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Water footprint of bio-energy and other primary energy carriers

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WATER FOOTPRINT OF BIO-ENERGY AND OTHER PRIMARY ENERGY CARRIERS

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Summary

Freshwater is essential for life on earth, not only for basic human needs such as food, fibre and drinking water, but also for a healthy environment. In the near future, important challenges are to meet basic needs and to ensure that the extraction of water does not affect freshwater ecosystems. At present, humanity already uses 26 percent of the total terrestrial evapotranspiration and 54 percent of accessible runoff. If the world population increases further, there is concern in several regions and countries with limited water resources if food and fibre needs of future generations can be met. In general, global change is often considered in relation to climate change caused by emissions of greenhouse gasses, such as CO_2 from fossil energy carriers. A shift towards CO_2-neutral energy carriers, such as biomass, is heavily promoted. Nowadays, the production of biomass for food and fibre in agriculture requires about 86% of the worldwide freshwater use often competing with other uses such as urban supply and industrial activities. A shift from fossil energy towards energy from biomass puts additional pressure on freshwater resources.

This report assesses the water footprint (WF) of bio-energy and other primary energy carriers. It focuses on primary energy carriers and expresses the WF as the amount of water consumed to produce a unit of energy (m^3/GJ). The report observes large differences among the WF's for specific types of primary energy carriers. For the fossil energy carriers, the WF increases in the following order: uranium (0.09 m^3/GJ), natural gas (0.11 m^3/GJ), coal (0.16 m^3/GJ), and finally crude oil (1.06 m^3/GJ). Renewable energy carriers show large differences in their WF. The WF for wind energy is negligible, for solar thermal energy 0.30 m^3/GJ, but for hydropower 22.3 m^3/GJ. For biomass, the WF depends on crop type, agricultural production system and climate. The WF of average biomass 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. 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 increasing contribution of energy from biomass to supply will bring with it a need for more water. This causes competition with other claims, such as water for food crops.

1. Introduction

Freshwater 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 percent of the total terrestrial evapotranspiration and 54 percent of accessible runoff (Postel et al., 1996). For a world population of 9.2 billion, as projected by the United Nations for 2050 (UN, 2007), there are reasons for profound concern in several regions and countries with limited water resources if food and fibre needs of future generations can be met (Fischer et al., 2002; 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 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 CO_2-neutral energy carriers, such as biomass, is heavily promoted. Other advantages of these renewable energy sources are a decreased risk of energy supply insecurity, resource diversification, and the absence of depletion risks (De 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 (2003) and has been developed further by Hoekstra and Chapagain (2007, 2008). Those authors define the WF as the total annual volume of freshwater 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 report is to assess the water footprint per unit of energy (m^3/GJ) of biomass and to compare these requirements with the water footprint of fossil energy carriers and other renewables (wind, solar energy and hydropower). Research questions are: (i) How much water is needed to provide energy from traditional fossil energy carriers?; (ii) What is the WF per unit of energy of food crops (e.g.

crops for sugar, starch and oil) and typical energy crops (e.g. trees and grasses); (iii) Does the location where biomass is produced influence the WF?; and (iv) How much additional water is needed if a shift occurs towards energy from biomass? First, the report estimates the WF of various types of biomass in m^3 per unit of energy (GJ). Next, it estimates the WF of fossil energy carriers and hydropower based on data from literature and compares these results with results for biomass. This information can be used to evaluate the total WF of energy for different scenarios.

2. System description

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, the non-renewable and the renewable energy 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 organic 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 *bioenergy*.

For the assessment of the WF of energy, this report considered the currently most important primary energy carriers that derive from sources in the first stage of the energy supply chain: crude oil, coal, natural gas, uranium, electricity from hydropower, solar energy, and wind, and biomass. Processes that make primary energy carriers available, almost always require water in varying amounts. This section provides an overview of primary energy carriers showing the processes that require water to make them available.

