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ANALYSIS

The water footprint of energy from biomass: A quantitative assessment and consequences of an increasing share of bio-energy in energy supply

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ABSTRACT

This paper assesses the water footprint (WF) of different primary energy carriers derived from biomass expressed as the amount of water consumed to produce a unit of energy (m^3/GJ). The paper observes large differences among the WFs for specific types of primary bio-energy carriers. The WF depends on crop type, agricultural production system and climate. The WF of average bio-energy carriers grown in the Netherlands is 24 m^3/GJ, in the US 58 m^3/GJ, in Brazil 61 m^3/GJ, and in Zimbabwe 143 m^3/GJ. The WF of bio-energy is much larger than the WF of fossil energy. For the fossil energy carriers, the WF increases in the following order: uranium (0.1 m^3/GJ), natural gas (0.1 m^3/GJ), coal (0.2 m^3/GJ), and finally crude oil (1.1 m^3/GJ). Renewable energy carriers show large differences in their WF. The WF for wind energy is negligible, for solar thermal energy 0.3 m^3/GJ, but for hydropower 22 m^3/GJ. Based on the average per capita energy use in western societies (100 GJ/capita/year), a mix from coal, crude oil, natural gas and uranium requires about 35 m^3/capita/year. If the same amount of energy is generated through the growth of biomass in a high productive agricultural system, as applied in the Netherlands, the WF is 2420 m^3. The WF of biomass is 70 to 400 times larger than the WF of the other primary energy carriers (excluding hydropower). The trend towards larger energy use in combination with an increasing contribution of energy from biomass will enlarge the need for fresh water. This causes competition with other claims, such as water for food.

1. Introduction

Fresh water is a prerequisite for life on earth. It is an essential natural resource for basic human needs such as food, drinking water and a healthy environment. In the coming decades, humanity will face important challenges, not only to meet these basic human needs but also to ensure that the extraction of water from rivers, streams, lakes and aquifers does not affect freshwater ecosystems to perform their ecological functions (Postel, 2000). Today, humanity already uses 26% of the total terrestrial evapotranspiration and 54% of accessible runoff (Postel et al., 1996). For a world population of 9.2 billion, as projected by the United Nations for 2050 (United Nations, 2007), there are reasons for profound concern in several regions and countries with limited water resources about whether food and fibre needs of future generations can be met (Fischer et al., 2001; Postel, 2000; Rockström et al., 2007; Vörösmarty et al., 2000).

The scientific as well as the international political community consider global change often in relation to climate

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change. It is generally accepted that emissions of greenhouse gasses, such as CO_2 from fossil energy carriers, are responsible for anthropogenic impacts on the climate system. A shift towards energy carriers that are supposedly CO_2-neutral, such as biomass, is heavily promoted. Other advantages of these renewable energy sources are an increase in energy supply security, resource diversification, and the absence of depletion risks (Vries et al., 2006). There are three categories of biomass for energy: (i) food crops, (ii) energy crops, and (iii) organic wastes (Minnesma and Hisschemöller, 2003). Food crops that are used for energy are, for example, sugar cane, providing ethanol, and rapeseed, providing biodiesel; typical energy crops are poplar and miscanthus, providing heat. The variety in organic wastes is enormous. Wastes are generated in agriculture (e.g. manure), industry or households.

Nowadays, the production of biomass for food and fibre in agriculture requires about 86% of the worldwide freshwater use (Hoekstra and Chapagain, 2007). 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).

A tool that has been developed for the calculation of water needs for consumer products is the concept of the water footprint (WF). This tool has been introduced by Hoekstra and Hung (2002) and has been developed further by Hoekstra and Chapagain (2007, 2008). Those authors define the WF as the total annual volume of fresh water used to produce the goods and services related to consumption. So far, the tool has been used to assess the WF of food and cotton consumption. The objective of this study is to assess the water footprint per unit of energy from biomass (in m^3/GJ) and to compare this with the WF of other primary energy carriers (oil, coal, gas, uranium, wind, solar energy and hydropower). In addition, the study aims to estimate how much additional fresh water is needed if a shift occurs towards energy from biomass and how this relates to the water needs for food and fibres.

