Ministry of Environment, 2007). Thus, the hydropower's capacity to produce energy depends on water availability to large amounts of water and droughts will be directly affecting energy production by hydropower. However, hydropower will not be directly affecting water availability for other uses as it is not a consuming use.

Apart from hydropower, in 2001, of 6 km^3 of water withdrawn for electricity generation, about 5 km^3 went to the cooling systems of thermal plants (Spanish Ministry of Environment, 2007). However, these figures have been increasing over the years. According to the model study, in 2005 the electricity generation sector withdrew around 8 km^3 of freshwater, of which 6.8 km^3 were used for the refrigeration of thermal and nuclear plants. Spanish thermo-electrical plants consume on an average just 5% of the total water that they withdraw for producing energy (Spanish Ministry of Environment, 2007) and the rest is returned to the sea or a river under special conditions,[2] as the cooling

[1] The total amount of water used for producing thermal energy, electricity and transportation fuels, provided by the model, will be calculated disregarding hydropower so as to be able to compare this figure with the total water withdrawn for human use estimated by the Spanish Ministry of Environment.

[2] The cooling system of thermal plants produces thermal pollution. The RDPH set a maximum temperature increase in rivers of 3 °C, and a maximum temperature of 30 °C for discharge into lakes or reservoirs. It set an increase of 1.5 °C in salmonid waters and 3 °C in cyprinid waters with peak discharge temperatures of 21.5 and 28 °C, respectively.

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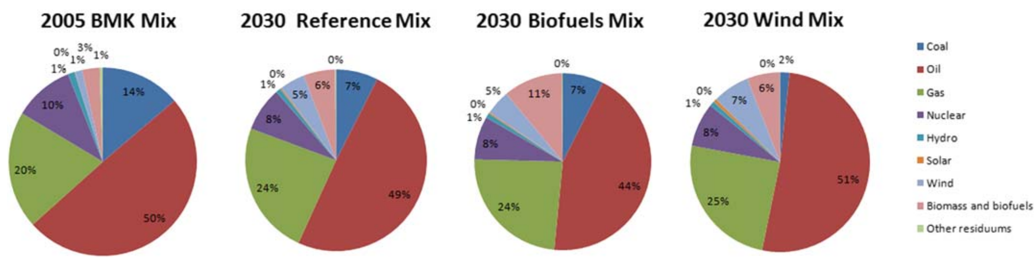

Fig. 4. Spanish energy-generation mix per energy source (%) (Spanish Ministry of Industry, 2006b; Spanish Electrical Industry Association, 2007) for different scenarios: 2005 BMK Mix = current fossil fuel mix; 2030 Reference Mix = projected mix in 2030; 2030 Biofuels Mix = projected mix in 2030 if 25% of fuels (for road transportation) were biofuels; 2030 Wind Mix = hypothetical mix where 37% of the electricity generation mix comes from wind power.

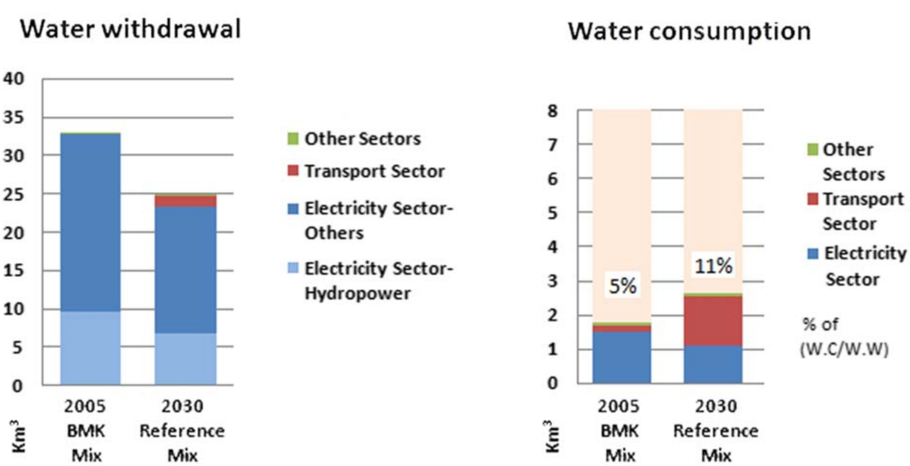

Fig. 5. Spanish total water withdrawal and consumption (km^3) for producing thermal energy, electricity and transportation fuels in different sectors for two scenarios: the 2005 BMK Mix (current fossil mix) and the 2030 Reference Mix (projected energy mix in 2030). These scenarios consider changes in the energy mix but not the projected rise in energy demand between 2005 and 2030. % of (W.C/W.W) refers to the % of water withdrawal which is consumed.

systems of thermal plants pollutes the water affecting the wildlife of the region. Most of the water consumed by the electricity sector is due to the evaporation of water from the supply lakes for hydropower generation.