Crude oil

Globally, the most important primary non-renewable energy carrier is crude oil or petroleum that forms the basis for oil products (e.g. kerosene, gasoline and heavy fuel oil). Production of crude oil is done by drilling wells and pumping the oil out. Primary production of crude oil includes well drilling and oil pumping from underground reservoirs (Blok, 2006). Gleick (1994) has estimated that about 2-8 m^3 of water per 10^3 GJ(thermal) is needed for drilling, flooding and treating crude oil. When the amount of crude oil pumped out decreases, extraction is improved by so-called secondary recovery that needs water in the form of steam to improve the viscosity of the crude oil and enhance pumping (Blok, 2006). Thermal steam injection requires 100-180 m^3 of water per 10^3 GJ(thermal) (Gleick, 1994).

Coal

The second important non-renewable primary energy carrier is coal, a sedimentary rock found both near the Earth's surface and in deeper deposits that needs to be recovered through mining (Blok, 2006). Open pit mining requires about 2 m^3 of water per 10^3 GJ(thermal), while underground mining operations require about 3-20 m^3 of water per 10^3 GJ(thermal) (Gleick, 1994). After mining the coal, it is often washed to remove nonfuel contaminants.

Natural gas

The third important non-renewable primary energy carrier is natural gas recovered by drilling wells into the underground. It needs limited treatment before use, for example, H_2S and CO_2 are generally removed. Crude oil and natural gas are often found together in porous reservoir rocks covered by a cap rock, from where the gas can be drilled. Gleick (1994) has estimated that plant operations require about 100 m^3 of water per 10^3 GJ(thermal).

Uranium

The fourth important non-renewable primary energy carrier is uranium, present in the Earth's crust in the form of ores with a content of uranium oxide (U_3O_8) between 0.01 and 1%. It is recovered from open pit and underground mines requiring water for processes like dust control and ore beneficiation. Requirements vary between 0.2 m^3 of water per 10^3 GJ(thermal) for underground mining, to 20 m^3 of water per 10^3 GJ(thermal) for open pit mining. The additional milling, refining and enriching of uranium requires another 20 m^3 of water per 10^3 GJ(thermal) (US Atomic Energy Comm., 1974)

Electricity from hydropower

Hydropower is the second most important renewable energy source after biomass. It uses the potential energy of water to drive turbines generating electricity. Dams in rivers create large water reservoirs (Shiklomanov, 2000; Blok, 2006). The water requirements for hydropower are mainly caused by evaporation and seepage from the reservoirs and are about 5-26 m^3 per 10^3 kWh(electric) (Gleick, 1994).

Solar energy

The radiation from the sun provides solar energy. Solar energy can be utilized in three ways: (i) heat production through solar collectors producing hot water; (ii) electricity production through PV cells; and (iii) electricity production through solar thermal power plants. These plants convert energy into hot air or steam used to generate electricity (Blok, 1994). Gleick (1994) has estimated that water requirements of solar thermal power plants are about 1 m^3 per 10^3 kWh(electric).

Electricity from wind energy

Wind energy utilizes the kinetic energy in the air to generate electricity. In wind farms, the average, annual energy generated varies between 0.05 and 0.25 GJ(electric) per m^2 (Blok, 2006). If the land remains available for other uses, for example for agriculture, no water requirements have to be allocated to wind energy. In that case, wind energy does not require water, whereas the water requirement for the construction of the turbines is negligible (Gleick, 1994).

Biomass

For the production of biomass, agriculture applies the natural land base and requires the input of freshwater for crop growth. Solar radiation is the principal driving force for 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 et al., 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.

2.2 The concept of the water footprint

Natural capital - air, land, habitats and water - is essential for the natural environment that performs basic functions for human existence and life on earth (Costanza and Daly, 1992) such as the provision of biomass. The availability of freshwater is a prerequisite for biomass growth. A 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 (2003), who defines the WF as the total annual volume of freshwater 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 freshwater 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, however. In general, the actual water content of products is negligible compared to their WF. The WF shows water use for consumption, termed utilization, inside and outside the national territory. Results are expressed as m^3/kg of product, m^3/capita/year, or as m^3/year on a national level. Globally, the main virtual water flows are related to utilization of soybeans (11%), wheat (9%), coffee (7%), rice (6%) and cotton (4%) (Hoekstra and Chapagain, 2008).

