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From water to energy: The virtual water content and water footprint of biofuel consumption in Spain

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ABSTRACT

Energy diversification and the use of renewable energy sources are key points in the European energy strategy. Biofuels are the most popular renewable resource option for the transport sector, and the European Union has established objectives that the Member States must adopt and implement. However, biofuel production at such a scale requires a considerable amount of water resources, and this water–energy nexus is rarely taken into account. This paper shows the strong nexus between water and energy in biofuel production and estimates the virtual water (VW) content and the water footprint (WF) from the raw material production that will be needed to reach the Spanish targets for biofuel consumption by 2010. The results show how the impact of such targets on the global and local water situation could be reduced through virtual water imports and, at the same time, how these imports could increase Spain's water and energy dependence. Hence, in order to manage water from an integral perspective of the territory, the inclusion of biofuel consumption objectives should go hand in hand with measures to reduce the demand of energy in the transport sector.

1. Introduction

Biofuel production has dramatically increased on an international scale (from 2000 to 2005, world ethanol production growth was 95% and that of biodiesel was 29.5% (IEA, 2007). On the basis of energy consumption projections within the transport sector, the European Union (EU) has established progressive compulsory consumption objectives for its member states to replace gasoline or diesel usage for transportation, as other regions of the world have already done. The compulsory biofuel share of the renewable energy consumption fixed by the EU for road transport was 2% for 2005 (COM (2003) 30) and is 5.75% for 2010 (COM (2003) 30) and 10% for 2020[1] (COM (2008) 29). As a member state, Spain has established its own national objective to have a 5.83% biofuel share of the gasoline and diesel consumption forecast by 2010 (Ministerio Industria y Comercio & IDAE, 2005). Currently, the Spanish biofuel share is 1.42% (CORES, 2008), mainly due to biodiesel. Spain has designed various measures to facilitate the achievement of this objective. For example, there is an exemption of the Special Taxes on Hydrocarbons (Spanish acronym: IEH) for the manufacture and import of biofuels (ethanol, methanol and some vegetable oils) in pilot plants for the first 5 years[2] and for the manufacture of biofuels in general until the year 2012[3] (Ley 23/2002).

There is considerable debate in scientific circles regarding how to manage the effects of large scale production and consumption of biofuels (a complete synthesis of this debate can be found in Russi, 2008, among other publications). Moreover, some papers discussing the reduction of CO_2 emissions derived from the use of biofuels instead of fossil fuels have been published recently. These

Abbreviations: BISP, second scenario combining Spanish biofuel imports with Spanish production; *C*, amount of grain or seeds of crop (*t*); CIEMAT, Energy, Environmental and Technological Research Centre (Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas); CWR, crop water requirement (m^3/ha); CY, crop yield (t/ha); CY_{dl}, crop yield of dry land; CY_{il}, crop yield of irrigated land; ER, effective rainfall (mm); INE, National Statistics Institute—Spain—(*Instituto Nacional de Estadística*); LHV, Lowe heating value; LCA, life cycle analysis; MARM, Environment Spanish Ministry (*Ministerio de Medio Ambiente, Rural y Marino*); MPOB, Malaysian Palm Oil Board; PS, population of Spain; RI, required irrigation (mm); SP, first scenario of Spanish production; SPD, third scenario of Spanish production in the case of drought; USDA, United States Department of Agriculture; VASAT, Virtual Academy for the Semi-Arid Tropics; VW, virtual water (m^3/t); VW_g, green virtual water; VW_b, blue virtual water; VW_{gdl}, green virtual water used in dry lands; VW_{gil}, green virtual water used in irrigated lands; WF, water footprint (m^3/cap/yr)

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[1] The 10% target includes all renewable energy sources used for transportation (e.g., hydrogen, electricity), not only biofuels.

[2] Ministerio de Economía y Hacienda. Real Decreto 774/2006, de 23 de junio, por el que se modifica el Reglamento de los Impuestos Especiales, aprobado por el Real Decreto 1165/1995, de 7 de julio. BOE 150:23983-23993, 24 de junio de 2006.

[3] Ley 23/2002, de 30 de diciembre, de Medidas Fiscales, Administrativas y del Orden Social. BOE 313: 46086-46191, 31 de diciembre de 2002.

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take into account the entire life-cycle of biofuels and the change in the use of land in order to produce raw materials and conclude that the issue of CO_2 reduction due to biofuel usage is still open to debate (Fargione et al., 2008; Righelato and Spracklen, 2007; Searchinger et al., 2008). Despite the increase of biofuel production and the amount of research about this issue, the potential effects of associated water consumption have not been rigorously analysed. Up until now, the consumption of water resources has not been taken into account as a barrier to reaching the above-mentioned objectives in areas with significant water shortages, such as the South and the East of Spain. Very few studies have analysed the relationship between biofuel consumption and pressure on water resources. De Fraiture et al. (2008) explored the land and water implications of global biofuel production in 2030 with a special focus on India and China. Gerbens-Leenes et al. (2008) assessed for bioenergy but not biofuels, and assessed the water footprint (explained below) of the biomass of some crops, comparing it with the water footprint of some fossil energy carriers and hydropower.