2. Method

2.1. *Primary energy carriers*

Energy exists in many forms, such as kinetic energy, chemical energy, electricity or heat. Among these various forms, conversions occur. Biological photosynthesis, for example, converts solar photonic energy into chemical energy forming biomass. Many substances such as food or plastics contain energy (Verkerk et al., 1986). In energy analysis, however, a substance is considered an *energy carrier* if the substance is predominantly used as a source of energy (Blok, 2006). Before energy is available in an applicable form for human utilization, for example, for warming a house, cooking or lighting, energy passes a number of stages in a supply chain (Blok, 2006). Energy carriers derive from energy sources, including both non-renewable and renewable sources. Primary energy carriers are defined as carriers directly derived from a natural source without any conversion process, while secondary energy carriers are the product of a conversion process (Blok, 2006).

Throughout history, humans have used renewable energy from biomass, for example wood for heating and cooking. The FAO (2006) defines biomass as material of organic origin, in non-fossilized form, such as agricultural crops and forestry products, agricultural and forestry wastes and by-products, manure, microbial biomass, and industrial and household waste. Biomass is applied for food (e.g. wheat), materials (e.g. cotton), or for energy (e.g. poplar). At present, biomass is the most important renewable primary energy carrier (Blok, 2006). Biomass is often converted into *biofuels,* renewable secondary energy carriers in solid, liquid or gaseous form. Examples are charcoal, ethanol, biodiesel, and biogas (Minnesma and Hisschemöller, 2003; Blok, 2006). The energy derived from these fuels is termed *bio-energy*.

2.2. *Biomass*

Biomass is an umbrella term for all the material flows that derive from the biosphere, such as food and feed crops, energy crops, and organic wastes, such as manure and crop residues. For the production of biomass, agriculture applies the natural land base, requiring the input of fresh water for crop growth. For the assessment of the water footprint of biomass, this study only took crops into account; wastes fell outside the scope of the study. In general, agriculture grows crops for their reproductive or storage organs that have an economic value when applied for food, feed or materials production. The harvested organs are termed crop yield, i.e. the harvested production per unit of harvested area for crop products (FAO, 2007). The growth of these organs requires the preceding growth of complete plants with stems and foliage, however (Gerbens-Leenes and Nonhebel, 2004). The ratio of the crop yield to the total biomass yield is termed the harvest index (HI) and shows large differences among crops (Goudriaan et al., 2001). For food or feed purposes, agriculture aims at the crop yield. For energy purposes, however, the total biomass yield can be applied rather than the crop yield. Therefore, this study considered the total biomass yield, which was calculated by dividing data on crop yields from the FAO (2007) by the HI. Table 1 shows the data on HI that were derived from agricultural studies (Goudriaan et al., 2001; Akhtar, 2004).

Biomass for energy can be divided into three categories: (i) trees; (ii) bio-energy crops; and (iii) food crops that can be applied for either food or energy. The study considered these three categories of crops and made assessments for fifteen plant species from the three categories mentioned above: poplar (tree), miscanthus (bio-energy crop), and for cassava, coconut, cotton, groundnuts, maize, palm oil, potato, wheat, rapeseed, sugar beet, sugar cane, sunflower, and soybean (food crops).

2.3. *Energy from biomass*

The basis for energy from biomass is the universal photosynthesis process that stores solar energy in chemical bonds.