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).

3. Methods

3.1 General

To make primary, non-renewable energy carriers available, several operations take place, many of which require water. The amount of water for a specific operation, however, varies. Requirements for the mining of coal, for example, vary between 2 m^3/1000 GJ for surface mining, to 20 m^3/1000 GJ for underground mining (Gleick, 1994). For the assessment of the WF's, the report summed the largest WF's per operation per energy carrier. It derived data from Gleick (1994). In this way, the report probably overestimated the WF of non-renewable, primary energy carriers. On the other hand, the return flow generates pollution of large water quantities so that the pollution volume (gray water) is underestimated.

In the category of primary, renewable energy carriers, the report distinguished between carriers from non-organic and carriers from organic sources, i.e. biomass. Carriers from non-organic sources for which the report calculated the WF were electricity from solar thermal power plants, from wind energy and from hydropower. For the assessment, the report derived data from Gleick (1994). The WF of hydropower was calculated by dividing data on global evaporation of artificial surface water reservoirs from Shiklomanov (2000) by information on hydroelectric generation from Gleick (1993) for the year 1990.

3.2 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 assessment of the WF of biomass, this report only took crops into account; wastes fell outside the report. 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, total biomass yield can be applied rather than crop yield. Total biomass yield was calculated by dividing data on crop yields from the FAO (2007) by the HI. Table 1 shows data on HI used in this report derived from agricultural studies (Goudriaan et al., 2001; Akhtar, 2004).

The report considered three categories of crops: (i) trees; (ii) bioenergy crops; and (iii) food crops. It made assessments for fifteen crops from the three categories mentioned above: poplar (trees), miscanthus (bioenergy crops), and for cassava, coconut, cotton, groundnuts, maize, palm oil, potato, wheat, rapeseed, sugar beet, sugar cane, sunflower, and soybean (food crops).

3.3 Energy from biomass

The basis for energy from biomass is the universal photosynthesis process that stores solar energy in chemical bonds. 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^{o} 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 report 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 (see also Appendix 3). Table 2 shows the heat of combustion 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 report calculated the HHV of the H-crops.

Table 1. Main characteristics for fifteen hypothetical crops (H-crops). Information on composition, harvest index and dry mass are averages of existing crops. Data were derived from agricultural studies.

	H-cassava	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	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
Composition dry mass (g /100 g)[c]															
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

a. Source: Goudriaan et al. (2001)
b. Source: Penning de Vries et al. (1989)
c. Source: Habekotté (1997)
d. Source: Akthar (2004)
e. Assumption.
f. Source: Nonhebel (2002)

Table 2. Heat of combustion (HHV) for six major groups of plant components (kJ/gram).

Plant component	Heat of combustion (kJ / gram)
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 (1989).

3.4 Calculation of the water footprint 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 report takes the complete growing season of the plant into account and accumulates 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 report 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 report 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 et al., 1998) to estimate reference evapotranspiration:

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

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). Appendix 4 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 report allocated the *CWR* to the total biomass yield *BY (c)* (tons/ha) calculated as follows:

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

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). Appendix 4 shows an overview of yield data; Table 1 shows an overview of *HI (c).*

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:

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

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) (see Table 2) with information on the composition of a H-crop (grams/gram) as shown in Table 1:

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

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:

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

4. Results and discussion

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

Table 3 shows the WF of operations that make the non-renewable energy carriers coal, uranium, crude oil and natural gas available.

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

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

Large differences among the WF of operations occur, resulting in large differences among average, total WF's of primary non-renewable 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, onshore oil extraction and production 0.006 m^3/GJ, and surface mining of coal only 0.004 m^3/GJ. For the non-renewable and renewable energy carriers (excluding biomass), the WF increases in the following order: electricity from wind energy (0.00 m^3/GJ), uranium (0.09 m^3/GJ), natural gas (0.11 m^3/GJ), coal (0.16 m^3/GJ), electricity from solar active space heat (0.27 m^3/GJ), crude oil (1.06 m^3/GJ) and finally hydropower (22.3 m^3/GJ). In the category of primary non-renewable energy carriers, the WF of crude oil is ten times the WF of uranium. Table 3 also shows that, except for hydropower, the average total WF of the renewables (excluding biomass) is smallest, of the non-renewables largest.