In the transportation sector, water consumption comes from the production, extraction or refining of raw materials such as oil or biomass. In 2005, the transportation sector consumed little water because Spain currently imports most of the raw materials needed to produce local biofuels, and biofuels represent less than 1% of the transportation fuels. The most water-intensive process is the production of biomass for obtaining biofuels.

3.2. Projected water requirements

In order to project future water requirements, the combination of energy resources for energy production used in Spain was considered, hereafter referred to as the "energy mix". The following scenarios were studied: the 2005 BMK Mix (the benchmark scenario) and the 2030 Reference Mix (the 2030 projected scenario according to the energy mix estimated for 2030 by the Spanish Electrical Industry Association, 2007). Both scenarios have been simulated under *ceteris paribus* conditions (only considering changes in the energy mix) so as to analyze only the effect of the energy mix without being affected by the rise in the energy demand projected for 2030.

In addition, two more scenarios will be presented: the 2030 Biofuels Mix (which has the same electricity mix as the 2030 Reference Mix) and the 2030 Wind Mix. These will be analyzed and compared with the previous scenarios in the next section.

The Spanish energy mixes by scenario are shown in Fig. 4.

The 2030 Reference Mix decreases total water withdrawal compared to the 2005 BMK Mix but it increases the total water consumptive use of the country by up to 25% (Fig. 5). The 2030 energy mix tends to be more water consumptive, because even though the use of coal, oil, nuclear and hydropower is reduced as the use of gas, wind and solar energies increases, the use of biomass also increases, which is water intensive.

In the electricity sector, the analysis shows that there is a decline in the water withdrawn and consumed for electricity generation in 2030 Reference Mix over the 2005 BMK Mix. This is due to a reduction of the water withdrawn for hydropower and a change of the energy mix, in which less water is required for the cooling systems of thermal plants; given that coal and nuclear plants would lose share in favour of natural gas plants, wind power and solar energy.

In the transportation sector, it is expected that an average of 5.75% of fuels used for road transportation between 2005 and 2030 will be biomass based (International Energy Agency, 2008). This will lead to an increase of more than 4 times the current water consumption for this sector.

However, the situation could be even direr; if, in 2030, Spain cultivated enough energy crops to produce all the bioethanol and biodiesel used in the country, the total water consumption would be twice the current annual water consumption of the entire Spanish population.

Finally, both the change in the energy mix (see Fig. 4—*Energy generation mix for* 2030 *Reference Mix*), and the rise in energy demand between 2005 and 2030 are considered in the 2030 Reference Mix Scenario, the total water consumption for produ-

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cing thermal energy, electricity and transportation fuels would more than double between 2005 and 2030. The transportation sector is expected to undergo the most significant rise in water consumption due to the projected increases in biofuels production at the expense of fossil fuels (Fig. 6).

3.3. Alternative scenarios

In the 2030 Biofuels Mix, where we implemented the European Targets of 25% biofuels for road transportation in 2030 (European Commission, 2006). In this scenario, the transportation sector consumed 4 times the amount of water estimated in the 2030 Reference Mix, almost 6 times the total water consumed by the electricity sector (Fig. 7). Domestically produced biofuels not only consume a lot of water, but they can also put pressure on the water supply for other purposes such as agriculture or domestic use. One possible solution is to continue to import a portion of the biofuels from regions with widespread water availability.

The ideal energy mix should be more focused on natural gas, wind and solar energies instead of biomass and nuclear, as can be seen in the 2030 Wind Mix (Figs. 4 and 7). The 2030 Wind Mix could reduce water withdrawal by almost 8% compared to 2030 Reference Mix. Disregarding water withdrawn by hydropower, this amount reaches 27% of the total water withdrawal by the other energy sources. However, the reduction in water consumption is less evident because a significant portion of water consumption is due to evaporation in the supply lakes where hydropower takes place.

This model indicates that water consumption can be reduced by importing the water-intensive raw materials required for producing biofuels and enhancing less water-consumptive technologies such as wind and solar energies.

Apart from these scenarios, there are other challenges that still lie ahead; for example, the possible rise in the use of electrical cars, which could demand huge increases in electricity production. Under the conditions of the 2030 Reference Scenario (see Fig. 4—*Energy generation mix for* 2030 *Reference Mix*), but assuming that 25% of road transportation ran on biofuels and 75% of vehicles were electric cars, a 90% rise in electricity production compared to the 2030 Reference Scenario would be required to match the increase in electricity demand. Consequently, the water withdrawal and the water consumption in the electricity sector would increase 150% and 90%, respectively. It might be premature to be concerned about these figures, but it is important to consider what new technologies will require in terms of electricity and the impact that will have on the water supply.

