The Water Footprint of Energy Carriers

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Abstract

Agriculture, providing biomass for different purposes, requires about 86% of the worldwide fresh water use. In many parts of the world, the use of water for agriculture already competes with other uses such as urban supply and industrial activities. A tool that addresses international virtual water flows is the concept of the Water Footprint, defined as the total annual volume of freshwater used to produce the goods and services related to a certain consumption pattern. So far, the tool has been used to assess the WF of food and cotton consumption. This study assesses the WF of various types of biomass for energy. Next, the study compares this WF with data on water requirements of other energy carriers. Results show large differences per unit of energy. The WF of wind energy is zero, of natural gas 0.10 m^3 per GJ, of coal 0.04, of nuclear energy 0.09, of thermal solar energy 0.3, of oil 0.8 and of biomass (average) 22.6 m^3 per GJ. This requirement competes with water for food, which lies in the same order of magnitude. Based on an energy use of 100 GJ per capita per year in western societies, a mix from coal, oil, nuclear energy and gas requires 26 m^3 of water, while 100 GJ from biomass requires 2260 m^3. Biomass requires much more water per unit of energy than the average fossil energy carrier. A shift in western societies from generally applied energy (fossil and nuclear energy) towards energy from biomass causes a ninety fold increase of the WF of energy and puts large claims on scarce fresh water resources. Strategies towards larger biomass use for energy should take this large WF into account.

Keywords: Sustainablity;Climate change,Eenergy,Biomass,Natural resource use,Water footprint

1. Introduction

The scientific as well as the international political community consider global change often in relation to climate change (IPCC, 2007). It is generally recognized that emissions of greenhouse gasses, such as CO2 from fossil energy carriers, are responsible for anthropological impacts on the climate system. A shift towards CO2-neutral energy carriers, such as biomass, is heavily promoted. Important issues in this respect are trade offs and interplays with other factors that play a role in global changes other than climate change, such as, for example, the availability and increased pressure on global water resources (Postel, 2000; Rockström et al., 2007; Vörösmarty et al., 2000).

The use of energy in society requires water. Energy carriers are often made available with water, for example, for coal mining (Gleick, 1994), or produced with water, for example, biomass. Biomass can be derived from a large variety of crops, such as sugar cane and maize to produce ethanol, jathropa and sunflower to produce oil, or miscanthus to produce heat. The production of energy crops, however, requires the input of freshwater, a scarce natural resource in a highly competitive context. Nowadays, the production of biomass for food and fibre in agriculture requires about 86% of the worldwide freshwater use (Hoekstra and Chapagain, 2008). In many parts of the world, the use of water for agriculture competes with other uses such as urban supply and industrial activities (Falkenmark, 1989), while the aquatic environment shows signs of degradation and decline (Postel et al., 1996). An increase of demand for food in combination with a shift from fossil energy towards energy from biomass puts additional pressure on freshwater resources. For the future, hardly any new land is available so all production must come from the natural resource base currently available (FAO, 2003), requiring a process of sustainable intensification by increasing the efficiency of the use of land and water (Fresco, 2006).

The objective of this study is to calculate the water footprint (WF) of different types of biomass and compare these results with the WF of other energy carriers, such as fossil energy carriers (coal, natural gas, oil), and types of energy, such as wind energy, hydropower and solar thermal electricity. The results obtained in this study provide insight into the WF of different energy carriers. These insights can contribute to a better understanding of the relationship between energy and water use.

2. Method

Energy derives from energy carriers, primary and secondary energy carriers. Primary energy carriers are energy carriers directly derived from a natural source without any conversion process, while secondary energy carriers are carriers that do not derive from a natural source and are the product of a conversion process (Blok, 2006). There is almost always water needed in a supply chain to make energy available for human activities. For the assessment of the WF of energy carriers, this study only took the primary energy carriers that derive from sources in the first link of the supply chain into account. It distinguished between primary, non-renewable energy carriers and primary, renewable energy carriers.