As mentioned before, the WF includes three types of water: green, blue 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 report 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 report probably underestimated the WF of some energy carriers that show large water pollution.

4.2 Energy from biomass

Table 4 shows the results for the calculated heat of combustion of the H-crop yields and rest fractions in MJ per kg dry mass. It shows that the heat of combustion varies between 15 MJ per kg for coconuts and 28 MJ for groundnuts. Table 5 shows the heat of combustion for the total biomass of the H-crop 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 5 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.

4.3 The water footprint of energy from biomass

Tables 6a-b show the results for the WF of energy from biomass expressed in cubic meters of water per unit of energy and in cubic meters per unit of mass for the fifteen crops grown in four different countries. 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 report, 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 general, some crops have a lower WF per unit of energy than other crops. In order to compare the WF of crops, Figure 1 shows the relative WF per country, where the WF of maize in that country is set to 1.

Table 4. Heat of combustion for the crop yield of H-crops and their rest fraction per unit of dry mass.

H-Crop and rest fraction	Heat of combustion HHV (MJ per kg dry mass)
Cassava	17.4
Cassava leaves	18.7
Coconut	15.1
Coconut shell	20.0
Cotton	23.3
Cotton stems	20.0
Groundnuts	27.9
Groundnut leaves	18.7
Maize	19.7
Maize stems	20.0
Miscanthus	20.0
Palmkernels[c]	23.6
Poplar	20.0
Poplar leaves	18.7
Potato	17.1
Potato leaves	18.7
Rapeseed	22.8
Rapeseed leaves	18.7
Sugarbeet	19.4
Sugarbeetleave	18.7
Sugarcane	19.6
Sugarcane stems	20.0
Soybeans	22.7
Soybeans leaves	18.7
Sunflower	23.6
Sunflowerstems	20.0
Wheat	18.7
Wheatstems	20.0

Table 5. 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)
Cassava	5.2
Coconut	9.1
Cotton	17.9
Groundnuts	8.3
Maize	16.8
Miscanthus	17.0
Oranges	12.9
Palmkernels[c]	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

Table 6a. WF of biomass for fifteen H-crops grown in the Netherlands, the US, 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

Table 6b. WF of biomass for fifteen H-crops grown in the Netherlands, the US, 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	--

Figure 1 shows that in the Netherlands, maize and wheat have the smallest WF, the WF of sugar beet is 50% larger, whereas the WF of miscanthus is twice the WF of maize, of poplar and potato two and a half the WF of maize, of sunflower three times and of oilseedrape seven and a half times the WF of maize. In the US, maize also has the smallest WF. The WF's of sugar beet and sugar cane are about 50% larger, poplar and potato two and a half times larger, groundnut and sunflower three times, and oilseedrape and cotton six and seven and a half times larger respectively. In Brazil, sugar cane shows about half the WF of maize; cotton and oilseedrape have two and a half and five times the WF of maize. The other crops have WF's in the same order of magnitude as maize. 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 favourable, the WF of oilseedrape and cotton unfavourable. 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 the report applied average yield data taken from production systems that probably overestimated yields 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 favourable WF than crops grown for food.

It is stressed that for the assessment of the WF, the report only took the energy content of biomass into account. The energy input for the agricultural system, for example for fertilizer and pesticides, fell outside the report. For high input agricultural systems, the energy input is substantial (Pimentel and Patzek, 2005) so that net energy yields are smaller than calculated in this report. This means that this report probably underestimated the WF of biomass from agricultural systems with relatively large energy inputs.