Table 1 – Main characteristics of fifteen hypothetical crops (H-crops)

	H-cassave	H-coconut	H-cotton	H-groundnut	H-maize	H-palm tree	H-potato	H-poplar	H-miscanthus	H-rapeseed	H-soybean	H-sugarcane	H-sugar beet	H-sunflower	H-wheat
Harvest Index (HI)	0.70[a]	0.30[a]	0.33[a]	0.25[a]	0.45[a]	1.00[a]	0.70[a]	0.71[f]	1.00[e]	0.32[a]	0.40[a]	0.60[a]	0.66[a]	0.31[d]	0.42[a]
Economic yield	Tuber[b]	Coconut[b]	Cottonboll[b]	pod+seed[b]	Whole tops[b]	Inflor+seed[b]	Tuber[b]	Wood[f]	Whole plant[e]	Inflor+seed[d]	Beans[a]	Whole tops[a]	Sugarbeet[a]	Inflor+seed[b]	Ear+grain[b]
Dry mass[b]	0.38	0.5	0.85	0.95	0.85	0.85	0.25	0.85	0.85	0.74	0.92	0.27	0.21	0.85	0.85
Composition dry mass (g/100 g)[c]															
Carbohydrates	87	4	40	14	75	45	78	62	62	7	29	57	82	45	76
Proteins	3	40	21	27	8	14	9	10	10	22	37	7	5	14	12
Fats	1	3	23	39	4	22	0	2	2	42	18	2	0	22	2
Lignins	3	14	8	14	11	13	3	20	20	2	6	22	5	13	6
Organic acids	3	0	4	3	1	3	5	2	2	1	5	6	4	3	2
Minerals (K,Ca,P,S)	3	39	4	3	1	3	5	4	4	26	5	6	4	3	2
Rest fraction	Leaves	Shells	stems	leaves	stems		leaves	Leaves		leaves	leaves	stems	leaves	stems	Stems
Dry mass[b]	0.38	0.50	0.85	0.15	0.85		0.13	0.85		0.13	0.15	0.27	0.21	0.85	0.85
Carbohydrates	52	62	62	52	62		52	52		52	52	62	52	62	62
Proteins	25	10	10	25	10		25	25		25	25	10	25	10	10
Fats	5	2	2	5	2		5	5		5	5	2	5	2	2
Lignins	5	20	20	5	20		5	5		5	5	20	5	20	20
Organic acids	5	2	2	5	2		5	5		5	5	2	5	2	2
Minerals (K,Ca,P,S)	8	4	4	8	4		8	8		8	8	4	8	4	4

Information on composition, harvest index and dry mass are averages of existing crops. Data were derived from agricultural studies.

[a] *Source:* Goudriaan et al., 2001.

[b] *Source:* Penning de Vries et al., 1989.

[c] *Source:* Habekotté, 1997.

[d] *Source:* Aktar, 2004.

[e] Assumption.

[f] *Source:* Nonhebel, 2002.

Although the efficiency of this process varies, it shows a linear relationship between intercepted global radiation and above ground plant biomass under conditions of sufficient water and nutrient supply (Goudriaan et al., 2001; Monteith, 1977). All plants use glucose as the molecule that stores energy from photosynthesis and as the basis for all other organic compounds that make up plant tissues (Penning de Vries, 1983). The five main categories of organic compounds are: carbohydrates, proteins, lipids, lignins and organic acids. The amount of glucose needed for a unit of organic compound differs, resulting in different energy values for the compounds. This means that the composition of the biomass determines the availability of energy from a specific biomass type, resulting in differences in combustion energy. Energy analysis defines the energy content of a fuel as the amount of heat that is produced during combustion at 25 °C at 1 bar. It distinguishes between the higher heating value (HHV) and the lower heating value (LHV) (Blok, 2006). For the HHV, energy analysis measures the heat content of water that is the product of the combustion process in the liquid form; in the case of LHV it measures the heat content in the gaseous form. Data on HHV and LHV become available from laboratory analyses and can be obtained from databases like the Phyllis database (ECN, 2007) or the database of the UT Wien (Reisinger et al., 1996). In general, however, organic systems, such as agriculture producing crops, show natural variation of its output, resulting in differences in crop composition (Gerbens-Leenes, 2006). Even for crops of the same type, variation occurs resulting in differences in HHV and LHV (ECN, 2007; Reisinger et al., 1996). For the assessment of the WF of energy from biomass, this natural variation forms a complication. To avoid large variation of results, this study defined hypothetical crops, H-crops, with a standardized composition derived from existing crops. Data were obtained from agricultural studies. Table 1 shows the fifteen H-crops and their main characteristics that formed the basis for the calculations.