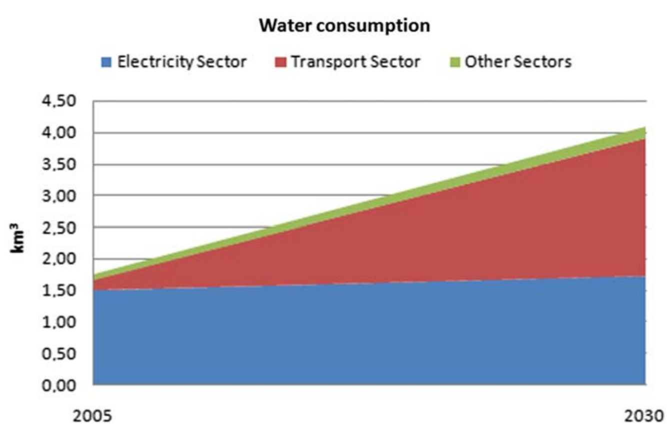

Fig. 6. Total water consumption trend (considering both changes in the energy mix and the projected rise in energy demand between 2005 and 2030) (km^3).

5. Conclusions and recommendations

Using a linear regional model, a small number of water impact assessments were analyzed for scenarios in which future energy demand vary depending on projected trends, energy policies and alternative technology available.

In Spain, the combination of energy resources is projected to be more than 25% more water consumptive in 2030 than the 2005 energy mix. In the transportation sector, if biofuels increased from 1% to 25% of the fuels used for transportation, they would consume almost 6 times the total water consumed by the electricity sector. However, if, in 2030, the energy mix was based on 37% wind power, water withdrawal would be reduced by almost 8% compared to the 2030 reference energy mix. This leads to the idea that, contrary to what it may seem, some of the latest energy policies based on more renewable portfolios promote use of water-intensive energies resources. While an energy mix

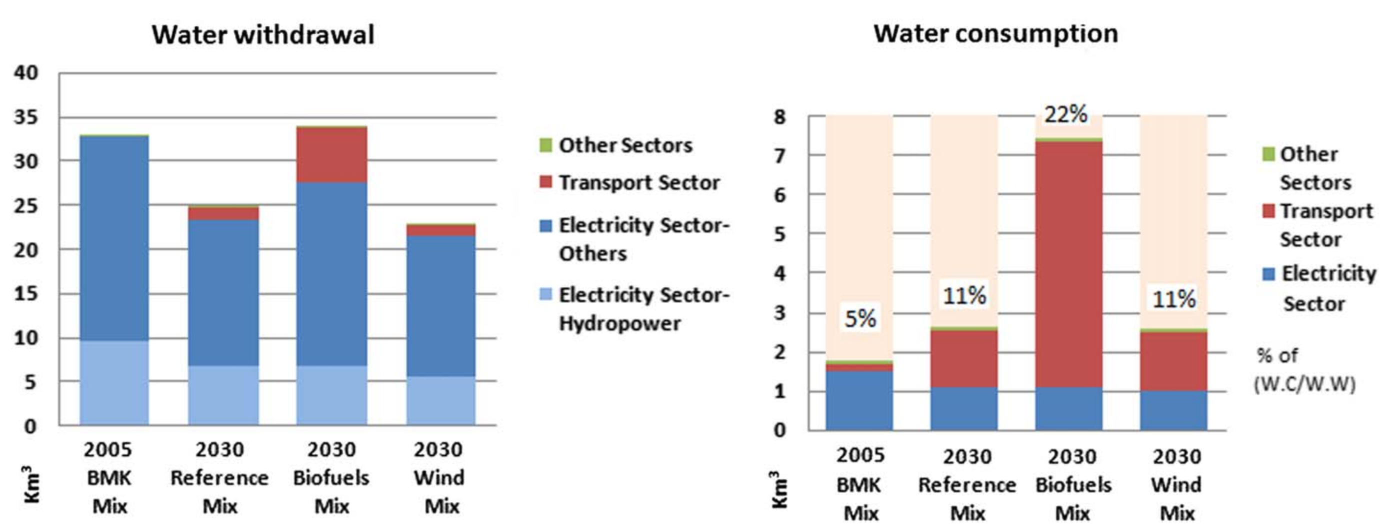

Fig. 7. Spanish total water withdrawal and consumption for producing thermal energy, electricity and transportation fuels in different sectors (km^3) for different scenarios: 2005 BMK Mix = current fossil fuel mix; 2030 Reference Mix = projected mix in 2030; 2030 Biofuels Mix = projected mix in 2030 if 25% of fuels were biofuels; 2030 Wind Mix = hypothetical mix where 37% of the electricity generation mix comes from wind power. These scenarios consider changes in the energy mix but not the projected rise in energy demand between 2005 and 2030. % of (W.C/W.W) refers to the % of water withdrawal which is consumed.

