Water footprint quantification of energy at a global level

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Abstract

Agriculture is by far the largest water user. This chapter reviews studies on the Water Footprint (WF) of bioenergy (in the form of first generation bio-ethanol and biodiesel) and compares the results with the blue WF of fossil energy and other types of renewables (wind, solar thermal energy and hydropower). The WF of bioenergy varies, depending on crop type applied, production location and agricultural practice. The blue water footprints of bioenergy and hydropower are much larger than for fossil, nuclear, wind and thermal solar energy. The blue WF of hydropower shows a large variation, between 0.3 and 850 m^3 per GJ, with an average probably somewhere between 20 and 70 m^3 per GJ.

The most water-efficient way to generate bioenergy is to use the total biomass, including parts without a large economic value, and generate heat. The generation of electricity is the second best option. Much research is presently done to develop the so termed second generation biofuels, biofuels generated from biomass waste. When this technique becomes available, large amounts of waste biomass can be converted into second generation biofuels. Also the development of third generation biofuels, biofuels from algae, is an interesting development that might decrease the WFs of biofuels.

When comparing different first generation biofuel practices, in general, it is more water efficient to produce bio-ethanol than biodiesel. The green WF of a typical biodiesel energy crop, rapeseed, is two times larger than the WF of ethanol from sugarcane and four times larger than ethanol from sugar beet. The blue WFs that have a larger environmental impact on water systems show a different pattern, however. For the dominant biofuel feedstocks, the global weighted average blue WFs increase in the following order: palm oil (0 m^3/GJ), ethanol from maize (8 m^3/GJ); ethanol from sugar beet (10 m^3/GJ), soybean oil (11 m^3/GJ), rapeseed oil (20 m^3/GJ), sunflower oil (21 m^3/GJ) and ethanol from sugar cane (25 m^3/GJ). Grey WFs related to water pollution are smallest for soybean and palm oil and for ethanol from sugar cane (6 m^3/GJ) and largest for rapeseed oil (29 m^3/GJ).

Our results provide new insights into the impacts of energy on the use and pollution of freshwater. This knowledge is a valuable contribution to future research and for policies concerning energy needs, freshwater availability and the choice whether to allocate water to food or to energy production.

1. Introduction

Fresh water of adequate quality is essential for the functioning of society and nature. Fresh water is a scarce natural resource. Most water on the planet earth is saline and cannot be used for societal needs. The oceans contain about 97.5 percent of available water in the form of salt water. Of the remaining 2.5 percent of fresh water, most is not accessible, because it forms part of ice or snow covers (Shiklomanov, 1997). Although the amount of water on the planet is constant, the annual freshwater supply in the form of precipitation is limited. Human activity consumes and pollutes great amounts of water, particularly through agricultural production (Hoekstra and Chapagain, 2007). Water use in agriculture, industry and households has increased sharply in the 20th century (Shiklomanov, 1997). Today, the increasing food demand, in combination with the shift towards a larger fraction of bioenergy in total energy supply, results in still increasing freshwater use (UNEP, 2009).

Natural precipitation is the main provider of water for agriculture. This is the so termed green water (Hoekstra et al., 2011). When precipitation is insufficient, farmers can apply irrigation, the so termed blue water. The irrigation sector has increased enormously in the past decades and is currently the largest water user, accounting for 61 percent of total water withdrawal globally. Between 1900 and 1995, the irrigated area expanded fivefold, from 50 to 250 million ha. Half of these irrigated areas are located in just four countries: China, India, the US and Pakistan (Shiklomanov, 1997). Today, about 80 percent of the agricultural water requirements are met by precipitation with the rest withdrawn from other sources, such as rivers and lakes (De Fraiture and Berndes, 2009). These withdrawals account for 70 percent of all human water use (UNEP, 2009).

Fresh water is becoming, more and more, a global resource, because water-intensive products are traded on global markets. International trade results in a spatial disconnection between consumers and the water resources used for making consumer products. Water footprint (WF) research shows the relationship between consumer goods and water consumption along supply chains, thereby addressing the link between consumption and production. By doing this, WF research offers a new perspective on how a consumer or producer relates to the use of freshwater systems (Hoekstra et al., 2011). The WF concept provides a tool to calculate water needs for consumer products and provides an indication of the total amount of freshwater used, directly and indirectly, along product supply chains (Hoekstra et al., 2011). The WF of a product, for example bio-ethanol, is the volume of freshwater used to produce the ethanol, measured over the complete supply chain. Important water-intensive products are crop and livestock commodities, natural fibers and bioenergy.

The next decades will see an increased demand for food (Tilman et al., 2002; FAO, 2003), as well as an increased demand for biofuels (See Eisenstraut in this publication, Stromberg et al., 2010). The corresponding necessary growth of agricultural output can be achieved in three ways: (a) an increase of agricultural land areas, (b) an increase of yield levels per unit of land (increase of land productivity), or (c) an increase of cropping intensities (e.g. by increasing multiple cropping and shortening the fallow periods). If agricultural land areas are increased, water use will probably increase by the same factor given that water input per unit of land usually remains the same. The increase of yield levels or cropping intensities might also increase water use in those cases where water is the limiting factor for crop growth.