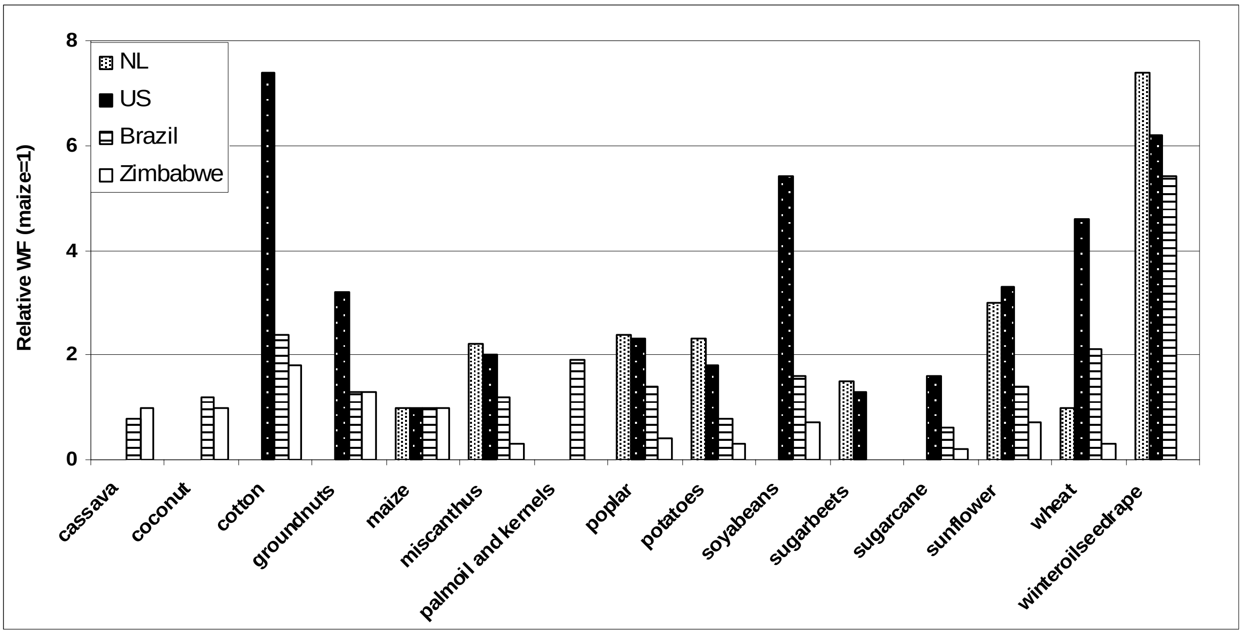

Figure 1. Relative water footprint (WF) for fifteen crops grown in the Netherlands, the United States, Brazil and Zimbabwe, where the WF of maize in the country considered is set to 1.

4.4 A shift towards energy from biomass

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 7 shows that the WF of non-renewables and renewables (excluding biomass) is much smaller than the average WF of biomass.

Table 7. Average water footprint for fossil energy carriers, electricity from active solar space heat, electricity form wind energy, biomass produced in the Netherlands, Brazil, the United States and Zimbabwe (m^3/GJ).

Primary energy carriers	Average water footprint (m^3/GJ)
Wind energy	0.00
Natural gas	0.04
Nuclear energy	0.09
Coal	0.16
Solar thermal energy	0.30
Crude oil	1.06
Biomass the Netherlands (average)	24.16
Biomass US (average)	58.16
Biomass Brazil(average)	61.20
Biomass Zimbabwe (average)	142.62
Biomass (average the Netherlands, US, Brazil, Zimbabwe)	71.54

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 is 70 to 400 times larger than the WF of the other primary energy carriers. This water requirement lies in the same order of magnitude than the per capita WF for food (Hoekstra and Chapagain, 2007). 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 freshwater. Estimates for 2015 show that total water needs for food will double, causing further degradation of ecosystems (Rockström et al., 2007). Strategies towards large use of biomass for energy purposes should take the large WF's of this energy source into account, as well as the competition with 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 freshwater (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 report can contribute to a better understanding of the environment-consumption relationship.