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based on wind and solar energy is less water intensive than any other scenario, a biomass-based energy mix (mainly to produce biofuels) can consume more than 10 times the amount of water than a fossil fuel based mix, depending on the raw materials used. Therefore, in areas where water is scarce, the local production of biofuels will not only reduce the amount of water available for energy production but it can also reduce the water supply for other purposes, including food crops.

Although these studies do not fully take into account the uncertainties in projected social and economical changes, they nevertheless provide an indication of the vulnerabilities and risks that can be reduced by considering the implications of the interrelations between water and energy. Power plant owners and developers will need to carefully consider the environmental risks associated with current water use and the growing challenge of water availability for new or existing plants. Power plants may be forced to adopt less water-intensive cooling technologies, such as dry or hybrid cooling, to reduce their water needs in certain areas in future. Furthermore, utilities in arid zones should focus on increasing investment in water-efficient electricity generation such as solar photovoltaic, wind power and coal gasification systems.

The development of this project has required an intensive research to collect regional data, which depends on the existence and availability of each region, and an exhaustive study of the water used in specific technological processes, whether in progress or under study. Also, the complexity and adequacy of the structure of the model chosen is a key factor to get an accurate and clear reflection of the real situation. We believe that future studies in this direction can be done regarding a deeper water-energy model that includes technical, economical and social issues. For instance, some energy model such as Markal, Geminis or EGEAS provide a detailed modeling of energy technologies and utilizations with energy–economy interactions captured through simple feedbacks that could work as a base to develop new models that entitle us to study, in deep, the risks of water management policies and practices.

A number of important technical, economical, political, environmental and social implications arise from water-energy linkages. Limited water supply is a reality today that is only projected to worsen in the future, as a consequence of climate change. Therefore, further and more in-depth analysis of the questions presented here is needed to provide guidance for governments and private sectors who will play an important role in mitigating and adapting to the future challenges of water and energy supply.

Acknowledgements

The support provided by the Ecole Polytechnique Federale de Lausanne, the Ministry of Industry and Environment, the Environmental Department of Union Fenosa, Endesa and Iberdrola, the Hydrological Planning Office of the Hydrographic Confederation of Ebro, Segura and Galicia and the US Western Water Assessment are gratefully acknowledged.

Appendix A. : methodology

The methodology to develop this study is presented, step by step, in Fig. 8.

Appendix B. : technology data matrix

The technology data matrix provides the water uses per energy unit produced sorted by energy source, economic sector and technology process. The Spanish technology matrix is shown in Tables 1 and 2.

The water withdrawal and consumption range per energy source and technology process are shown in Table 3.

Assumptions:

- When it comes to the water resources in Spain, one of the main problems to analyze the water consumption efficiency comes from the lack of reliable and periodical data of the water uses in Spain (Spanish Government, 2007). That is why, this study will get several references from reports carried out in other countries, such as US and Canada, where various organizations have been studying the water-energy linkages during many years and collected data about the water uses per technology process.
- Water withdrawal and consumption for obtaining uranium in Spain is dismissed as, only the last part of the uranium refining process is carried out in the country, by ENUSA, in which, water uses are minimal.
- In most of the transformation processes to extract and refine coal, oil and gas; water is mainly consumed or contaminated (not directly re-usable for any other purposes) while the production of biomass requires water for energy crops cultivation. Therefore, the model assumes that all the water withdrawn for extracting and refining coal, oil, gas, biomass and other residuum is totally consumed in the transformation processes whether it is evaporated or just not re-usable.
- Wind power and solar energy consume almost no water compared to other energies therefore its effect will be negligible.

A1: The amount of water withdrawn and consumed varies depending on several variables such as the type of process carried out (Gleick, 1994). Water uses in the coal and oil industry extracted from the Spanish National Institute of Statistics (1999) and the use of water in "The water use in the Spanish economy" report carried out by the Spanish Ministry of Environment (2007) in the framework of the Agua Program.