Bioenergy production may divert land, water and other resources away from the production of food and feed (Fischer et al., 2009). In many countries, agricultural water use competes with other uses, such as urban supply and industrial activities (Falkenmark, 1989), causing the aquatic environment to show signs of degradation and decline (Postel et al., 1996). Crop growth (for biomass production) requires freshwater; and agricultural activity associated with feedstock production is by far the largest user of water, followed by industrial activities (WWAP, 2009). In general, increased biofuel production will probably require more water (Berndes, 2002; De Fraiture et al., 2008) and a shift from fossil energy towards bioenergy might put additional pressure on freshwater resources.

Today, some of the world’s most important agricultural areas show signs of water scarcity (De Fraiture and Berndes, 2009) such as North India, Pakistan and North China (Shah et al., 2007). Water shortages are the result of a mismatch between demand for fresh water and its availability over space and time. China and India will account for one third of the world population and will demand one third of the world’s energy supply by 2030 (De Fraiture and Berndes, 2009) so they aim to partly replace transport fuels from fossil sources by biofuels, such as bio-ethanol and biodiesel (Yang et al., 2009). This is expected to increase water scarcity, because China and India have already overexploited their natural water resources

(De Fraiture et al., 2008; Muller et al., 2008). Sufficient water for agriculture is available in Latin America and Sub-Saharan Africa (Muller et al., 2008), excluding South Africa (Jewitt et al., 2009). All of the above suggest that biofuel-related water consumption might aggravate water scarcity in many countries. In all, about thirty developing countries face water scarcity and it is expected that by 2050, over fifty developing countries will suffer from water shortages (Fischer et al., 2009). It is therefore important to have insight into the relationship between agricultural output, water consumption and water availability in order to properly allocate the water to food or to bioenergy (e.g. biofuels).

Biofuel production does not only affect the quantity of water resources but can also affect the quality of such resources (Stromberg et al., 2010). Apart from water, other important agricultural inputs for feedstock production include nutrients (such as nitrogen and phosphorus) and agrochemicals for controlling pests, diseases and weeds. When agricultural yields increase, the demand for nutrients expressed per unit area also increases (De Wit, 1992). Part of these inputs leach to water bodies and cause water pollution (UNEP, 2009; Simpson et al., 2009; Stromberg et al., 2010). Ethanol production, for example, has serious implications for coastal water quality and will almost certainly worsen already serious hypoxic conditions in many locations around the world (Simpson et al., 2009). Sugarcane expansion is one of the main drivers of increased fertilizer and agrochemical use in Brazil which has been linked to water pollution and ecosystem deterioration (Martinelli and Filoso, 2008).

In this chapter, we present the WF concept to assess the water requirements of different biofuel production practices. Initially, we summarize the WF methodology and review the recent bioenergy WF studies that have estimated WFs per unit of bioenergy (m3/GJ). Next, we compare WFs of bioenergy with WFs of fossil energy carriers, nuclear energy and the WFs of renewables (wind, solar thermal and hydropower). The chapter gives WFs of various types of bioenergy in m3 per unit of energy (GJ) and covers the main producing countries, including developing countries, transition countries and industrialized countries.

2. The Water Footprint

The water footprint (WF) is a multi-dimensional indicator, giving water consumption volumes by source and polluted volumes by type of pollution. The WF of a product is defined as the volume of freshwater used for its production at the place where it was actually produced (Hoekstra et al., 2011). In general, product’s actual water contents are negligible compared with their WF. For many products, such as bioenergy, the water used (or consumed) during the agricultural production stage makes up the bulk of the product's total life-cycle water use.

The WF concept includes three components—green, blue and grey water—and distinguishes between direct and indirect water use, taking into account the water use along supply chains. The components of WFs are specified geographically and temporally. Green water refers to the precipitation on land that does not run off or recharge the groundwater, but is stored in the soil as soil moisture and water that stays on top of the soil and on the vegetation. Green water eventually evaporates or transpires through plants. It can be made productive for crop growth. The green WF in crop growth is equal to the volume of evapotranspiration from the field from sowing to harvesting plus the volume of water incorporated into the crop.

The blue WF refers to consumption of blue water resources, i.e. fresh surface and groundwater. Water consumption does not mean that the water disappears, because it remains within the hydrological cycle and always returns somewhere. Blue water consumption refers to the following four cases: (i) water evaporates; (ii) water is incorporated into products; (iii) water does not return to the same catchment area where it came from; and (iv) water does not return in the same period.

The grey WF refers to pollution and is defined as the volume of freshwater required to assimilate the load of pollutants based on existing ambient water quality standards (Hoekstra et al., 2011). The grey component of the WF is:

$$\text{Grey WF} = [(\alpha \times AR) / (c_{max} - c_{nat})] / Y \qquad (1)$$

where AR is the chemical application rate to the field per ha (kg/ha), α is the leaching-runoff fraction, cmax, is the maximum acceptable concentration of the pollutant (kg/m^3), cnat, is the natural concentration for the pollutant considered (kg/m^3) and Y is the crop yield (ton/ha).