In order to study biofuels, not only the price of fuel production, but also all the resources needed for agricultural yield must be considered, with water being one of the major input components. In fact, agriculture is the most water-intensive human activity (Postel et al., 1996; Hoekstra and Chapagain, 2007). Therefore, it is important to refer to comprehensive research before implementing policies regarding demand-side water management and the sustainable use of water resources. Classical interpretations of water as a commodity or a production factor do not reflect the issue of the sustainable use of water resources (Savenije, 2002). Therefore, the need to apply an integral focus to water resource management is increasingly evident in water policies, especially in the current context of climate change. In this context of integral water and territorial planning, virtual water and water footprint are among the appropriate tools in the demand-side water management paradigm (Velázquez, 2008).

Here we investigated this relationship between biofuels and water by estimating the virtual water content and water footprint of the Spanish biofuel consumption targets. We argue that our data can be useful in determining the impact of biofuel production on water resources and its competition with other modes of water utilization.

This paper is structured as illustrated below. We first explain the methodology used in virtual water and water footprint estimations. Then we present a case study and discuss the results. Finally, we present our conclusions and comments on the issue as a whole.

2. Definitions and methodology—virtual water (VW) and water footprint (WF)

In order to reach our objectives of determining the impact of biofuel production on water resources, two concepts are used as physical indicators: virtual water (VW) and water footprint (WF). Both try to estimate the water content in a product or service, but there are some important differences between them. The descriptions of these indicators are presented below, including their objectives, differences and respective methodologies.

2.1. Definitions, objective and differences

The virtual water content of a product is defined as the volume of water used for its production (Allan, 1993). Hoekstra and Hung (2002) developed the most common methodology used nowadays to evaluate this factor. The concept of virtual water gains relevance when applied to trade between countries or regions, because imports and exports involve "virtual water transfers" (Velázquez, 2007). As the endowment of water and the amount of water used varies according to the place of production, virtual water trade between countries can be a way to save water on a global scale (Oki and Kanae, 2004; De Fraiture et al., 2004; Chapagain et al., 2006; Yang et al., 2006), as well as a way to increase efficiency[4] in the use of global water resources. Moreover, a country could preserve its domestic water resources by importing water-intensive products instead of producing them itself. This is particularly relevant for those countries with low water endowment (Aldaya et al., 2008).

Hoekstra and Chapagain (2008) noted that water savings are produced from the physical point of view even though virtual water is not included as a criterion in import and export planning. Thus, although the international and national trade rules do not consider the water intensity of products, the physical (water) trade has been made. There are also examples that show how, in certain cases, water-intensive products are exported following a criterion that is not based on the availability of water, since they are exported from places with water scarcity (Dietzenbacher and Velázquez, 2007) to places where water is abundant (Van Oel et al., 2008). There are other factors involved in a country's decision of whether to import or produce a particular product. A country's water endowment does not define its comparative advantage because it does not represent all of the opportunity costs of production (Wichelns, 2004). Moreover, the logic of comparative advantage applied to water could generate problems if not used in the appropriate context (Chapagain et al., 2006).[5]

In relation to VW trade and considering water savings through imports, Hoekstra (2003) distinguished two different approaches to the concept: real VW and theoretical VW. The real virtual water content of a product is the volume of water used to produce it at the place of production; in other words, it is the amount of water that a country (or a region) will have to use in order to produce a good or service instead of importing it. Instead, theoretical VW shows the potential water savings if a region decides to import a product instead of producing it.

The other important concept related to water consumption is water footprint (WF). Hoekstra (2002) defined the WF of a country (or individual) as "the total amount of freshwater that is used to produce the good and services consumed by a nation" (or "individual"). This concept was introduced to demonstrate the relationship between a country's water consumption and the use of its water resources (Hoekstra and Chapagain, 2008). The water footprint has two components: one internal (the portion of the water footprint that refers to the use of the country's water resources) and one external (the portion of the water footprint that exerts pressure on other countries' water resources) (Van Oel et al., 2008).

The main difference between these two concepts is that VW is defined from the perspective of production and WF is defined from a consumption point of view, though both are used to estimate the water content in a product or service (Velázquez et al., 2009).

[4] In our opinion, the concept of water efficiency should be carefully used in the water management context because it is a relative concept. Efficiency associates the amount of water consumed with another variable, in most cases a monetary variable. In this context, an improvement in water efficiency is understood as an increase of monetary production associated with the use of water, i.e., something good and desirable. However, this efficiency could be achieved at a high water cost, especially in those areas with water scarcity.

[5] The comparative advantage theory (an important rule of international trade) says that a country or region will specialize in a production for which it has a comparative advantage related to another country. According to that theory, a drought country must not specialize in water intensive products. However, many countries (for example, some developing countries) have water problems but need to produce water-intensive products that form the basis of their diet. In this sense, the comparative advantage theory could generate problems if not used in the appropriate context.