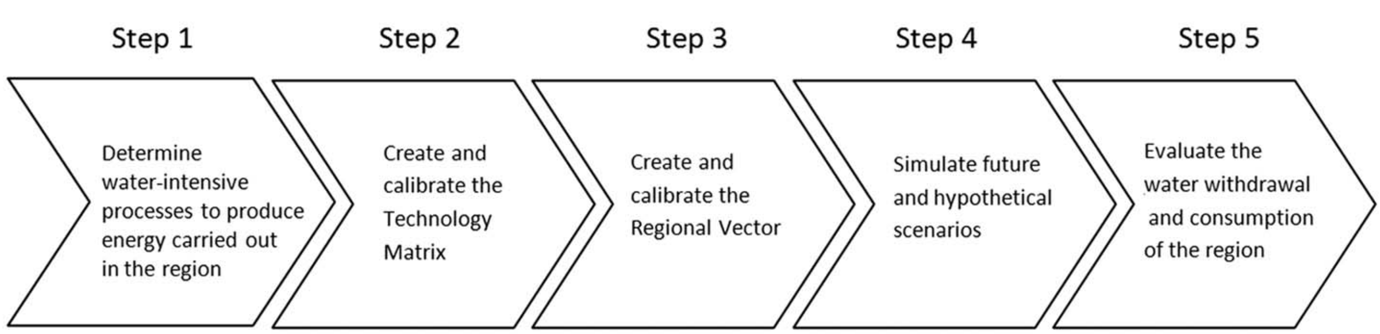

Fig. 8. Methodology for the water needs analysis.

Table 1
Spanish water withdrawal per energy source, economic sector and technology process (l/MWh = liters of water per MWh of electricity) or (m^3/toe = m^3 of water per toe of primary energy).

	Electricity sector			Transport sector			Other sectors		
	Production of raw materials (l/MWh)	Refining of raw materials (l/MWh)	Electricity generation (l/MWh)	Production of raw materials (m^3/ktoe)	Refining of raw materials (m^3/ktoe)	Transport use (m^3/ktoe)	Production of raw materials (m^3/ktoe)	Refining of raw materials (m^3/ktoe)	Other uses (m^3/ktoe)
Coal	70.00	50.00	31,046.74	–	–	–	247.68	174.00	–
Oil	1300.00	200.00	24,321.56	4536.98	697.80	–	4536.98	697.98	–
Gas	45.00	–	13,674.89	–	–	–	156.99	–	–
Nuclear	–	–	75,361.77	–	–	–	–	–	–
Hydro	20,000.00	–	791,676.83	–	–	–	–	–	–
Solar	–	–	–	–	–	–	–	–	–
Wind	–	–	1.00	–	–	–	–	–	–
Electric	biomass	6628.69	600.00	31,046.74	–	–	–	–	–
–									
Other	residuums	1292.00	1984.54	31,046.74	–	–	–	–	–
–									
Thermal	biomass	–	–	–	–	–	–	23,123.34	–
–									
Bioethanol	–	–	–	608,509.01	–	–	–	–	–
Biodiesel	–	–	–	816,860.61	–	–	–	–	–
Biogas	–	–	–	–	–	–	–	–	–

Table 2
Spanish water consumption per energy source, economic sector and technology process (l/MWh = liters of water per MWh of electricity) or (m^3/toe = m^3 of water per toe of primary energy).

	Electricity sector			Transport sector			Other sectors		
	Production of raw materials (l/MWh)	Refining of raw materials (l/MWh)	Electricity generation (l/MWh)	Production of raw materials (m^3/ktoe)	Refining of raw materials (m^3/ktoe)	Transport use (m^3/ktoe)	Production of raw materials (m^3/ktoe)	Refining of raw materials (m^3/ktoe)	Other uses (m^3/ktoe)
Coal	70.00	50.00	1552.34	–	–	–	247.68	174.00	–
Oil	1300.00	200.00	1216.08	4536.98	697.80	–	4536.98	697.98	–
Gas	45.00	–	684.74	–	–	–	156.99	–	–
Nuclear	–	–	1568.67	–	–	–	–	–	–
Hydro	20,000.00	–	–	–	–	–	–	–	–
Solar	–	–	–	–	–	–	–	–	–
Wind	–	–	1.00	–	–	–	–	–	–
Electric	biomass	6628.69	600.00	1552.34	–	–	–	–	–
–									
Other	residuums	1292.00	1984.54	800.00	–	–	–	–	–
–									
Thermal	biomass	–	–	–	–	–	–	23,123.34	–
–									
Bioethanol	–	–	–	608,509.01	–	–	–	–	–
Biodiesel	–	–	–	816,860.61	–	–	–	–	–
Biogas	–	–	–	–	–	–	–	–	–

A2: Ref. A1. It includes coal washing and transportation (Gleick, 1994).