Table 2 shows the higher heating values (HHV) for the five major groups of plant components in kJ/gram from Penning de Vries et al. (1989). Based on the composition of the H-crop and the HHV of the crop component, the study calculated the HHV of the H-crops.

2.4. *The concept of the water footprint (WF)*

Natural capital—air, land, habitats and water—is essential for the natural environment that performs functions essential for human existence and life on earth (Costanza and Daly, 1992) such as the provision of biomass. The availability of fresh water is a prerequisite for biomass growth. Solar radiation is the principal driving force behind the evaporation of water. There are many equations available to estimate the evaporation of water, for example the Penman–Monteith equation that requires input of meteorological data (Allen, 1998). The FAO has used this equation for the development of the computer program CROPWAT (FAO, 2007), a useful tool for farmers for irrigation planning and management. Another tool that assesses water requirements for crops as well as international virtual-water flows related to the trade of crops and crop products is the concept of the water footprint (WF). This tool has been introduced by Hoekstra and Hung (2002), who define the WF as the total volume of fresh water used to produce the goods and services related to a certain consumption pattern. The WF of a product (commodity, good or service) is defined as the volume of fresh water used for the production of that product at the place where it was actually produced (Hoekstra and Chapagain, 2007). Most of the water used is not contained in the product itself. In general, the actual water content of products is negligible compared to their WF. The WF is expressed in m^3/kg of product, m^3/capita/year, or in m^3/year on a national level. The WF of a product is not restricted to the country in which it is consumed, because trade of water-intensive products implies trade in water in virtual form. The main virtual-water flows between nations are related to international trade in soybeans (11%), wheat (9%), coffee (7%), rice (6%) and cotton (4%) (Hoekstra and Chapagain, 2008).

Table 2 – Heat of combustion for six major groups of plant components (kJ/g)

Plant component	Heat of combustion (kJ/g)
Carbohydrates	17.3
Proteins	22.7
Fats	37.7
Lignins	29.9
Organic acids	13.9
Minerals (K,Ca,P,S)	0.0

Source: Penning de Vries et al., 1989.

Calculations of a WF are made by summing daily crop evapotranspiration (mm/day) over the growing period of a crop. 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 refers to 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 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 (Hoekstra and Chapagain, 2008). An important aim of this paper is to provide insight into the WF of primary energy carriers from biomass and compare this to the WF of other primary energy carriers. It therefore did not make a distinction between green, blue and gray water.

2.5. *Calculation of the WF of biomass*

The WF of biomass differs from the WF of other energy carriers because biomass derives from plants that need water for growth. For the assessment of the WF, the study takes the complete growing season of the plant into account and accumulates data on daily crop evapotranspiration (ET_c in mm/day) over the growing period of the crop using the FAO program CROPWAT. 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 is the calculation of the water requirement of crop *c*, CWR(*c*) (m^3/ha), in a specific area. This 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:

$$\mathrm{CWR}(c) = 10^* \sum_{d=1}^{1p} K_c(c)^* \mathrm{ET}_o \tag{1}$$

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 shown in Table 1 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). 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 consists of the calculation of the 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. The total biomass yield BY(*c*) has been calculated as follows:

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

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). Table 1 shows an overview of HI(*c*).

Step 3 is the calculation of the water footprint of crop *c* per unit of mass, $\mathrm{WF}_M(c)$ (m^3/ton). This has been done by dividing the crop water requirement by the biomass yield:

$$\mathrm{WF}_M(c) = \frac{\mathrm{CWR}(c)}{\mathrm{BY}(c)} \tag{3}$$

Step 4 is the calculation of the average energy content of a hypothetical crop *c*, *E*(*c*) (GJ/ton). This has been done by combining data on higher heating values of plant components (HHV in kJ/g=GJ/ton) (see Table 2) with information on the composition of a H-crop (g/g) as shown in Table 1:

$$E(c) = \mathrm{HI}(c)^*\mathrm{DM}_Y(c)^*\sum_{i=1}^{5} C_i^*A_{y,i} + (1 - \mathrm{HI}(c)^*\mathrm{DM}_r(c)^*\sum_{i=1}^{5} C_i^*A_{r,i} \tag{4}$$