2.1 The concept of the Water Footprint

The concept of the Water Footprint (WF) addresses water requirements for products, commodities, goods and services, as well as international virtual water flows related to the trade of products. It has been introduced by Hoekstra and Hung (2002) and has been developed further by Chapagain and Hoekstra (2004). The WF is the total volume of freshwater used to produce the goods and services consumed by an individual or community. A WF can be calculated for any well-defined group of consumers, including a family, business, village, city, province, state or nation. A WF is generally expressed in terms of the volume of freshwater use per year (Hoekstra and Chapagain, 2008). The WF of a product, a commodity, good or service, produced or manufactured at a specific business unit often using ingredients from a supply chain, is the total volume of freshwater that is used directly or indirectly to produce the product (Gerbens-Leenes and Hoekstra, 2008). The WF consists of three components: green, blue and gray virtual-water. The green virtual-water content of a product refers to the rainwater that evaporated during the production process, mainly during crop growth. The blue virtual-water content of a product refers to the surface and groundwater applied for irrigation that evaporated during crop growth. The gray virtual-water content of a product is the volume of water that becomes polluted during production. It is defined as the volume of water needed to dilute pollutants to such an extent that the quality of the water remains above agreed water quality standards (Hoekstra and Chapagain, 2008). So far, the WF has been calculated for a large range of products but not for energy carriers.

2.2 The water footprint of primary energy carriers (excluding biomass)

The category of primary non-renewable energy carriers includes crude oil, coal, and natural gas, the fossil energy carriers, and uranium, providing nuclear energy. The primary renewable energy carriers include wind, sun, hydropower and biomass. For the assessment of the WF of non-renewable energy carriers and for electricity from wind and sun, the study derived data from Gleick (1994). The WF of hydropower was calculated by dividing global evaporation of reservoirs (Shiklomanov, 2000) by the hydroelectric generation (Gleick, 1993) for the year 1990. The WF of biomass is addressed in the next section.

2.3 The water footprint of energy from biomass

The study considered four categories of biomass for energy: (i) trees; (ii) bio-energy crops; (iii) food crops and (iv) crops for materials. It made assessments for fifteen crops from the four categories mentioned above: poplar (trees), miscanthus (bio-energy crops), and for cassava, coconut, groundnuts, maize, palm oil, potato, wheat, rapeseed, sugar beet, sugar cane, sunflower, soybean (food crops), and cotton (crops for materials). The study considered four different countries, Brazil, the Netherlands, the United States and Zimbabwe. Areas where specific crops are grown were derived from the United States Department of Agriculture (USDA, 2007). For the assessment of the WF of energy from biomass, the study used a standardized composition for crops, termed H-crops, derived from existing crops. Data were obtained from Gerbens-Leenes at al. (2008).

For the assessment of the WF, the study took the complete growing season of the plant into account and accumulated data on daily crop evaporation (ET_c in mm/day) over the growing period of the crop using the FAO program CROPWAT. However, where Hoekstra and Chapagain (2007, 2008) allocate total evaporation to the crop yield (kg/ha), this study allocated total evaporation to biomass yield, because crop yields refer to the crop component usable for food, feed or materials production, while it is total biomass yield that is relevant for energy production. The study calculated the WF of energy from biomass (m^3/GJ) in five steps.

Step 1: calculation crop water requirement (*CWR)* (m^3/ha)

The calculation of the water requirement of crop c *CWR (c)* (m^3/ha) in a specific area was done by applying the calculation model CROPWAT (FAO, 2007) that is based on the FAO Penman-Monteith method (Allen, 1998) to estimate reference evapotranspiration:

$$CWR\ (c) = 10 * \sum_{d=1}^{lp} K_c\ (c) * ET_o \tag{1}$$

where the factor 10 is applied to convert mm into m^3/ha. The summation is done over the complete growing season of crop c, where *lp* is the length of the growing period in days. ET_o is the reference crop evapotranspiration (mm/day) of a hypothetical surface covered with grass not short of water. $K_c\ (c)$ is the crop coefficient that includes effects that distinguishes evapotranspiration of field crops from grass.

Calculations were done for the fifteen crops mentioned above grown in four different countries: Brazil, the Netherlands, the United States and Zimbabwe. For these countries, the main agricultural areas where specific crops are grown were derived from the USDA (2007). Appendix 3 gives an overview of these areas. For these areas, climatic data that were used as input for the model CROPWAT, were derived from the database of Müller and Hennings (2000).

Step 2: calculation total biomass yield (*BY*)(tons /ha)

The difference between total biomass yield and crop yield consists of a rest fraction that is not suitable for food, feed or materials production but can be used for energy production. This study allocated the *CWR* to the total biomass yield *BY (c)* (tons/ha) calculated as follows:

$$BY\ (c) = \frac{Y(c)}{HI(c)} \tag{2}$$

Where *Y (c)* is the crop yield (tons/ha) and *HI (c)* is the harvest index for crop c. Data on yields were derived from the FAO (2007), data on HI were derived from (Goudriaan et al., 2001; Akhtar, 2004). An overview of yield data and HI can be found in Gerbens-Leenes et al. (2008).