A3: Water uses in thermal plants depend on fuel, cooling system type (once-through cooling, pond cooling, cooling towers and dry cooling) and plant type (steam and combined-cycle) according to the Electric Power Research Institute (2002), National Energy Technology Laboratory (2007) and National Renewable Energy Laboratory (2003). In Spain, while the water uses for energy production data is mainly collected according to fuel, technology system and river basins, the energy data is gathered per fuel, technology system and autonomous region. Data about water uses in electricity production belongs to energy producers. The study took a representative sample of the major electricity producers comprising 80% of the electricity production market to evaluate water needs for thermal plants. Data was collected from the sustainability reports of Endesa (2006), Iberdrola (2006) and Unión Fenosa (2006). These values were compared and contrasted with the water withdrawal and consumption rates given by "The water use in the Spanish economy" report carried out by the Spanish Ministry of Environment (2007) in the framework of the Agua Program.

A4: Ref. A3

A5: Ref. A1. Considering water use in oil extraction, production and onshore oil (Gleick, 1994).

A6: Ref. A1. Considering water use in oil processing (Gleick, 1994).

A7: Ref. A3

A8: Ref. A3

A9: Ref. A1. To estimate the water used in the extraction of gas, information was extracted, sorted by source of energy and process type, from studies carried out by the US Department of Energy (2006) and considering water use in onshore gas production (Gleick, 1994).

A10: Ref. A3

A11: Ref. A3

A12: Ref. A3. In the case of nuclear plants, specific information sorted by thermal system, cooling system and river basin is provided by Hispagua, Spanish Nuclear Forum (2006) and Spanish

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Table 3
Water usage range per energy unit produced sorted by energy source and technology process. (W.W = water withdrawal; W.C = water consumption)

		Low value	Estimated value	High value
A1	W.W. or W.C. for coal extracting (l/MWh)	13	70	78
A2	W.W. or W.C. for coal refining (l/MWh)	13	50	52
A3	W.W. for electricity generation from coal (l/MWh)	1134	31,047	189,000
A4	W.C. for electricity generation from coal (l/MWh)	756	1552	1815
A5	W.W. or W.C. for oil extracting (l/MWh)	191	1300	32,324
A6	W.W. or W.C. for oil refining (l/MWh)	90	200	233
A7	W.W. for electricity generation from oil (l/MWh)	0	24,322	189,000
A8	W.C. for electricity generation from oil (l/MWh)	0	1216	1814
A9	W.W. or W.C. for gas extracting (l/MWh)	10	45	32,300
A10	W.W. for electricity generation from gas (l/MWh)	0	13,675	189,000
A11	W.C. for electricity generation from gas (l/MWh)	0	684	1814
A12	W.W. for electricity generation from nuclear power (l/MWh)	1890	75,362	226,800
A13	W.C. for electricity generation from nuclear power (l/MWh)	1512	1569	2722
A14	W.C. for hydropower generation in supply lakes (l/MWh)	10,000	20,000	70,000
A15	W.W. for hydropower generation (l/MWh)	715,000	791,676	3145,000
A16	W.W. or W.C. for biomass production (l/MWh)	–	6629	–
A17	W.W. or W.C. for biomass refining (l/MWh)	–	600	–
A18	W.W. for electricity generation from biomass (l/MWh)	1134	31,047	189,000
A19	W.C. for electricity generation from biomass (l/MWh)	1134	1552	1814
A20	W.W. or W.C. for extracting residuums (l/MWh)	200	1292	3000
A21	W.W. or W.C. for residuums refining (l/MWh)	–	1985	–
A22	W.W. for electricity generation from residuums (l/MWh)	1134	31,047	189,000
A23	W.C. for electricity generation from residuums (l/MWh)	756	800	1814
A24	W.W. or W.C. for bioethanol production (m^3/ktoe)	–	608,509	–
A25	W.W. or W.C. for biodiesel production (m^3/ktoe)	–	816,860	–
A26	W.W. or W.C. for biogas production (m^3/ktoe)	–	0	–

Nuclear Society (2005). Since all the nuclear plants are based on American technology, except for Trillo Plant built with German technology, water uses will be contrasted with the American nuclear plant technology.

A13: Ref. A12

A14: Initially, an average consumption rate can be estimated by figures provided in some of the studies carried out by the National Renewable Energy Laboratory (2003). Besides, water consumption in supply lakes due to hydropower generation is currently less than 5% of the water withdrawn for turbine flow.