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2.2. Methodology of virtual water (VW)

The methodology used to estimate the virtual water content of a product was developed by Hoekstra and Hung (2002) and includes the process of cultivating raw materials and the various industrial stages until the final product is obtained. However, we decided to focus on the water used to obtain raw materials (i.e. agricultural products), leaving the study of the rest of the industrial and commercial steps, which indeed would increase the overall water intensity of the process, for future research.[6]

The virtual water content of an agricultural product (m^3/t) is estimated from the volume of water used during the crop's growth period (m^3/ha), called the crop water requirement (CWR) (Hoekstra and Chapagain, 2007, 2008). The volume of water used by a crop has two components: green water (rain[7] or soil humidity water evapotranspired by the crop) and blue water (irrigation water evapotranspired by the crop). It is important to differentiate between them because the use of green water in agriculture is related to more sustainable practices than the use of blue water (Aldaya et al., 2008). Thus, VW is green virtual water (VWg) plus blue virtual water (VWb)

$$VW = VWg + VWb \tag{1}$$

In Spain, most provinces[8] have a fraction of dry production (without irrigation) and a fraction of irrigated production of the same crop. Irrigated crops combine rainwater and irrigation water and usually have a higher yield than those grown in dry lands. Therefore, we can split green virtual water (VWg) into two components, the green water used in dry lands (VWgdl) and the green water used in irrigated lands (VWgil), which is usually associated with a higher yield

$$VWg = VWgdl + VWgil \tag{2}$$

The green virtual water content of the crop (VWg) has been estimated as the ratio of effective rainfall (ER) for each crop yield (CY) (Chapagain et al., 2006) of dry or irrigated land, depending on the case[9]

$$VWgdl = ER.10/CYdl \tag{3}$$

$$VWgil = ER.10/Cyil \tag{4}$$

The irrigation water used is considered equal to the required irrigation[10] (RI) (Chapagain et al., 2006) in each single province or region for each single crop. We estimated the blue virtual water of a province or region by dividing the irrigation water used by the irrigated crop's yield in that province or region or by the crop's yield in the country

$$VWb = (RI.10/CYil) \tag{5}$$

We estimated the green and blue virtual water content of each crop for the main producing provinces or regions (i.e., those that produce a significant percentage of the totality of each particular crop). The joint production of the selected provinces or regions must always add up to at least 90% of the country's total production of that particular crop (Aldaya et al., 2008).

To estimate the national average, we separately weighted green (split into green water in dry land and in irrigated land when the data allowed it) and blue water with the respective production share of each province or region in relation to the country's total production.

We estimated CWR, effective rain and required irrigation by means of the CROPWAT software (FAO, 2007b),[11] which is based on the Penman–Monteith method to estimate the reference crop's evapotranspiration (Allen et al., 1998). Crop coefficients, crop parameters and crop calendars are data required by the CROPWAT software, and we obtained them from the database of the software itself. When they were not included, we used the data from Allen et al. (1998). Note that these calendars and parameters are for food production and not for using crops as raw materials to produce biofuels. Therefore, it is possible that the optimal harvest date, for example, could be different.

The conceptual differences between theoretical and real virtual water were previously outlined. In this study, we only estimated real virtual water. This choice has its limitations since it does not allow an estimation of the amount of water savings due to imports. Nevertheless, the estimation of real VW demonstrates the differences between the various scenarios while the theoretical estimation is left for future research.

2.3. Methodology of water footprint (WF)

There are two ways to approach water footprint estimates, the bottom-up and the top-down approaches (Van Oel et al., 2008). The first approach uses the consumption data of a product as a starting point, while the latter uses production, import and export data. Due to the absence of data specifying the final use of crop imports (e.g., food or energy use), in this paper, we used the bottom-up approach. In other words, we estimated the water footprint of biofuel consumption, and to do so we used the targets specified within the *Plan de Energías Renovables en España* (PER, Plan of Renewable Energies in Spain, 2005) for 2010.

We used the same method as Russi (2007) to calculate the amount of grain and oil seed required, using the lower heating value (LHV) to convert energy units into mass units. We used a LHV of 37 MJ/kg for biodiesel and 27 MJ/kg for ethanol (COM (2008) 19); these values are consistent with those described in Russi (2008) and ECN (2007).[12] Then we used CIEMAT[13] (2005, 2006) data values for the ethanol or oil that can be extracted from seeds. Thus, in order to estimate the water footprint, we multiplied the virtual water content of every crop (VW) by the amount of grain or seeds of that crop in tonnes (*C*) needed to

[6] For further information on the industrial phases, CIEMA studies can be consulted. They estimate, for example, that 1.50, 1, 2.90 and 3.40 m^3 of water is used, respectively, for each tonne of sunflower, rapeseed, soy and palm oil production (CIEMAT, 2006).

[7] In general, the amount of rainwater that the plant can absorb is slightly less than the total amount of rainfall. Due to, for example, surface run-off or percolation, the crop cannot make complete use of the rainfall. We use the ratio of rainwater useful for plants (effective rain, as in Hoekstra and Chapagain, 2008).