Step 3: calculation Water Footprint biomass crop c, $WF_M(c)$, (m^3/ton)

The Water Footprint of crops per unit of mass, $WF_M\ (c)$ (m^3/ton), was calculated as follows:

$$WF_M\ (c) = \frac{CWR(c)}{BY(c)} \tag{3}$$

Step 4: calculation average energy content of a H-crop *(c)*, *E (c)* (GJ/ton)

The calculation of the average energy content of a hypothetical crop, *E (c)* (HHV in GJ/ton), was done by combining data on heat of combustion of plant components (HHV in kJ/gram = GJ/ton) with information on the composition of a H-crop (grams/gram). Data were derived from Gerbens-Leenes at al. (2008).

$$E\ (c) = HI\ (c) * DM_Y(c) * \sum_{i=1}^{5} C_i * A_{y,i} + (1\text{-}HI\ (c) * DM_r(c) * \sum_{i=1}^{5} C_i * A_{r,i} \tag{4}$$

HI (c) is the harvest index of crop c, $DM_Y(c)$ is the fraction of dry mass in the crop yield, and $DM_r(c)$ is the fraction of dry mass in the rest fraction, *C* is the heat of combustion of component *i* (HHV in kJ/gram), *A* is the amount of component *i* in the DM of the crop yield or rest fraction (grams/gram).

Finally, ***Step 5*** calculates the WF of energy from biomass $WF_E\ (c)$ (m^3/GJ) by dividing results from step 3 by results from step 4:

$$WF_E\ (c) = \frac{WF_M\ (c)}{E(c)} \tag{5}$$

3. Results and discussion

3.1 The water footprint of energy from biomass

Table 1 shows the heat of combustion (HHV) for the total biomass of the fifteen crops expressed in MJ per kg fresh weight. Differences among heat of combustion values are much larger among crops when the values are expressed per unit of fresh weight rather than per unit of dry mass. Table 1 shows a difference of a factor of five between the lowest and highest values. In general, crops showing small water contents and large oil contents have relatively large heat of combustion values, for example palmkernels and sunflower. Crops that have a large water content and a small oil content have small values, for example, potato and sugarcane.

Table 1. Heat of combustion of the total biomass of H-crops per unit of fresh weight

H-Crop	Heat of combustion total biomass (MJ per kg fresh weight)
Cassave	5.2
Coconut	9.1
Cotton	17.9
Groundnuts	8.3
Maize	16.8
Miscanthus	17.0
Palmkernels	20.0
Poplar	16.6
Potato	3.5
Rapeseed	6.8
Sugarbeet	3.8
Sugarcane	5.1
Soybeans	9.9
Sunflower	17.9
Wheat	16.5

Tables 2 and 3 show the results for the WF of energy from biomass expressed in cubic meters of water per unit of energy (m^3/GJ) and in cubic meters per unit of mass (m^3/GJ) for the fifteen crops grown in four different countries.

Table 2. WF of biomass for fifteen H-crops grown in the Netherlands, the United States, Brazil and Zimbabwe (m^3/GJ)

	m^3/GJ			
H-Crop	The Netherlands	United States	Brazil	Zimbabwe
Cassava	--	--	29.7	204.7
Coconut	--	--	48.8	204.7
Cotton	--	135.0	95.6	355.6
Groundnuts	--	57.6	51.4	253.6
Maize	9.1	18.3	39.4	199.6
Miscanthus	19.7	37.1	48.8	63.8
Palm oil and kernels	--	--	75.2	--
Poplar	22.2	41.8	55.0	72.0
Potatoes	20.9	45.8	30.7	64.8
Soybeans	--	99.3	61.1	138.0
Sugar beets	13.4	23.3	--	--
Sugarcane	--	30.0	25.1	31.4
Sunflower	26.9	60.6	54.3	145.5
Wheat	13.8	84.2	81.4	68.7
Winteroilseedrape	67.3	113.3	205.2	--
Average	24.2	58.2	61.2	142.6

Differences among WF's of biomass were large, dependant on the type of biomass, the agricultural system applied and climatic conditions. For the types of biomass included in this study, the largest difference was found between maize grown in the Netherlands and cotton grown in Zimbabwe; the WF of the cotton was forty times the WF of Dutch maize. In Brazil, sugar cane shows about half the WF of maize, cotton and oilseedrape two and a half and five times the WF of maize. The other crops have WF's in the same order of magnitude than maize.