A15: In an ordinary hydrological year, the turbine flow uses more than 17,000 hm^3 for direct power generation (hydropower). Specifically, turbine capacity reaches 17,500 hm^3 in the hydropower plants of exclusive use and it reaches 21,850 hm^3 in the hydropower plants of sharing use (Spanish Ministry of Environment, 2007). The maximum electricity production considering the total potential of the water resources is 3145 m^3/Mwh (Spanish Ministry of Environment, 2007). In an ordinary year, about 715 m^3 of water is withdrawn to produce 1 Mwh of electricity.

A16: The biomass for thermal purposes and electricity generation comes from forest residues, agricultural waste and energy crops. Only biomass coming from energy crops production, directly, requires water irrigation. Both agricultural waste and forest residues are byproducts of the harvest (Institute for Diversification and Saving of Energy, 2006). Thus, water consumption will not be directly imputed to them. Estimations will be done according to energy crops water requirements.

A17: Biomass requires processing to be used in biomass-fuelled steam plants (Hirayama, 2006).

A18: Ref. A3

A19: Ref. A3

A20: Ref A1. It includes residuum from fossil transformation processes, municipal solid waste (MSW) and industrial waste.

A21: Ref A20

A22: Ref. A3

A23: Ref. A3

A24: The raw material needs for obtaining bioethanol are filled with wine alcohol, in a small proportion, and the rest, with cereals (domestically produced or imported) and beet. This study estimates that, in Spain, only a 10% of the bioethanol production comes from local cultivation. The water consumption per energy crop is shown in Table 4.

A25: The production of biodiesel is a simple and well-known process from a technical point of view. From 1000 kg of oil, 156 kg of methanol and 9.2 kg of potash, it can be obtained 965 kg of biodiesel and 178 kg of unrefined glycerin with a methanol recovery of 23 kg (Fernandez et al., 2008). Most of the biodiesel produced in Spain in 2004 was obtained from a mixture comprising 50% of imported palm oil, 25% of soybean oil obtained from national production of imported grain and 25% of rape oil from rapeseed grains cultivated in Spain (Estirado and Lucini, 2006). Currently in Spain, the 80% of energy crops produced for obtaining biodiesel comes from rapeseed (Blázquez, 2007). The water consumption per energy crop is shown in Table 5.

A26: In Spain, biogas has thermal and electrical uses and it is obtained from the treatment of four types of biodegradable waste. The main one is municipal solid waste (MSW) of landfills and industrial waste from breweries, sugar, alcohol, milk and others. The two other resources come from the sewage treatment plant (WWTP) and the livestock waste, especially slurry (Association of Energy Renewable Producers, 2005). Currently, the transformation of these resources into biogas requires small amounts of water compared to the fossil fuel transformation processes mentioned above or the energy crops cultivation; that is why, due to the magnitude of the figures, these processes will be considered negligible in terms of water consumption and withdrawal.

Appendix C. : regional scenario data vector

The regional scenario data vector provides the energy-generation mix per energy source, economic sector and technology process for selected scenarios. The production and refining of raw materials will vary depending on the import–exports and the capacity of the country so as to consider only local processes carried out. Energy production data per energy source will be

Table 4
Own elaboration of the water consumption for the cultivation of bioethanol according to the virtual water footprint (Water Footprint Organization, 2004) and the energy content (Tees Forest Organization, 2005) (Fernandez et al., 2008) and an estimated production mix.

Bioethanol		% source	Water needs (*X*) (m^3/t)	Energy content (*Y*) (kg/ l_ethanol)	Water consumption (dam^3/ktoe)
Cereals/crops	Wheat	0.77	1227	2.50	5583.91
	Barley	16.00	1070	2.50	4869.43
	Sunflower	67.43	1367	2.50	6119.70
	Corn	0.01	646	2.50	3123.33
	Oat	0.04	1751	2.50	7968.57
	Soybeans[a]	0.01	2714	2.50	12,149.88
	Rapeseeds	6.70	3284	2.50	14,701.62
	Pataca[a]	0.01	202	1.20	434.06
	Sorghum	0.02	721	0.87	1123.25
Roots	Beets	6.00	55	10.00	984.88
Cane	Sugar cane	3.00	133	12.28	2924.63
	Palm cane[b]	0.01	1053	15.00	28,284.07

[a] Future crops currently under study in Spain. The "% source" refers to the energy sources mix to produce bioethanol in Spain. Calculations: water consumption (m^3/ktoe) = $X\,m^3$ water/t oil × 1t/1000 kg × *Y* kg oil/1 l_ethanol × 1l/23 MJ × 4.1868 MJ/1 Mcal × 1E10 Mcal/1 Mtoe × 1 Mtoe/1000 ktoe × 1 dam^3/1000 m^3 = $X \times Y \times 1.820$.
[b] It has not been considered in the average rate for not being a representative crop in Spain yet.