HI(*c*) is the harvest index of crop *c*, $\mathrm{DM}_Y(c)$ is the fraction of dry mass in the crop yield, and $\mathrm{DM}_r(c)$ is the fraction of dry mass in the rest fraction, *C* is the heat of combustion of component *i* (HHV in kJ/g), A is the amount of component *i* in the DM of the crop yield or rest fraction (g/g).

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

$$\mathrm{WF}_E(c) = \frac{\mathrm{WF}_M(c)}{E(c)} \tag{5}$$

3. Results

3.1. *The WF of energy from biomass*

Tables 3a–b show the results for the WF of energy from biomass expressed in cubic meters per unit of biomass (fresh weight) and in cubic meters of water per unit of energy for the fifteen crops grown in the four different countries.

Table 3a shows that differences among WFs of biomass are 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 sugar beets grown in the Netherlands and cotton grown in Zimbabwe; the WF of the cotton was 125 times the WF of Dutch sugar beets. Table 3a also shows that for the crops considered, large differences occur within countries. In the Netherlands, for example, sugar beets, potatoes and maize have small WFs, while oilseedrape and sunflower show relatively large WFs.

Table 3b shows the results per unit of energy provided by the total biomass of the crop for the four countries considered. Because some crops have larger water contents than others, for example sugar beets and potatoes, the comparison of the WF of energy provides a better insight in differences among crops and countries than a comparison based on fresh weight. Still, differences among crops and countries are very large. The largest difference was found between maize grown in the Netherlands and cotton grown in Zimbabwe; the WF of the cotton was 40 times the WF of Dutch maize.

3.2. *The relative WF of energy from biomass*

Results show that, in general, some crops have a lower WF per unit of energy than other crops. In order to compare the WF of crops in a specific country, Fig. 1 a–d shows the relative WF for the crops per country.

Table 3a – Water footprint of biomass for fifteen crops grown in the Netherlands, the United States, Brazil and Zimbabwe (m^3/ton)

Crop	*m^3/ton*			
	The Netherlands	United States	Brazil	Zimbabwe
Cassava	–	–	156	1074
Coconut	–	–	444	1843
Cotton	–	2414	1710	6359
Groundnuts	–	477	426	2100
Maize	153	308	664	3363
Miscanthus	334	629	828	1082
Palm oil and kernels	–	–	1502	–
Poplar	369	696	915	1198
Potatoes	72	111	106	225
Soybeans	–	979	602	1360
Sugar beets	51	88	–	–
Sugarcane	–	153	128	160
Sunflower	481	1084	972	2603
Wheat	150	1388	1360	1133
Oilseedrape	459	773	1460	–

Table 3b – Water footprint of biomass for fifteen crops grown in the Netherlands, the United States, Brazil and Zimbabwe (m^3/GJ)

Crop	*m^3/GJ*			
	The Netherlands	United States	Brazil	Zimbabwe
Cassava	–	–	30	205
Coconut	–	–	49	203
Cotton	–	135	96	356
Groundnuts	–	58	51	254
Maize	9	18	39	200
Miscanthus	20	37	49	64
Palm oil and kernels	–	–	75	–
Poplar	22	42	55	72
Potatoes	21	32	31	65
Soybeans	–	99	61	138
Sugar beets	13	23	–	–
Sugarcane	–	30	25	31
Sunflower	27	61	54	146
Wheat	9	84	83	69
Oilseedrape	67	113	214	–
Average	24	57	62	142