The pollutants generally consist of fertilizers (nitrogen, phosphorus, etc.) and agrochemicals. One has to consider only the ‘waste flow’ to freshwater bodies, which is generally a fraction of the total agricultural application to the field. One needs to account for only the most critical pollutant, that is the pollutant for which the above calculation yields the highest water volume (Hoekstra et al., 2011).

The method is the global standard for water footprint assessment, which is the most comprehensive method for assessing water consumption and pollution along supply chains (Hoekstra et al., 2011). The method is supported by the Water Footprint Network that includes over 150 partners, including for example WWF, the World Business Council for Sustainable Development and many universities.

3. Bioenergy

Bioenergy is energy derived from biomass, material of organic origin in non fossilized form, e.g. agricultural crops, forestry products, agricultural and forestry wastes and by-products, manure, microbial matter, and wastes from industry or households (FAO, 2006). Bioenergy includes different forms of energy, e.g. heat and electricity from the burning of biomass, or biofuels, for example, bio-ethanol and biodiesel. In general, a distinction is made between first, second and third generation biofuels. First generation biofuels are the presently available biofuels produced using the starch, sugar, or oil fraction of a crop. Applying conventional techniques, these fractions are converted into ethanol by fermentation or into biodiesel by extracting and processing the oil (Worldwatch Institute, 2007).

Future developments in the area of biofuels are, for example, the development of so termed second generation and third generation biofuels, such as biodiesel from algae (see also Gerbeens-Leenes et al. in this publication). For the second generation biofuels, cellulosic biomass of, for example, crop wastes or woody residues from forestry, is applied as a feedstock. There are two basic conversion technologies, thermo-chemical conversion, e.g. pyrolysis, and biochemical conversion, e.g. biological conversion into ethanol (Worldwatch Institute, 2007). At present, research is done to develop second generation biofuels from agricultural waste, such as pyrolysis oil and ethanol. Pyrolysis oil, however, still misses the quality of first-generation biodiesel, because it contains hundreds of different components formed during the decomposition of the cellulosic biomass in the feedstock. Pyrolysis oil has a low quality, is unstable, has a high acidity and viscosity and it has a relatively low energy content. Moreover, it is not miscible with petrol and is corrosive to engines (De Miguel Mercader et al., 2010). Another problem is the instability of pyrolysis oil, especially during storage, referred to as ‘‘aging” (Oasmaa and Czernik, 1999). Aging causes greater viscosity and a possibly unwanted change in chemical composition of pyrolysis oil. Biological conversion into ethanol, e.g. by fermentation, also finds itself in an experimental stage (Worldwatch Institute, 2007, Park et al., 2010). When the production of second generation biofuels is technically and economically possible, large amounts of feedstocks are available.

A second interesting development is the production of biodiesel from algae, the so termed third generation biofuels. To date, microalgae-based biofuel production has not yet been commercialized to a large scale, but there is a wide interest for this new biofuel, for example from the US army for aviation (Cullom, 2010) and from the aviation industry (Holmgren, 2009). Biodiesel from algae can reduce WFs compared to presently applied biodiesel (Yang et al., 2010).

3.1 Bio-ethanol

Bio-ethanol is a liquid biofuel. Globally, 75 percent is used for transportation (Worldwatch Institute, 2007). Industry produces 95 percent of the bio-ethanol by fermenting sugar and starch (carbohydrates), mainly from sugar cane, sugar beet and maize (Berg, 2004). Sugar cane is a perennial crop growing in tropical climates. Over the period 1998-2007, Brazil produced 30 percent of the global sugar cane, India 21 percent, China 7 percent, and Thailand and Pakistan 4 percent each (FAO, 2011). Sugar beet is a root crop growing in temperate climates. The main producers are France (12 percent of global production), the US (11 percent), Germany (10 percent), the Russian Federation (8 percent), Turkey (6 percent), the Ukraine (6 percent), Poland (5 percent), Italy (4 percent) and China (4 percent) (FAO, 2011). Although sugar beet has high ethanol yields per hectare (Rajagopal and Zilberman, 2007), the use for bio-ethanol is limited compared to sugar cane. Maize grows in moderate and sub-tropical climates. The US (40 percent of global production) and China (20 percent of global production) are the main producers (FAO, 2011). About half of the maize is used for animal feed, the other half for industrial purposes, such as bio-ethanol. In 2019, bio-ethanol production is expected to require 40 percent of the maize grown in the US (Economic Research Service/USDA, 2009).

3.2 Biodiesel

First generation biodiesel is produced from oilseed crops, e.g. rapeseed, soybean, sunflower, palm, coconut or jatropha. The vegetal oil is extracted. Sometimes it can be used directly, in the form of straight vegeTable oil, sometimes a conversion step is needed, especially in temperate climates, because straight vegeTable oil has a high viscosity at low temperatures (Worldwatch Institute, 2007). The biodiesel is manufactured by applying transesterification, in which oil reacts with an alcohol giving an alkyl ester of a fatty acid with a higher viscosity. In Europe, rapeseed is the main feedstock for biodiesel, with some sunflower. In the US, soybean is the main feedstock. In tropical countries, the main feedstocks are palm, coconut and jatropha oil.