[8] Spanish administrative unit of territory.

[9] Factor 10 is meant to convert mm into m^3/ha.

[10] As with rainfall, required irrigation is not the same as effective irrigation. However, there are barely any data on the latter and they are very difficult to obtain in a study of this scale (Hoekstra and Chapagain, 2008). To solve this problem, we assume that for crops that were irrigated, effective irrigation was equal to required irrigation, which can be estimated through the CROPWAT software from FAO. (〈http://www.fao.org/nr/water/infores_databases_cropwat.html〉).

[11] Although this software is adequate for these purposes, it must be taken into account that we are using CROPWAT on a national level, with the limitations that this practice implies. Other software packages more appropriate for application on a regional level have already been developed (for example, the Andalusian Government has its own software adapted to its geographical and climatic conditions). Even FAO has developed another program, AQUACROP, that improves on the former (http://www.fao.org/nr/water/aquacrop.html).

[12] We would like to point out that, although we included this specification in our estimation, the heat emitted by a biofuel varies depending on the crop from which it is produced (Demirbas, 2008); still, there are differences within the same crop (ECN, 2007). Other methodologies to estimate the heat produced by a crop can be found in Gerbens-Leenes et al. (2008). Biofuel LHV is always lower than that of fossil fuels: 42.8 MJ/kg for diesel and 43.7 MJ/kg for gasoline (ECN, 2007).

[13] Energy, Environmental and Technological Research Centre (Centro de Investigaciones Energeticas, Medioambientales y Tecnológicas), an important Spanish public research organisation that studies energy and the environment.

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Q3 **Table 1**
Characteristics of scenarios.

Year of study	Scenario 1 SP 2002	Scenario 2 BISP 2002	Scenario 3 SPD 2005
DATA			
Climate (a)	CLIMWAT[a]—FAO (2007a, b)	CLIMWAT—FAO (2007a, b)	CLIMWAT—FAO (2007a, b)
Yield	MARM (1999–2007)[b]	Palm oil—Malaysia—FAOSTAT 2005 Cereals—France—FAO (2008), Agro-Maps Soy—Aldaya et al. (2008)	MARM (1999–2007)
Crop sowing (b)	USDA, 2006[c] Rapeseed—Provedo and Díez (2006)	Malasya—VASAT[d] France—USDA Soy—Aldaya et al. (2008)	USDA (2006) Rapeseed: Provedo and Díez (2006)
CROPS			
Crop used for ethanol (CIEMAT, 2005)	Wheat: 56% Barley: 44%	50% self-produced cereal 50% imported cereal from France	Wheat: 56% Barley: 44%
Crop used for biodiesel (CIEMAT, 2006)	Sunflower: 60%	Rapeseed: 25% (5% Spanish, 95% imported from France) Soya: 40% (imported from USA)	Sunflower: 60%
	Rapeseed: 40%	Palm oil: 25% (imported from Malasya) Sunflower: 10% (Spanish)	Rapeseed: 40%

[a] CLIMWAT—data from FAO database, climate water.
[b] MARM—Spanish Ministry of the Environment (Spanish Acronym: *Ministerio de Medio Ambiente, Rural y Marino*).
[c] USDA—United States Department of Agriculture Database.
[d] VASAT—Virtual Academy for the Semi-Arid Tropics.

produce the total amount of biofuel consumed by the population of Spain (PS) in one year.

$$WF = \sum (VW.C)/PS \tag{6}$$

3. The water consumption of biofuel in Spain

We apply the previous methodology to the biofuel usage in Spain. We first specify the different scenarios that we consider in our case study, followed by a description of the assumptions that were used and finally the results.

3.1. Scenarios

There are many possibilities when defining scenarios, because neither the geographical origin of the raw materials nor the ratio of each crop used has a fixed allocation, but they depend on the market price (CIEMAT, 2005, 2006). CIEMAT issues published life cycle analyses (LCA) of ethanol and biodiesel (CIEMAT, 2005, 2006) that focused on CO_2 emissions. We used raw material ratios and geographical origin from the basic scenarios of the LCA and some from the alternative scenarios[14] used in the sensibility analysis of the LCA of CIEMAT (2005, 2006).[15]

We will consider three different scenarios: (a) Real VW for Spanish Production (SP); (b) Real VW combining Spanish Biofuel Imports with Spanish production (BISP) and (c) Real VW for Spanish Production in the case of Drought (SPD). Table 1 summarises data, crops and other characteristics.

In the second scenario (IBSP), we estimated real virtual water of a more realistic situation. We consider the possibility of combining the Spanish production of raw materials with Spanish imports. Thus, we estimate the amount of water embedded in the raw materials that Spain produces and in those that Spain imports. Regarding the latter, we estimate the amount of water that each producer country had to consume in order to produce those raw materials, according to the real virtual water concept.

The ratio of the amount of raw materials needed to produce ethanol and biodiesel is mentioned in Table 1. We considered cereal imports coming from France, which is the main country exporting cereal to Spain (MARM, 1999–2007).