Fig. 1a shows that in the Netherlands, maize has the smallest WF. The WF of sugar beet is 50% larger, whereas the WF of miscanthus is twice the WF of maize, the WF of poplar and potato 2.5 times, the WF of sunflower 3 times and the WF of oilseedrape 7.5 times. Fig. 1b shows that in the US, maize also has the smallest WF. The WFs of sugar beet and sugar cane are about 50% larger, poplar and potato 2.5 times larger, groundnut and sunflower 3 times, and oilseedrape and cotton 6 and 7.5 times larger respectively. Fig. 1c shows that in Brazil, sugar cane has a bit more then half the WF of maize; cotton and oilseedrape have 2.5 and 5 times the WF of maize. Fig. 1d shows that 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 WFs in the same order of magnitude or smaller. In general, the WF of maize is favourable, the WF of oilseedrape and cotton unfavourable. Fig. 1 shows that some crops that are specifically grown for energy, i.e. miscanthus, poplar and oilseedrape have a relatively large WF compared to a food crop such as maize. An exception is poplar grown in Zimbabwe. For this crop the study applied average yield data taken from production systems that probably overestimated yields in that country, so that it underestimated the WF of poplar. From a water perspective, crops specifically grown for energy do not have a more favourable WF than crops grown for food.

It is stressed that for the assessment of the WF, the study only took the energy content of biomass into account. The energy input for the agricultural system, for example for fertilizers and pesticides, fell outside the study. For high-input