4. Water footprint of first generation biofuels

Recently, Mekonnen and Hoekstra (2010) have developed a new method of estimating green and blue water consumption at a high spatial resolution. That method takes actual irrigation rather than irrigation requirements into account. Earlier studies calculated blue WFs as differences between crop water requirements and effective rainfall, assuming irrigation requirements are met. In many cases, this leads to an overestimation of blue water use. The new method is a large improvement of water use estimates compared to the earlier WF calculations. The study provides a comprehensive global database of green, blue and grey WFs of crops and derived crop products, including bio-ethanol and biodiesel, at a spatial resolution of 5 by 5 arc minute. Gerbens-Leenes and Hoekstra (2012) derived data from that study and performed a detailed study of bio-ethanol WFs for the main producing countries as well as the main producing US states.

4.1 Water footprint of sugar cane, sugar beet and maize

The WF of biofuels, e.g. bio-ethanol from sugar cane, sugar beet or maize, is dominated by the agricultural phase, i.e. feedstock production. Process water use varies between 0 m^3 per ton (in the case of sugar beet where the water from the beet itself is used) to 21 m^3 per ton (Gerbens-Leenes and Hoekstra, 2012). Other processes during the biofuel's life cycle, such as feedstock transportation and processing, are much less water intensive. Figure 1 shows the WFs of sugar cane (m^3/ton), Figure 2 the WFs of sugar beet and Figure 3 the WFs of maize. There are large differences for similar crops that are caused by differences in climate and differences in yields (ton per ha). Some countries have unfavourable WFs, far above the global average. For example, for sugar cane production in Cuba, Pakistan, India, Vietnam and Thailand. Egypt, India and Pakistan heavily rely on blue water for irrigation. For sugar beet, Iran, China, Egypt and Ukraine have WFs far above the global average, while western European countries have WFs below the global average. Especially grey WFs are great for Poland and China, indicating that much nitrogen is leaking or applied in too large amounts, polluting water bodies. For maize, developing countries like India, Nigeria, Mexico and the Philippines have relatively great WFs, while developed countries like Germany, France, the US, Canada and Spain have relatively small WFs. For all three crops, Egypt almost completely relies on irrigation.

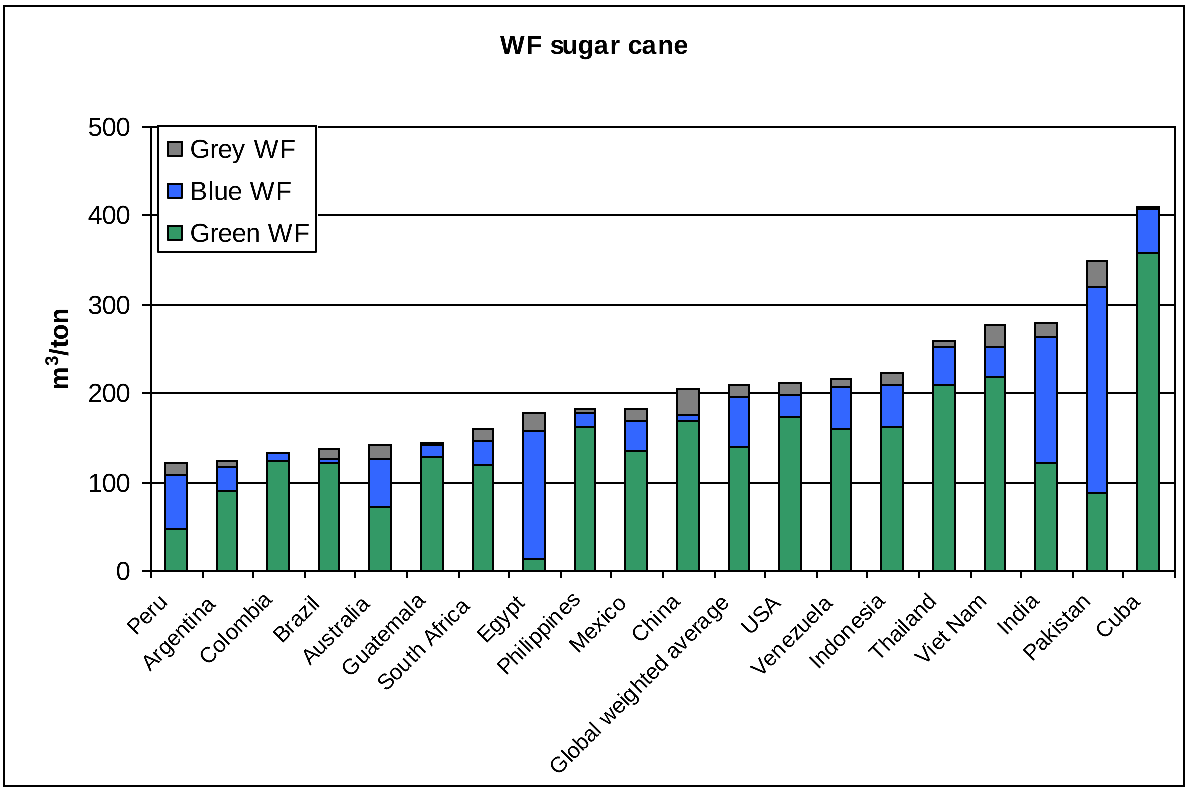

Figure 1: The water footprint of sugar cane for the main producing countries including the weighted global average value (Source: Gerbens-Leenes and Hoekstra, 2012)