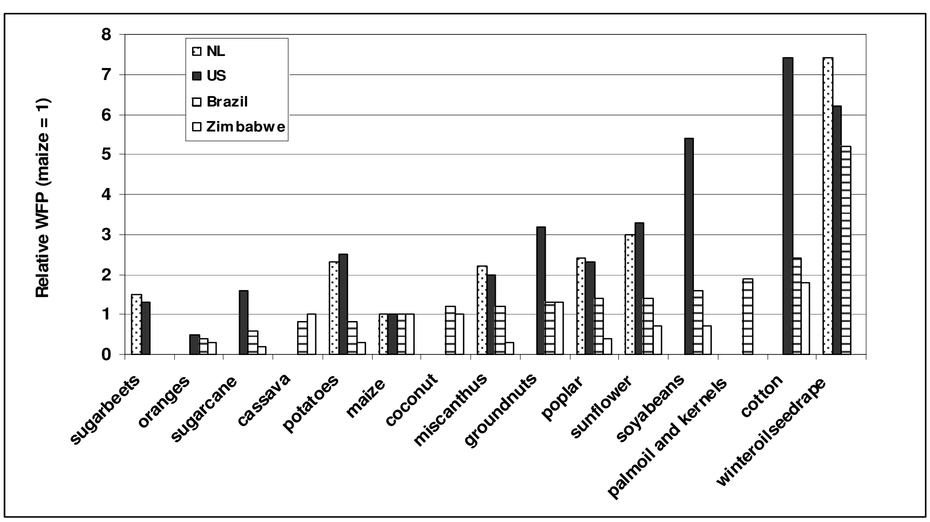
Table 3. WF of biomass for fifteen H-crops grown in the Netherlands, the United States, Brazil and Zimbabwe (m^3/ton)

	m^3/ton			
H-Crop	The Netherlands	United States	Brazil	Zimbabwe
Cassava	--	--	155.9	1074.2
Coconut	--	--	444.0	1842.5
Cotton	--	2414.0	1709.5	6358.7
Groundnuts	--	477.1	425.7	2100.5
Maize	153.3	307.7	663.9	3363.1
Miscanthus	334.0	629.1	827.5	1081.8
Palm oil and kernels	--	--	1502.2	--
Poplar	369.4	695.6	915.2	1198.1
Potatoes	72.4	111.3	106.4	224.6
Soybeans	--	978.7	602.2	1360.5
Sugar beets	50.5	87.7	--	--
Sugarcane	--	152.8	127.9	160.0
Sunflower	481.3	1084.3	971.6	2603.4
Wheat	150.0	1388.4	1360.3	1132.8
Winteroilseedrape	459.0	772.7	1459.5	--

In Zimbabwe, only cotton has a WF that is substantially larger than the WF of maize, twice the value of maize. All other crops have WF's in the same order of magnitude or smaller. In general, the WF of maize is favorable, the WF of oilseedrape and cotton unfavorable. Figure 1 also shows that some crops that are specifically grown for energy, i.e. miscanthus, poplar and winteroilseedrape have a relatively large WF compared to a food crop such as maize. An exception is poplar grown in Zimbabwe. For this crop, however, the study applied general yield data that probably overestimated yield levels in that country, so that it underestimated the WF of poplar. From a water perspective, crops grown for energy do not have a more favorable WF than crops grown for food.

Table 4 shows the WF of operations that make the non-renewable energy carriers coal, uranium, crude oil and natural gas available. Large differences among the WF of operations occur, resulting in large differences among average, total WF's of non-renewable energy carriers. The WF of underground uranium mining, for example, is negligible, whereas the WF of deep mining of coal is 0.012 m^3 per GJ, onshore oil extraction and production 0.006 m^3 per GJ, and surface mining of coal only 0.004 m^3 per GJ. For the non-renewable energy carriers, the WF increases in the following order: uranium (0.09 m^3 per GJ), natural gas (0.11 m^3 per GJ), coal (0.16 m^3 per GJ), and finally crude oil (1.06 m^3 per GJ). In this category, the WF of crude oil is ten times the WF of uranium.

Figure 1. Relative WF in the Netherlands, the United States, Brazil and Zimbabwe, where the WF of maize in the country considered is set to 1.



3.2 The water footprint of primary energy carriers (excluding biomass)

As mentioned before, the WF includes three types of water, green water, blue water and gray water. The first two are related to water use, the latter to water pollution. Gray water is defined as the amount of water needed to dilute pollutants emitted to the natural water system during the production process to the extent that the quality of the ambient water remains beyond agreed water quality standards. To make energy carriers available, it is possible that water becomes polluted. For example, underground coal mining sometimes leads to contamination of water (Gleick, 1994). This study did not take pollution, and thus gray water into account. In this way, it probably underestimated the WF of some energy carriers that show large water pollution.