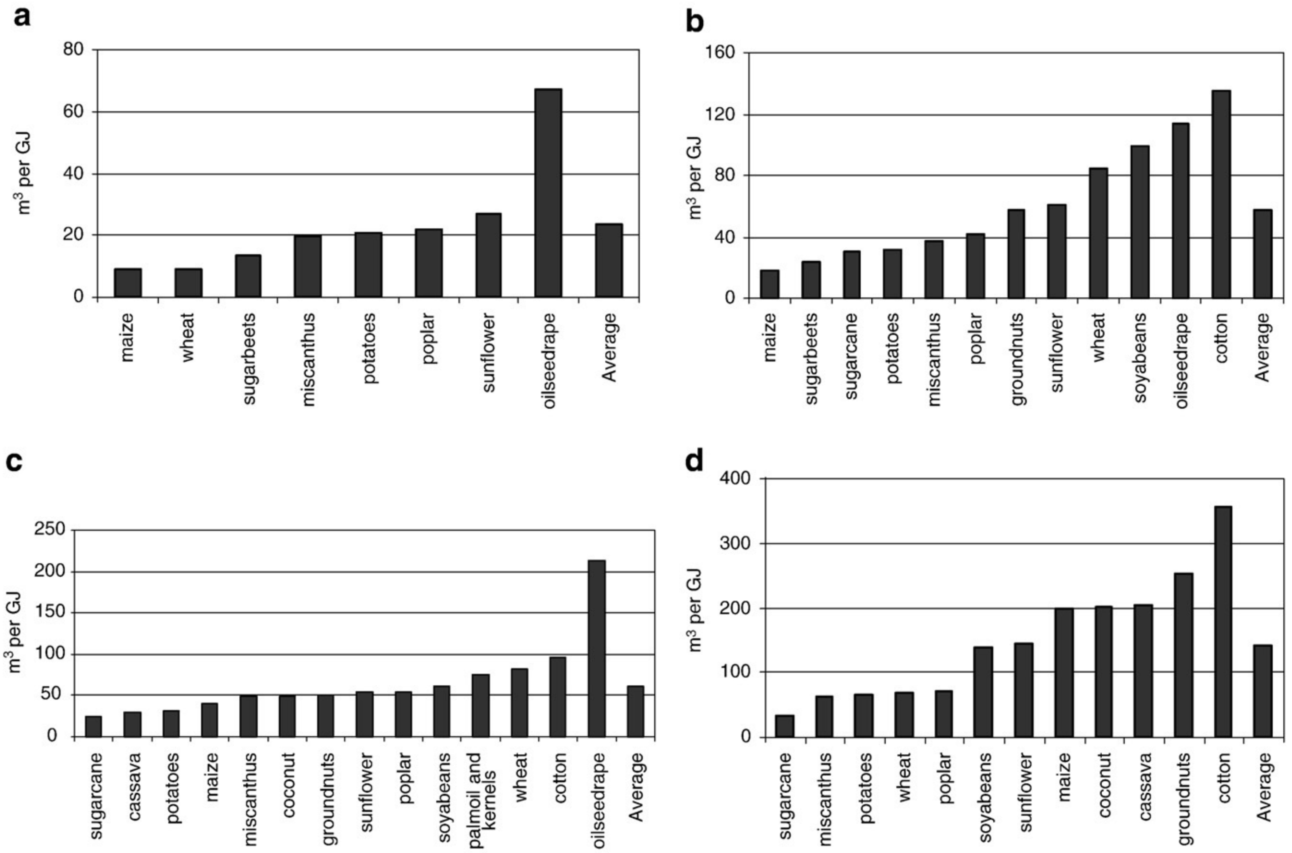

Fig. 1 – a–d WF for fifteen crops grown in four countries. Fig. 1a shows the WF of eight crops grown in the Netherlands; fig. 1b shows the WF of twelve crops grown in the United States; fig. 1c shows the WF of fourteen crops grown in Brazil and fig. 1d shows the WF of twelve crops grown in Zimbabwe.

agricultural systems, the energy input is substantial (Pimentel and Patzek, 2005) so that net energy yields are smaller than calculated in this study. This means that this study probably underestimated the WF of biomass from agricultural systems with relatively large energy inputs.

4. Discussion

4.1. *The WF of other primary energy carriers compared to the WF of biomass*

At present, the most important primary energy carriers that derive from sources in the first stage of the energy supply chain include crude oil, coal, natural gas, uranium, electricity from hydropower, solar energy and wind (Blok, 2006). Processes that make these primary energy carriers available, almost always require water in varying amounts. Gleick (1994) has made estimates for the WF of crude oil, coal, natural gas, uranium, solar energy and wind. Large differences among the WF of operations occur, resulting in large differences among average, total WFs of these energy carriers. The WF of underground uranium mining, for example, is negligible, whereas the WF of the deep mining of coal is 0.012 m^3/GJ, the WF of onshore oil extraction and production 0.006 m^3/GJ, and the WF of surface mining of coal 0.004 m^3/GJ. Also, the generation of hydropower requires fresh water. A rough estimate was made by dividing global evaporation from artificial surface water reservoirs (Shiklomanov, 2000) by the global hydroelectric generation (Gleick, 1993) for the year 1990. Table 4 shows the WF of coal, uranium, crude oil, natural gas and hydropower, as well as the averages for energy from biomass for the four countries included in this study.

The WF increases in the following order: electricity from wind energy (0.0 m^3/GJ), uranium (0.1 m^3/GJ), natural gas (0.1 m^3/GJ), coal (0.2 m^3/GJ), electricity from solar active space heat (0.3 m^3/GJ), crude oil (1.1 m^3/GJ) and finally hydropower (22 m^3/GJ). In the category of primary non-renewable energy carriers, the WF of crude oil is ten times the WF of uranium.

As mentioned before, the WF includes three types of water: green, blue and gray water. The first two refer to water use (the evaporative part), 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 took pollution, and thus gray water into account to a limited extent only by assuming that the return flows (water volumes that do not evaporate but return to ground water and surface water systems) are polluted. In reality, one cubic meter of return flow generally pollutes much more water than one cubic meter. In this way, the study probably underestimated the WF of some energy carriers that show large water pollution.

Table 4 – Water footprint of primary energy carriers (m^3/GJ)

	Average water footprint (m^3/GJ)
Primary energy carriers (excluding biomass and hydropower)	
Wind energy[a]	0.0
Nuclear energy[a]	0.1
Natural gas[a]	0.1
Coal[a]	0.2
Solar thermal energy[a]	0.3
Crude oil[a]	1.1
Primary energy carriers: hydropower and biomass	
Hydropower[b]	22
Biomass the Netherlands (average)	24
Biomass US (average)	58
Biomass Brazil(average)	61
Biomass Zimbabwe (average)	143
Biomass (average the Netherlands, US, Brazil, Zimbabwe)	72

Averages for fossil energy carriers, electricity from active solar space heat, and electricity from wind energy derive from Gleick (1994). Averages for biomass and hydropower derive from this study.