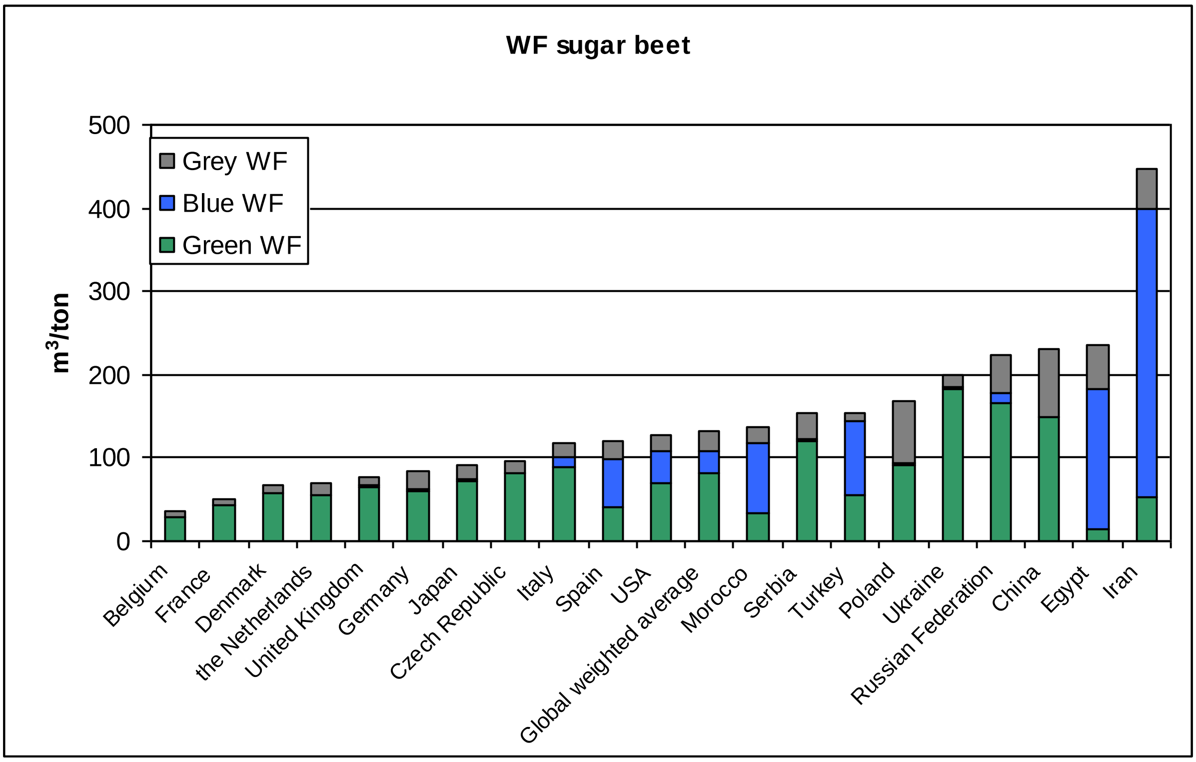

Figure 2: The water footprint of sugar beet for the main producing countries including the weighted global average value (Source: Gerbens-Leenes and Hoekstra, 2012)