To estimate virtual water in the exporting countries, we used administrative units of a higher level than that of the Spanish provinces (e.g., the entire country in the case of Malaysia), because the available information was less detailed and more difficult to find.[16] The Malaysian Palm Oil Board (MPOB) offers data on Malaysian crude palm oil production indicating that the Malaysian peninsula is the area with the largest palm oil production in the country. Then, assuming that crude palm oil production must be located near palm oil plantations, we used data from the meteorological station of the peninsular capital, Kuala Lumpur. To obtain the Malaysian palm oil yield for year 2002, we used the FAOSTAT database (FAO, 2005). To obtain the sowing time of Malaysian palm oil, we used information from the Virtual Academy for the Semi-Arid Tropics (VASAT). As the French yield and production data of 2002 were available at FAO's Agro-MAPS database (FAO, 2008), we used this information instead of that provided by FAOSTAT because the FAO Agro-MAPS database information is more detailed and allowed us to use the French regions as the unit of analysis. We used the USDA-database (2006) to obtain the sowing time of French crops and the estimate by Aldaya et al. (2008) on green and blue water for US soy. Q1

Finally, in the third scenario (SPD), as the estimation of virtual water varies according to changes in rainfall conditions, we are interested in carefully studying the relationship between water and energy through biofuel production and in analysing how the

[14] The LCA of biodiesel considers a greater number of alternative scenarios during sensibility analysis; we do not analyse all, as this study is not a LCA. From those scenarios, we believed it was more interesting to analyse the scenario that combines sunflower and rapeseed oil because they can be produced within Spain and allow us to draw a Spanish production scenario. Other crops have been considered in other studies, like cardoon (*Cynara cardunculus*), a less water-intensive crop than wheat, barley, soy or palm (Gual and Velázquez, 2007), or sugar beet (MARM, 1999–2007).

[15] To establish their scenarios, CIEMAT consulted important Spanish biofuel producers: Abengoa Bioenergía, Bioetanol Galicia and Ecocarburantes for ethanol and ACCIONA Biocombustibles and MOYRESA for biodiesel.

[16] As an example, it was impossible to define Malaysi palm oil cropping areas.

virtual water content of biofuels can be affected in a year of drought.[17] To depict a scenario of drought we used the rainfall and the productivity data from 2005,[18] when rainfall reached minimal levels at many Spanish meteorological stations (*Ministerio de Medio Ambiente*-—MMA—2006). As a consequence, the crop yields (t/ha) decreased with respect to the reference year, mainly in dry farming. This reduction of yield varied depending on each crop, and was more dramatic in the case of cereals. We considered the same crops as in the first scenario, and production and yield data were extracted from MARM (1999–2007).

3.2. Assumptions

In order to set a framework for our analysis, it was necessary to establish a certain number of assumptions, as mentioned below:

(1) We considered that the raw materials needed to produce biofuels are composed of cereals and oil seeds only.[19]
(2) We assumed that all the biofuel in question is being produced within Spain.
(3) We did not take into account the possibility of generating a variety of by-products at the different production stages, which could be reintroduced in the production line or reutilised in other sectors, therefore saving resources.
(4) We took into account the targets of Spanish biofuel consumption for 2010, according to the PER (2005).

These assumptions were used for the following reasons:

First, in Spain, there are currently no ethanol plants, either projected or in construction, except the ones that already existed when the PER (2005)[20] was written, declaring their intention to use wine wastes. Hence, in 2010, the production obtained from this kind of raw material will be the same as today: 26,000 tonnes (see footnote 20). Spanish biodiesel plants use mainly first generation vegetable oils, although they could possibly utilise used oils. There are currently eight plants, of the 30 already built in the Spanish territory, that employ used oils (see footnote 20). It is therefore difficult to quantify the use of these oils. Further research is needed to calculate the amount of water saved (and the associated use of land) through transforming raw materials that do not originate from agriculture.

Second, we assumed that Spain is not importing biodiesel or ethanol and that all the biofuel in question is being produced within the country, while we did consider the possibility of importing raw materials. Moreover, the plants already built, together with those that are under construction, have enough capability to generate the amount of biofuel required to reach the 2010 targets (see footnote 20).

Third, the different production stages generate a variety of by-products that could be reintroduced into the production line or reutilised in other sectors, therefore saving resources. This is an interesting aspect in energy terms. Water-wise, it could affect our estimate because water could be saved by replacing agricultural products with biofuel by-products in those industry sectors that allow it, such as feed production. Then, the amount of water saved by means of this replacement of raw materials could be deducted from the amount of water needed for the whole process (Russi, 2007). However, we did not take this possibility into account because it is not clear whether the supply of by-products would flood the feed manufacture demand (Russi, 2008; Giampietro et al., 1997; CIEMAT, 2006).

Fourth, the targets of Spanish biofuel consumption for 2010, according to the PER (2005), are 866 ktoe of ethanol and 1334 ktoe of biodiesel, for a total of 2200 ktoe of biofuels.