5. Conclusions

This report 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 report 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 report 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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Appendix 1: List of abbreviations

BY	biomass yield
CO_2	carbon dioxide
CWR	crop water requirement
FAO	Food and Agriculture Organization of the United Nations
GJ	gigajoule
H-crops	hypothetical crops
HHV	Higher heating value
H_2S	dihydrogensulfide
kJ	kilojoule
kWh	kilowatthour
LHV	Lower heating value
m^3	cubic meter
PV	photovoltaic
WF	water footprint

Appendix 2: List of definitions

Biofuel	Renewable secondary energy carrier derived from biomass in solid, liquid or gaseous form. Examples are charcoal, ethanol, biodiesel and biogas.
Biomass	Material in non-fossilized form. Examples are agricultural crops, forestry products, agricultural and forestry wastes and by-products, manure, microbial biomass, and industrial and household organic waste.
Blue component of the water footprint	Volume of surface and groundwater evaporated as a result of the production of the product or service. For example, for crop production, the "blue" component is defined as the sum of the evaporation of irrigation water from the field as the evaporation of water from irrigation canals and artificial storage reservoirs. It is the amount of water withdrawn from ground- or surface water that does not return to the system from which it came.
Crop yield	Harvested production per unit of harvested area for crop products
Evapotranspiration	Evaporation from the soil where crops are grown including the transpiration of water that actually passes crops
Fossil energy	Non-renewable energy derived from plant material stored in the earth's crust for millions of years, such as oil, natural gas and coal. The use of fossil energy causes emissions of carbon dioxide that contributes to global warming
Green component of the water footprint	Volume of rainwater that evaporated during the production process. This is mainly relevant for agricultural products (e.g. crops or trees) where it refers to the total rainwater evapotranspiration (from fields and plants).
Grey component of the water footprint	Volume of freshwater needed to dilute polluted freshwater flows that leave a specific site after being used by the business at that site to such an extent that the quality of the

	sewage water remains above agreed water standards.
Harvest index	Ratio of crop yield to total biomass yield
Primary energy carrier	Energy carriers directly derived from a natural source without any conversion process
Renewable energy	Energy deriving from renewable sources, mostly solar irradiation. Examples are biomass energy, wind energy and solar energy.
Secondary energy carrier	Energy carriers that do not derive from a natural source and are the product of a conversion process
Water footprint	An indicator of water use that looks at both direct and indirect water use of a consumer or producer. The water footprint of an individual, community or business is defined as the total volume of freshwater that is used to produce the goods and services consumed by the individual or community or produced by the business. The water footprint of an intermediate or final product (including energy) is defined as the total volume of freshwater that is used directly or directly to produce the product. Water use is measured in terms of water volumes consumed (evaporated) and/or polluted per unit of time. A water footprint can be calculated for any well-defined group of consumers (e.g. an individual, family, village, city, province, state or nation) or producers (e.g. a public organization, private enterprise or economic sector). The water footprint is a geographically explicit indicator, not only showing volumes of water use and pollution, but also the locations.

Appendix 3: Composition dry mass crops

	Composition dry mass (g per 100g)[a]						
	carbo-hydrates	proteins	fats	lignins	organic acids	harvest index[b]	percentage of water[b]
Cassava	87	3	1	3	3	0.70	62
Cassava leaves	52	25	5	5	5		62
Coconut	4	40	3	14	0	0.30	50
Coconut shell	62	10	2	20	2		50
Cotton	40	21	23	8	4	0.33	15
Cotton stems	62	10	2	20	2		15
Groundnuts	14	22	39	14	3	0.25	5
Groundnut leaves	52	25	5	5	5		85
Maize	75	8	4	11	1	0.45	15
Maize stems	62	10	2	20	2		15
Miscanthus	62	10	2	20	2	1.00	15
Palmkernels[c]	45	14	22	13	3	1.00	15
Poplar	62	10	2	20	2	1.00	15
Poplar leaves	52	25	5	5	5		15
Potato	78	9	0	3	5	0.70	75
Potato leaves	52	25	5	5	5		87
Rapeseed	7	22	42	2	1	0.32	26
Rapeseed leaves	52	25	5	5	5		87
Sugarbeet	82	5	0	5	4	0.66	79
Sugarbeetleave	52	25	5	5	5		79
Sugarcane	57	7	2	22	6	0.60	73
Sugarcane stems	62	10	2	20	2		73
Soybeans	29	37	18	6	5	0.40	8
Soybeans leaves	52	25	5	5	5		85
Sunflower	45	14	22	13	3	0.31	15
Sunflower stems	62	10	2	20	2		15
Wheat	76	12	2	6	2	0.42	15
Wheat stems	62	10	2	20	2		15