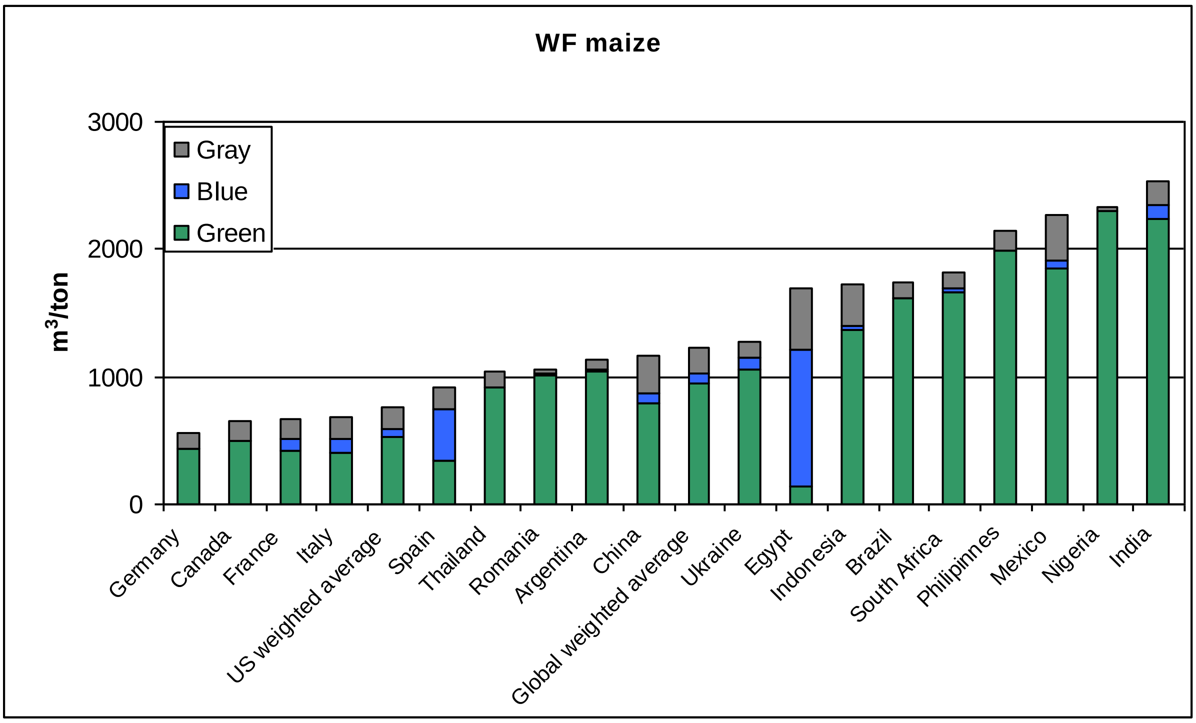

Figure 3: The water footprint of maize for the main producing countries including the weighted global average value (Source: Gerbens-Leenes and Hoekstra, 2012)

Table 1 gives the WFs for maize in the main producing states in the US, as well as the US weighted average. The Table shows that variation among the states is small, with Nebraska and Illinois the only exceptions. Nebraska uses a relatively great amount of blue water, while Illinois has a great grey WF. In this way, these states influence the average US values. US values, however, are much smaller than global averages, indicating relatively favourable production and climatic circumstances.

US State	**Green WF**	**Blue WF**	**Grey WF**
	m^3 per ton	m^3 per ton	m^3 per ton
Illinois	578	5	192
Indiana	526	7	172
Iowa	553	2	177
Michigan	466	14	163
Minnesota	525	4	165
Nebraska	443	191	153
North Carolina	528	4	152
Pennsylvania	458	3	158
Wisconsin	465	3	158
US weighted average	522	63	176
US SD	± 127	± 63	± 78

Table 1: Green, blue and grey WFs for maize in the main producing states in the US, US weighted average values and standard deviations (Mekonnen and Hoekstra, 2010)

The WFs of bio-ethanol are a function of crop WFs, product and value fractions, and process water use. Table 2 gives the product and value fractions that determine the WF multiplication ratio. It shows that for the production of bio-ethanol, maize is the most favourable crop with a multiplication ratio of 4.3. Sugar cane is the most unfavourable crop, requiring fifteen times the crop WF to produce bio-ethanol (m^3 per ton). Results for WFs of crops indicate that process water use is almost negligible compared to crop WFs.

Product	**Product fraction**	**Value fraction**	**WF multiplication ratio**
Cane bio-ethanol	0.06	0.89	14.8
Beet bio-ethanol	0.09	0.92	10.2
Maize bio-ethanol	0.15	0.65	4.3

Table 2: Product fractions, value fractions and WF multiplication ratios for bio-ethanol from sugar cane, sugar beet and maize (Source: Gerbens-Leenes and Hoekstra, 2012)

Table 3 gives the weighted global average green, blue and grey WFs of bio-ethanol (m^3/GJ ethanol) from sugar cane, sugar beet and maize (Mekonnen and Hoekstra, 2010), indicating that green WFs increase from sugar beet to sugar cane to maize. Sugar cane requires most blue water per unit of ethanol, however, whereas pollution is greatest in the production of bio-ethanol from maize.

	Green WF	**Blue WF**	**Grey WF**
	m^3/GJ ethanol	m^3/GJ ethanol	m^3/GJ ethanol
Sugar beet	31	10	10
Sugar cane	60	25	6
Maize	94	8	19

Table 3: Weighted global average green, blue and grey WFs of bio-ethanol from sugar cane, sugar beet and maize (Source: Mekonnen and Hoekstra, 2010)

4.2 Water footprint of biodiesel

Mekonnen and Hoekstra (2010) have calculated the WFs of biodiesel from oilcrops for the main producing countries. For jatropha, Gerbens-Leenes et al. (2009c) and Hoekstra et al. (2009) have calculated green and blue WFs for locations distributed over the Jatropha curcas belt (between 300 N and 350 S), including Brazil, Indonesia, Nicaragua, Guatemala and India. For the purposes of this chapter, we adopt the WF estimates of biodiesel from Mekonnen and Hoekstra (2010) and Gerbens-Leenes et al. (2009c). Table 3 (a Source: Gerbens-Leenes et al. 2009c and b Source: Mekonnen and Hoekstra, 2010) gives the green, blue and total WFs of jatropha for five different locations and their average values, of palm oil, rapeseed, sunflower oil and soybean oil for some large producing countries and global weighted average values. The blue WFs of biodiesel from jatropha oil are greatest. The green WFs of biodiesel from rapeseed oil and palm oil are smallest. The Table also shows that differences among locations and averages for countries are large.