Table 5
Own elaboration of the water consumption for the cultivation of biodiesel according to the virtual water footprint (Water Footprint Organization, 2004) and the energy content (Tees Forest Organization, 2005).

Biodiesel		% source	Water needs (*X*) (m^3/t)	Water consumption (dam^3/ktoe)
Oils	Sunflower	8	1367	1490.95
	Soybeans	8	2714	2960.09
	Rapeseeds	80	3284	3581.77
	Palm oil	4	1053	1148.48
Weighted average				3267.44

The "% source" refers to the energy sources mix to produce bioethanol in Spain. Calculations: water consumption (m^3/ktoe) = $X\,m^3$ water/t oil × 1 t/1000 kg × 1000 kg oil/965kg_biodiesel × 1 kg/1000 g × 0.88g/1 ml × 1000 ml/1 l × 1 l/35 MJ × 4.1868 MJ/1 Mcal × 1E10 Mcal/1 Mtoe × 1 Mtoe/1000 ktoe × 1 dam^3/1000 m^3 = $X \times 1.09086$.

Table 6
The regional scenario data vector for 2005 BMK Mix per energy source, economic sector and technology process (MWh = Mwh of electricity) or (ktoe = kilotoe of primary energy).

	Electricity sector				Transport sector				Other sectors			
	Production of raw materials (GWh)	Refining of raw materials (GWh)	Electricity generation (GWh)	Electricity generation (%)	Production of raw materials (ktoe)	Refining of raw materials (ktoe)	Transport use (ktoe)	Transport use (%)	Production of raw materials (ktoe)	Refining of raw materials (ktoe)	Other uses (ktoe)	Other uses (m^3%)
Coal	21,018.25	2969.02	69,326.00	24.22	0.00	0.00	0.00	0.00	584.83	82.61	1929.00	3.82
Oil	28.57	10,564.26	12,243.97	4.28	92.55	34,228.67	39,671.00	99.35	62.14	22,981.03	26,635.00	52.78
Gas	403.05	0.00	85,043.23	29.71	0.00	0.00	0.00	0.00	87.00	0.00	18,358.00	36.38
Nuclear	0.00	0.00	60,126.00	21.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hydro	29,301.00	0.00	29,301.00	10.24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Solar	0.00	0.00	108.68	0.04	0.00	0.00	0.00	0.00	0.00	0.00	69.00	0.14
Wind	0.00	0.00	22,924.00	8.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Electric	biomass	3170.18	3170.18	3170.18	1.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00												
Other	residuums	3960.80	3960.80	3960.80	1.38	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00												
Thermal	biomass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3477.00	0.00	3477.00
6.89												
Bioethanol	0.00	0.00	0.00	0.00	160.56	0.00	160.56	0.40	0.00	0.00	0.00	0.00
Biodiesel	0.00	0.00	0.00	0.00	62.44	0.00	62.44	0.16	0.00	0.00	0.00	0.00
Biogas	0.00	0.00	0.00	0.00	36.00	0.00	36.00	0.09	0.00	0.00	0.00	0.00

collected from the International Energy Agency (2008). The 2005 BMK Mix is shown in Table 6.

The description of the selected scenarios per energy mix is shown in Table 7.

The 2030 Reference Mix Scenario is a projected scenario. Moreover, this scenario is projected to fulfill some of the objectives proposed by the Spanish government in the Spanish Renewable Plan for 2010. It includes that renewable energies

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Table 7
Description and source of information per scenario.

Scenario	Description	Source
2005 BMK mix	2005 energy mix	Spanish Ministry of Industry (2006a,b)
2030 Reference mix	Electricity generation projections for 2030	Spanish Electrical Industry Association (2007), European Renewable Energy Council (2008), European Commission (2006)
2030 Biofuels mix	Hypothetical scenario for 2030 where 25% of the transportation fuels came from biofuels	Own elaboration, based on 2030 scenario
2030 Wind mix	Hypothetical scenario for 2030 where renewable energies account for 50% of the electricity generation: wind power (37%), hydropower (7%), biomass (3%) and solar energy (3%)	Own elaboration, based on 2030 scenario

account for 12% of primary energy and 30% of electricity generation and biofuels account for 5.75% of the transportation fuels.

The Spanish 2030 Biofuels Mix Scenario matches the European objectives for transportation fuels in 2030.

These scenarios are created under *ceteris paribus* assumptions so as to provide the analysis of the importance of the energy mix without the results being influenced by the rise in energy demand. Therefore, to evaluate both the influence of the energy mix and the energy demand rise, an additional case is presented.

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