a. Source: Penning de Vries, 1989
b. Source Goudriaan et al., 2001
c. Source: Arrieta et al., 2007

Appendix 4: Agricultural information for the main crops in the U.S., Brazil, the Netherlands and Zimbabwe

Crop information of crops grown in the United States and crop water requirements per growing period.

United States						
Crop	Yield (ton per ha 2005[a])	Most important state	Contribution state to total production %	Weather station	Latitude and longitude	Crop water requirement (mm per growing season)
Cotton	6.0	Texas	27	Amarillo	35.23°N 101.7°W	1011
Groundnuts	3.3	Georgia	42	Atlanta	33.65°N 84.42°W	633
Maize	9.3	Iowa	19	Des Moines	41.58° N 93.62°W	635
Miscanthus	18.8	Iowa[b]		Des Moines	41.58° N 93.62°W	710
Poplar	17.0	Iowa[b]		Des Moines	41.58° N 93.62°W	710
Potato	43.5	Iowa[b]		Des Moines	41.58° N 93.62°W	691
Rapeseed	1.6	Iowa[b]		Des Moines	41.58° N 93.62°W	377
Red winterwheat	2.8	Kansas	24	Dodge City	37.77°N 99.97°W	926
Sugarbeet	50.0	Minnesota	31	Minneapolis	44.88°N 93.22°W	666
Sugarcane	67.8	Florida	50	Tampa	27.95 °N 82.45 °W	1725
Soybeans	2.9	Iowa	16	Des Moines	41.58° N 93.62°W	710
Sunflower	1.7	North Dakota	51	Bismarck	46.77°N 100.75°W	604

[a] Source FAO, 2007
[b] Assumption because of lack of data.

Crop information of crops grown in Brazil and crop water requirements per growing period.

Brazil, weather station Tres Lagoas 20.78°S, 51.70°W		
Crop	Yield (ton per ha 2005[a])	Crop water requirement (mm per growing season)
Cassava	13.6	304
Coconuts	10.5	1557
Cotton	1.4	744
Groundnuts	2.3	395
Maize	3.1	304
Miscanthus	18.8	1557
Poplar	17.0	1557
Potato	30.7	335
Rapeseed	1.7	770
Sugarcane	73.0	1557
Sunflower	1.6	502
Soybeans	2.2	331
Winterwheat	1.9	639

[a] Source: FAO, 2007

Crop information of crops grown in the Netherlands and crop water requirements per growing period.

The Netherlands, weather station Eelde		
Crop	Yield (ton per ha 2005[a])	Crop water requirement (mm per growing season)
Maize	12.2	416
Miscanthus	18.8	628
Poplar	17.0	628
Potato	41.6	430
Rapeseed	3.7	530
Sugarbeet	65.2	499
Sunflower	2.5	385
Winterwheat	8.6	308

[a] Source: FAO, 2007

Crop information of crops grown in Zimbabwe and crop water requirements per growing period.

Zimbabwe		
Crop	Yield (ton per ha 2005[a])	Crop water requirement (mm per growing season)
Cassava	4.4	670
Coconut	2.1	1290
Cotton	0.5	1017
Groundnuts	0.6	649
Maize	0.7	498
Miscanthus	18.8	1290
Oranges	5.8	1290
Poplar	17.0	1290
Potato	15.9	511
Sugarcane	76.5	2037
Sunflower	0.7	546
Soybeans	1.6	558
Wheat	3.0	818

[a] Source: FAO, 2007

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