3.3. Results and discussion: virtual water

The results for the three scenarios are gathered in Table 2. Scenario 1 shows the real virtual water of Spanish production, i.e., the amount of water required if all biofuels are produced in Spain.[21] Results show that not only is ethanol's amount of virtual water content lower than biodiesel's, but also the share of the crop production used to produce ethanol with green water only is higher (85% and 84% of the total production of wheat and barley, respectively, versus 78% and 37% for sunflower and rapeseed[22] production in 2002, according to MARM (1999–2007)). In other words, the amount of water needed to produce ethanol is less than the amount used to produce biodiesel, but the PER (2005) still opts for biodiesel. These results confirm our previous hypothesis: energy objectives may not coincide with water endowment or availability.

In the second scenario, the results show the real virtual water or amount of water used by the crops grown within the Spanish territory combined with the imports. As we mentioned before, the real virtual water content of a product is the volume of water used to produce it at the place of production (Hoekstra and Chapagain, 2008). In our case, real virtual water is estimated in this second scenario by including the water that Spain needs for its production and the amount of water that other countries (countries from which Spain imports these raw materials) need in order to produce soy and palm oil. By comparing both scenarios, we have a general idea of the implications in terms of water use when changing the geographical origin of raw materials.

The total amount of virtual water used in the second scenario is less than in the first scenario for both ethanol and biodiesel. This happens because the countries chosen for this second

[17] In the case of drought, the share of dry and irrigated crops may vary: imposed irrigation restriction and deviation towards other uses (e.g. urban supply) may increase the share of non-irrigated crops or influence the farme decision on which crops to cultivate, favouring less water-requiring crops.

[18] The reason for referring to 2005 as a "drought" year is as follows: according to the "Public Bank of Environmental Indicators" (Environment Ministry of S-pain—Ministerio de Medio Ambiente, Rural y Marino), the percentage of normal rain (PPN—Porcentaje de Precipitación Normal—in their Spanish acronyms) is one of the indicators of drought in Spain. It is calculated as the relationship between accumulated precipitation in one year and the annual average of precipitation, specific to a region and a period of time. According to the PPN from Meteorology National Institute (Subdirección General de Climatología y Aplicaciones de la Agencia Estatal de Meteorología—AEMET-) and Environment Ministry, 2005 was the most severe drought year in the period (1941–2007).

[19] We used (CIEMAT, 2005, 2006) data values for the ethanol or oil that can be extracted from seeds.

[20] This information is available at the virtual meeting point of all Spanish ethanol and Biodieselspain, Centro de debate y Marketplace de biocombustibles-, 〈http://www.biodieselspain.com〉 [accessed on January 2009].

[21] As we noted in the Introduction, this study focuses on the production of biofuel in Spain. The main difficulty in estimating virtual water is finding the most appropriate water database. In this context, we are conscious that it is not rigorous to use national data on the uses of water because of the differences in climate and geographical conditions between regions, which differently affect each crop water consumption. Nevertheless, and despite this data limitation, we used the official database from the CIEMAT.

[22] The ratio of irrigated rapeseed in Spain has varied dramatically in the years for which information is available. For instance, it was 83% in 1996, 84% in 1998, 87% in 1999, 87% in 2001, 43% in 2003, 28% in 2004, 22% in 2005 and 23% in 2006. The total production of rapeseed is higher in those years with a lower ratio of dry farming production (MARM (1999–2007)). It is clear that the causes underlying the trend towards an increased ratio of dry farming are not related to rainfall conditions in the case of rapeseed production. This trend can mask the results of the third scenario, because it will influence the ratio of biodiesel blue water content so that it is lower in 2005 (drought conditions) and higher in 2002 (normal rainfall conditions), the opposite of the trend observed for the rest of the crops considered.

Table 2
Results VW[a].

	Scenario 1 (SP)			Scenario 2 (BISP)			Scenario 3 (SPD)		
	Ethanol (m^3/t)	Biodiesel (m^3/t)	Ratio of biofuels[b]	Ethanol (m^3/t)	Biodiesel (m^3/t)	Ratio of biofuels	Ethanol (m^3/t)	Biodiesel (m^3/t)	Ratio of biofuels
VWg	1286	2848	0.60	841	1084	0.70	1136	2380	0.49
VWb	771	2130	0.40	440	403	0.30	1101	2649	0.51
VW	2056	4977		1281	1487		2237	5029	

[a] Ethanol and biodiesel are expressed in m^3/t because virtual water is expressed in these units. Nevertheless, it should be appropriate in future studies to express them in m^3/MJ or $m^3/ktoe$ since these units could be useful to illustrate the water and energy nexus.
[b] The ratio of biofuels is the percentage of water assigned to blue versus green.

Q2 scenario have greater crop yields than Spain (FAO, 2005) and because their water requirements are lower (FAO, 2007b). It seems that their water productivity (t/m^3) is greater than Spain's, thus making these imports reasonable.[23]

On the other hand, we can see that in this scenario that the biofuels' ratio of blue virtual water content is lower than in the previous scenario and that the ratio of green virtual water increases. Therefore, our findings agree with other studies (Aldaya et al., 2008) in emphasizing the importance of green virtual water in the international trade of agricultural products, mostly when the flow is established from green water-rich[24] countries to countries with "blue water[25]-based economies" (Aldaya et al., 2008).