[a] *Source:* Gleick (1994).

[b] *Source: calculated based on* Gleick (1993) *and* Shiklomanov (2000).

4.2. *A shift towards energy from biomass or hydropower*

At present, average direct and indirect energy use in western societies is about 100 GJ per capita per year (Kramer et al., 1994; Vringer and Blok, 1995; Noorman and Schoot Uiterkamp, 1998; Moll et al., 2005). This energy is generated with a mix of primary energy carriers, mainly non-renewables (coal, oil, natural gas and uranium) and some renewable energy from hydropower (Blok, 2006; BP, 2007). Table 4 shows that the WF of biomass and hydropower is much larger than the WF of the other primary energy carriers. Based on the average per capita energy use in western societies, a mix from coal, crude oil, natural gas and uranium requires about 35 m^3 per capita per year. If the same amount of energy is generated through the growth of biomass in a high productive agricultural system, as applied in the Netherlands, the WF of 100 GJ is 2420 m^3. In the United States, where yields are lower than in the Netherlands, the WF is 5820 m^3 per capita per year, in Brazil 6120 and in Zimbabwe even 14260 m^3 per capita per year. This means that the WF of biomass and hydropower is 70 to 400 times larger than the WF of the other primary energy carriers. This water requirement competes with the water needs for food and materials. The WF of the Netherlands for food, beverages (coffee and tea) and cotton is 1200 m^3 per capita per year, the WF of the United States is 2500 m^3 and the WF of Brazil is 1400 m^3 per capita per year (Hoekstra and Chapagain, 2008). For the Netherlands and the United States, a complete shift from fossil energy to energy from biomass would triple the annual per capita WF. For Brazil, the WF would become even five times larger. Moreover, food consumption patterns are changing (Gerbens-Leenes and Nonhebel, 2002): globally, a transition is taking place towards more affluent consumption. Especially the consumption of meat, dairy and beverages increases. This will not only require more land, but also more fresh water. Estimates for 2015 show that total water needs for food will double, causing further degradation of ecosystems (Rockström et al., 2007). Strategies towards substantial use of biomass or hydropower for energy purposes should take the large WFs of these energy sources into account, as well as the competition between water for bio-energy and water for food.

The current and future economic development, for example in China and India, not only causes an increasing need for energy, but also for more affluent foods and thus for natural resources, such as fresh water (Gerbens-Leenes, 2006). The global resources are inadequate to meet, let alone sustain the current western life style for each individual. Insights obtained in this study can contribute to a better understanding of the environment–consumption relationship.

4.3. *Uncertainties*

It is stressed that the data presented in this study are based on rough estimates of freshwater requirements in crop production. The data show the direction of changes and give an indication of their magnitudes. For the assessment of the WF of energy from biomass, the study integrated information from several sources, each of which adds a degree of uncertainty. For example, the calculations using the model CROPWAT required input of meteorological data that are averages over several years rather than specific annual data. The data presented do thus not reflect annual variations. Moreover, the study included only four countries; results for other countries may be different. Also, the study derived rather old data on water requirements for the other primary energy carriers from literature. Since 1994, efficiency in water use for mining may have increased. The factors mentioned above imply that numbers presented here are indicative. However, the differences in WF's are so large that the conclusions can be supported. In this way, the study provides new insights into the relationship between the energy and the water system.

5. Conclusions

This article has clarified the freshwater implications of a large-scale introduction of biomass for energy purposes. It has shown the relationship between fresh water and energy, especially between fresh water and bio-energy. The 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 conditions, and climatic circumstances. 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 specifically grown for energy purposes, such as poplar, miscanthus or oilseedrape, do not show more favourable WF's than food crops, such as, maize.

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 fresh water. 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 substantially more water, which will raise a conflict between 'water for food' and 'water for energy'.

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