When WFs for bio-ethanol are compared to WFs for heat (m^3 per GJ), in general, it is much more favorable to generate heat rather than produce biofuels. Depending on crop type, WFs for heat generation are much lower than bio-ethanol WFs. For example, the WFs of bio-ethanol from cassava are 50 percent higher than the WFs of heat generated from cassava while the WFs of ethanol from barley are four times the WF of heat from barley (Gerbens-Leenes et al., 2009b). However, there are differences in the quality of the energy. Biofuels can be used directly for transportation purposes, for example, while heat is energy of a lower quality. It can be applied for space heating, or needs to be converted into another energy carrier, for example into electricity. In an earlier study, we estimated the WF of bio-electricity from the WF of total crop biomass, including stems and leaves, assuming a maximum efficiency of 59 percent for the conversion of heat into bio-electricity (Gerbens-Leenes et al., 2009a). This means that part of the energy is lost in the conversion process.

		Green WF	**Blue WF**	**Grey WF**
		m^3/GJ oil	m^3/GJ oil	m^3/GJ oil
Jatropha oil a	India	575	1116	
	Guatemala	156	174	
	Nicaragua	120	187	
	Indonesia	184	109	
	Brazil	160	91	
	Average	239	335	
Rapeseed oil b	India	141	129	20
	China	118	0	42
	Germany	86	0	21
	Global weighted average	145	20	29
Soybean oil b	United States	250	15	2
	Argentina	335	1	2
	Italy	185	21	0
	Brazil	349	0	2
	Global weighted average	326	11	6
Palm oil b	Philippines	144	0	13
	Thailand	97	0	8
	Indonesia	128	0	9
	Malaysia	117	0	5
	Honduras	102	0	4
	Global weighted average	150	0	6
Sunflower oil b	France	175	2	74
	Germany	227	0	199
	United States	446	16	54
	Global weighted average	428	21	28

Table 3: Green, blue and grey WFs of jatropha, palm oil, rapeseed, soybean oil and sunflower oil biodiesel for different locations and weighted global averages

4.3 Water Footprints of conventional energy carriers

At present, important energy carriers include fossil energy carriers (petroleum, coal and natural gas), uranium, and electricity from hydropower (IEA, 2006). Promising renewables are solar and wind energy. We also give the blue WFs for these important energy carriers. For petroleum, coal, natural gas and uranium, we derived data from literature (Argonne National Laboratery, 2011; Gleick, 1994). For electricity from hydropower, we estimated the global blue WF by dividing the global evaporation of reservoirs (Shiklomanov, 2000) by the hydroelectric generation (Gleick, 1993) for the year 1990. Next, we compared these results with information on blue WFs of hydropower from Mekonnen and Hoekstra (2012). Table 4 gives an overview of the blue WFs of different energy forms other than bio-energy. Although most data are rather old, they give at least an indication. WFs of petroleum, coal, natural gas, nuclear energy, solar thermal energy and wind electricity generation are all smaller than the WFs of first generation biofuels.

For hydropower, Gerbens-Leenes et al. (2009b) have found an average global blue WF of 22 m^3/GJ, while Mekonnen and Hoekstra (2012) have arrived at an average value of 68 m^3/GJ. WF values per unit of generated electricity, however, show enormous variation. For example, the Lubuge power plant in China uses only 0.5 m^3/GJ of generated electricity. On the other hand, the Akosombo dam and Kpong power plant in Ghana use 850 m^3/GJ of generated electricity, which is the highest WF for any energy source discussed in this chapter so far. In general, blue WFs of hydropower are much greater than the WFs of other energy sources.

For fossil fuels, it should be noted that the water required over time to grow the vegetation that finally has accumulated and turned into fossil fuel, is excluded from the figures presented. For a fair comparison between the water footprint of bioenergy and fossil fuels, this historically accumulated water consumption, i.e. the green WF, should be accounted for. Another issue is that at present we lack data on water pollution for the conventional energy carriers. This also makes it impossible to make a fair comparison between bioenergy, for which we calculated the grey WFs, and the conventional energy carriers.