Table 4 also shows that the WF of electricity from solar active space heat and from wind is negligible, but that the WF of electricity from hydropower is substantial. The large WF of hydropower is mainly caused by large evaporation of water from reservoirs required to generate electricity.

Table 4.Average water footprint for operations that make energy carriers available and average total water footprint for coal, uranium, crude oil, natural gas, electricity from active solar space heat, hydropower and electricity form wind energy (m^3 per GJ)

Operation	Average water footprint (m^3 per GJ)	Operation	Average water footprint (m^3 per GJ)
Coal		**Crude oil**	
Surface mining	0.004	Onshore oil exploration	0.000
Deep mining	0.012	Onshore oil extraction and production	0.006
Slurry Pipelines	0.063	Enhanced oil recovery	0.120
Beneficiation	0.004	Water flooding	0.600
Other plant operations	0.090	Thermal steam injection	0.140
Total (average)	0.164	Forward combustion/air injection	0.050
		Micellar polymer	8.900
Uranium		Caustic injection	0.100
Open pit uranium mining	0.020	Carbon dioxide	0.640
Underground uranium mining	0.000	Oil refining (traditional)	0.045
Uranium milling	0.009	Oil refining (reforming and hydrogenation)	0.090
Uranium hexafloride conversion	0.004	Other plant operations	0.070
Uranium enrichment: gaseous diffusion	0.012	Total (average)	1.058
Uranium enrichment: gas centrifuge	0.002		
Fuel fabrication	0.001	**Natural gas**	
Nuclear fuel processing	0.050	Gas processing	0.006
Total (average)	0.086	Pipeline operation	0.003
		Plant operations	0.100
Other		Total (average)	0.109
Electricity from hydropower	22.300		
Electricity from solar active space heat	0.265		
Electricity from wind energy	0.000		

3.3 Comparisons of the water footprint among different energy carriers

The comparison of the water footprint among different energy carriers shows large differences, for example, between the category of fossil energy carriers on the one hand and the category of biomass on the other. The average WF of a mix of uranium, natural gas, coal and crude oil is only 0.35 m^3 per GJ. The average WF of high yielding biomass grown in the Netherlands is 24.2 m^3 per GJ. This means that a shift from fossil energy towards energy from biomass puts large claims on scarce freshwater resources. Based on the energy use of 100 GJ per capita per year in western societies (Kramer et al., 1994; Vringer and Blok, 1995; Noorman and Schoot Uiterkamp, 1998; Moll et al., 2005), a mix from coal, crude oil, nuclear energy and gas requires 35 m^3 of water, while 100 GJ from biomass requires 2420 m^3, about seventy times as much water. In the United States, where yields are lower than in the Netherlands, the WF of 100 GJ from biomass is 5820 m^3, in Brazil 6120 and in Zimbabwe even 14260 m^3. This means that the WF of energy from biomass is 70 to 400 times larger than the WF of energy from the non-renewable, primary energy carriers. This requirement competes with water for food, which lies in the same order of magnitude. Strategies towards larger biomass use for energy should take this large water footprint into account.

4. Conclusions

This study has clarified the freshwater implications for a large scale introduction of biomass for energy purposes. It has shown the relationship between freshwater and energy, especially between freshwater and biomass for energy purposes. Results show large differences between the average WF of non-renewable primary energy carriers on the one hand and the average WF of energy from biomass on the other. But also within the two categories large differences occur. The WF of non-renewable primary energy carriers increases in the following order: uranium, natural gas, coal and finally crude oil, which shows a WF of ten times the WF of uranium. Within the category of biomass for energy purposes, differences are even larger. These differences are caused by differences in crop characteristics, agricultural production situations, climatic circumstances, as well as by local factors. For example, the WF per unit of energy of cotton grown in Zimbabwe is forty times the WF of maize grown in the Netherlands. Biomass grown for energy purposes, such as poplar, miscanthus or winteroilseedrape, however, do not show more favourable WF’s than food crops, such as, maize.

When a shift occurs towards larger use of biomass, the WF of energy increases substantially. The study shows that the WF of energy from biomass is 70 to 400 times larger than the WF of a mix of energy from non-renewable sources. The current and future economic development causes a continued need for natural resources, such as freshwater. A shift towards biomass energy, as promoted to decrease the impact of fossil energy on the climate system, will bring with it a need for more water. The concept of the WF and the results for biomass presented in this study have led to new insights with respect to the large impact of energy from biomass on the use of freshwater resources. This knowledge can be a valuable contribution to research concerning energy needs and freshwater availability for the near future.

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