In the first scenario, we saw that to produce one tonne of ethanol and biodiesel, the ratio of green virtual water was higher than that of blue virtual water mainly in the case of ethanol. A change in rainfall conditions could change this ratio, increasing the use of irrigation water and consequently increasing the magnitude of the impact. By comparing the first and third scenarios, we can see that the amount of green water used by the crops was lower in the case of drought due to the fact that the amount of effective rain was lower.

On the other hand, we notice that the ratio of blue VW content in the third scenario is the highest. Still comparing the first and third scenarios, we can observe a modest increase in the amount of virtual water content in this last scenario, 8% and 1% for ethanol and biodiesel, respectively, while there is a 32% increase in the land required[26] to produce a tonne of biofuel. This increase is associated with the decrease in crop yields in this scenario. Consequently, to produce the same amount of ethanol or biodiesel, less water per hectare is needed in this scenario. Note that the increase in the amount of VW occurs to a lesser extent than the increase of land. Relating this result to Table 2, it can be observed that the use of blue water is more efficient than the use of green water in terms of cubic meters per cultivated hectare. This makes sense, considering that farmers can provide the amount of water needed by the plant whenever it is requested. However, there are other factors (such as plant acclimatisation or adaptation of the harvest date) that contribute to increased water use efficiency under drought conditions, which we did not take into account in our methodology. The critical point is that increased blue water use could be more efficient, but not necessarily more sustainable. However, blue water use is associated with increased environmental impacts due to the energy needed to pump water and to the effects of water excess (salinisation and waterlogging), which affect soil properties (Pimentel et al., 2004). Hence, biofuels' amount of virtual water content depends on yearly rainfall conditions. Such conditions can trigger a greater use of blue water, whose effects on the environment extend beyond just the increased pressure on the water resources and whose magnitude can be estimated, but not through this methodology.

Table 3
Results for WF. Seeds (thousands of tonnes) and WF ($m^3/cap/yr$)[a]

	Scenario 1 (SP)		Scenario 2 (BISP)	
Crop	Seeds	WF	Seeds	WF
Wheat, Spain	2466	143	1233	72
Wheat, France	–	–	1233	20
Barley, Spain	2268	62	1134	31
Barley, France	–	–	134	11
ETHANOL	4734	205	4734	133
Sunflower, Spain	2164	181	360	30
Rapeseed, Spain	1545	222	48	7
Rapeseed, France	–	–	918	19
Soya, USA	–	–	3278	100
Palm oil, Malaysia	–	–	2177	43
BIODIESEL	3709	403	6781	199
Total biofuel WF	–	608	–	332
Total Biofuel Internal WF	–		–	140
Total Biofuel External WF	–		–	192

[a] Data for Spanish population in 2010 is a forecast made by the National Statistics Institute (*Instituto Nacional de Estadística –INE-*), on January 1, 2008.

3.4. Results and discussion: water footprint

The results show the amount of seeds of each crop needed to produce one tonne of ethanol and one tonne of biodiesel according to the shares defined by (CIEMAT, 2005, 2006) and described in Table 3 and their corresponding WF in scenarios 1 and 2.[27] The results also show the WF of the total amount of biofuels needed to meet the Spanish objective proposed by the PER (2005). This WF implies a notably increased pressure on Spanish water resources because it is equivalent to a 49% increase

[23] To know precisely the amount of water saved due to imports, an estimate of theoretical virtual water would be necessary, but we leave this for further investigations.

[24] Rain or soil humidity water evapotranspired by the crop, according to previous definitions.

[25] Irrigation water evapotranspired by the crop.

[26] Since we know the amount of seeds needed and the crop yields for each scenario, just a simple calculation allowed us to estimate the necessary land in this case, which is 7.15 million ha versus the 4.80 million ha needed in the first scenario.

[27] At the beginning, we estimated the physical indicators (VW and WF) for a drought scenario since these situations are common in some regions of Spain. Nevertheless, as the first and third scenarios refer only to internal production, the first results indicate a similar virtual water amount (see Table 2) and also a similar water footprint. The relevant difference lies in the ratios of green water and blue water used in each scenario. These results have allowed us to make new estimations on this issue, which we will elaborate on in future research.