	Average blue WF (m^3/GJ)
Energy carrier	
Petroleum a	0.06-0.14
Coal b	0.2
Natural gas b	0.1
Nuclear energy b	0.1
Solar thermal energy b	0.3
Wind energy b	0.0
Hydropower c,d	0.3–850

Table 4: Average blue water footprints of different energy carriers (m^3/GJ)

a Source: Argonne National Laboratery, 2011
b Source: Gleick (1994)
c Source: Gleick (1993) and Shiklomanov (2000)
d Source: Mekonnen and Hoekstra (2012)

5. Discussion

In assessing the WFs of bioenergy, the WF of the gross energy output from crops was taken into account. Energy inputs in the production chain, such as energy requirements in the agricultural system (e.g. energy use for the production of fertilizers and pesticides) or the energy use during the industrial biofuel production process were excluded. For high-input agricultural systems, energy input is substantial (Giampietro and Ulgiatti, 2005; Pimentel and Patzek, 2005), so that net energy yields are smaller than presented here. This means that this overview underestimates the WF of bioenergy from agricultural systems with relatively large energy inputs. Future studies should take this aspect into account.

The WFs presented in this chapter are based on rough estimates of freshwater requirements in crop production, in combination with theoretical maximum conversion efficiencies in heat, bio-electricity and biofuel production. The studies have integrated data from several sources, each adding a degree of uncertainty. Meteorological data, for example, are averages over several years rather than data for a specific year and do not reflect annual variations. Calculations of crop water requirements are sensitive to input of climatic data and assumptions concerning the start of the growing season. The data on energy carriers from the literature (Gleick, 1994) give an indication of blue water requirements, but are probably outdated. Therefore, results are indicative. However, the differences among the WFs of different energy carriers are so great that they support general conclusions with respect to relative WFs of different types of bioenergy, crops and countries.

It is worth mentioning that the WF of second generation biofuels will be higher than the WFs of heat generation, because the biomass needs to be converted into biofuel which will have a conversion efficiency of less than 100 percent. How much of the WF of a crop that delivers both food and second-generation energy will be allocated to the energy component, depends on the value of the energy derived from one kilogram of harvested crop relative to the value of food coming from the same kilogram of crop.

Especially the WFs of bioenergy and hydropower are large. A policy relevant question is whether (and to what extent) water should be used for food, fibers or fuel. This is especially relevant in developing countries with increasing populations, such as China and India, where the demand for food will increase. Large biofuel and hydropower programs may need large amounts of water, making it unavailable for food production. Another issue is the sustainability of energy with large water requirements. Whether the WF related to the production of bioenergy and hydropower is sustainable or not depends on two criteria: the geographic context and the characteristics of the production process itself (Hoekstra et al., 2011). A WF is unsustainable when the process is located in a so termed hotspot, a catchment where during a certain period of the year environmental water needs are violated or when pollution exceeds waste assimilation capacity. For example, when ethanol from sugarcane is produced in North India, an area where water stress occurs, this is unsustainable. A WF is also considered unsustainable when the WF of the process can be reduced or avoided altogether. One could argue that allocating water to bioenergy or hydropower with large WFs is unsustainable, because other renewables (e.g. sun and wind) have much smaller WFs. If the choice is made to produce bioenergy, however, the agricultural practices chosen should produce the feedstock in the most water-efficient way. The reduction of green WFs can be achieved by increasing land productivity. Blue WFs can be reduced with more efficient irrigation or by selecting alternative crops. Grey WFs can be reduced by applying fewer chemicals (thanks, for example, to the use of precision agriculture). We have shown the large differences in grey WFs among countries. An example of this is provided by Eastern Europe countries which have relatively large grey WFs indicating an inefficient use of chemicals. Large improvements are possible under such scenarios.

6. Conclusions

The blue water footprints of fossil and nuclear energy and renewables like wind and thermal solar energy are much smaller than the blue WFs of hydropower and bioenergy. For hydropower, blue WFs show a large variation, between 0.3 and 850 m^3 per GJ. On average, the blue WF of hydropower lies between 20 and 70 m^3 per GJ.

The most water-efficient way to generate bioenergy is to use total biomass, including parts without a large economic value, and generate heat. The generation of electricity is the second best option. Much research is presently done to develop the so termed second generation biofuels, biofuels generated from biomass waste. When this technique becomes available, large amounts of waste biomass can be converted into second generation biofuels. Also the development of third generation biofuels, biofuels from algae, is an interesting development that might decrease the WFs of biofuels.

When comparing different first generation biofuel practices, in general, it is more water efficient to produce bio-ethanol than biodiesel. The green WF of a typical biodiesel energy crop, rapeseed, is two times larger than the WF of ethanol from sugarcane and four times larger than ethanol from sugar beet. The blue WFs that have a larger environmental impact on water systems show a different pattern, however. For the dominant biofuel feedstocks, the global weighted average blue WFs increase in the following order: palm oil (0 m^3/GJ), ethanol from maize (8 m^3/GJ); ethanol from sugar beet (10 m3/GJ), soybean oil (11 m^3/GJ), rapeseed oil (20 m^3/GJ), sunflower oil (21 m^3/GJ) and ethanol from sugar cane (25 m^3/GJ). Water pollution is smallest for soybean and palm oil and for ethanol from sugar cane (6 m^3/GJ) and largest for rapeseed oil (29 m^3/GJ).

Our results provide new insights into the impacts of bioenergy on the consumption and pollution of freshwater. This knowledge is a valuable contribution to future research and for policies concerning energy needs, freshwater availability and the choice whether to allocate water to food or to energy production.

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