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in Spain's current internal water footprint due to the consumption of agricultural goods.[28]

The first scenario is not suitable for Spain because, despite its self-production, the country imports a considerable amount of cereals and oil seeds. For instance, in 2002, Spain produced 6822 thousand tonnes of wheat, 8362 tonnes of barley, 771 tonnes of sunflower seeds and 11 tonnes of rapeseed seeds (*Instituto Nacional de Estadística,* INE); but 6475, 1575, 430 and 15 thousand tonnes of wheat, barley, sunflower and rapeseed were imported, respectively (*Cámaras ~~Españolas~~ de Comercio*/Spanish Chambers of Commerce, database of Spanish imports and exports). To reach the 5.83% objective, Spain should produce considerable amounts of raw materials. The case of biodiesel is the most remarkable because the amount of oil seeds needed (see Table 3) is greater than both production and imports, always in the year of reference. Other reasons that make the first scenario unfeasible are physical, for example, the amount of land and water needed. On the other hand, as we mentioned above, in the process of deciding which raw materials to use, price is one of the key factors and, consequently, competition with the food industry has an important role, although this is not the focus of our research. In summary, we can expect that in order to reach the objective for 2010, Spain will increase the current imports of cereals and oil seeds. The second scenario represents this situation.

Biofuels' internal water footprint (see Table 3) causes an 11% increase in Spain's current internal water footprint due to the consumption of agricultural goods. In this scenario, biofuels' water footprint is divided into an external[29] water footprint and an internal[30] water footprint. In comparison with the previous scenario, there is a smaller impact of biofuels on domestic water resources in terms of water footprint because the internal water footprint would increase only by 276 m^3/cap/yr, at the expense of a 29% increase in Spain's current external water footprint due to consumption of agricultural goods.[31]

4. Conclusion

Reaching a level of biofuel consumption that represents 5.83% of the gasoline and diesel final energy consumption will entail an increase in Spanish water resources due to the need for raw materials. The use of tools like virtual water and water footprint can tell us how to use water in a more sustainable way and, therefore, how to reduce the pressure on water resources.

By including these tools when planning for the supply of raw materials, Spain would see a reduction in the pressure on national water resources, and this reduction would also happen at a global level because raw materials would be imported from countries with higher water yields. This is true as long as we consider the virtual water content as a factor that is important enough to determine the country's import structure.

In this case, it would be necessary to put a limit on the internal and external biofuel water footprint in order to ensure a real reduction in the use of water at a global level, avoiding the generation of perverse incentives, i.e., the transfer of the pressure on water resources onto other countries, generating overexploitation and ineffectiveness in water management. On the other hand, reducing the pressure on domestic water resources may simultaneously mean increasing the external water dependence. If we consider that water dependence is linked to importing energy inputs, we should evaluate to what extent biofuels are reducing national energy security.

The water impacts of biofuels also depend on the use of blue water, which mainly varies depending on the amount of the annual rainfall distribution. In terms of water usage (cubic meters per cultivated hectare), the use of blue water is more efficient than the use of green water,[32] but is associated with energy and environmental impacts. Water savings produced by the use of other raw materials, like those used in the second and third biofuel generations, are left for further research.

Biofuels strengthen the water–energy nexus to an extent that cannot be ignored. If the present objectives are reached and more ambitious objectives are incorporated in the future, we will have to influence the energy demand in order to influence the water demand in a demand-side water management system. Nevertheless, as we said before, other factors play a role in the import system, mainly the price of raw materials. We listed the proposals by Hoekstra and Chapagain (2008), aiming to strike a balance among sustainability, efficiency and equity in the global use of water resources. If virtual water and water footprints are adopted as physical indicators in planning the production of raw materials, some institutional arrangements should follow to guarantee that they are not transformed into yet another tool for supply-side policies. In that sense, it is important to note that when we speak about reducing the pressure on domestic water resources, we are also speaking about transferring the pressure on water resources over to other countries, thus exceeding the limits of domestic water resources and also ignoring the possibility that water scarcity can be induced by causes other than drought. If other rules are not introduced to level the playing field, countries with the ability to pay for the raw materials produced in other countries will not have to worry about an unsustainable increment of the pressure on their domestic water resources. Although physical connections can be easily ignored, we need to consider the water–energy nexus because the interdependence of water and energy can also manifest in a country's economy as one of the consequences of increased biofuel imports.

We agree with Hoekstra and Chapagain that a limit should be set on the water footprint of a country. However, determining that limit is a sensitive matter that requires more research along these lines.

It might seem evident that an increase in biofuel consumption will lead to an increase in the amount of water used. However, this fact is largely being ignored as increasing numbers of countries promote biofuel production without taking into account the concomitant effects on water and other resources. Hence, we think it is imperative that researchers in this field study this issue systematically and provide the data to concerned authorities so that they can make informed decisions. This aspect is especially relevant in areas with water problems (e.g. Southern Spain), where promoting biofuel production could further deplete the already scarce water resources, thereby instigating water conflicts and undermining the local economy.

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[28] The Spanish water footprint of the consumption of agricultural goods produced within the national territory using domestic water resources is 1251 m^3/(person/yr). (Hoekstra and Chapagain, 2008).

[29] Part of the water footprint that exerts pressure on other countries' water resources.

[30] Part of the water footprint that refers to the use of the country's water resources.

[31] The Spanish water footprint of the consumption of agricultural goods produced outside of the national territory using foreign water resources is 671 m^3/cap/yr (Hoekstra and Chapagain, 2008).

[32] If we consider it in the full life cycle scale.

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