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– 8 –

The Water Footprint of Bio-Energy

A.Y. Hoekstra, P.W. Gerbens-Leenes, and Th.H. van der Meer

INTRODUCTION

The water sector is becoming more energy-intensive. Think, for example, of the energy needed for desalination of salt or brackish water, for pumping groundwater from deeper and deeper and for large interbasin water transfer schemes. At the same time, the energy sector is becoming more water-intensive—especially because of the increasing focus on biomass as a source of energy. All energy scenarios for the coming decades show a shift toward an increased percentage of bio-energy. This chapter focuses on the question of how much water is involved in the production of bio-energy.

The source of bio-energy can be crops specifically grown for that purpose, natural vegetation, or organic wastes (Minnesma and Hisschemöller 2003). Many of the crops used for bio-energy can also—alternatively, not at the same time—be used as food or feed. Biomass can be burnt to produce heat and electricity, but it can also be used for the production of bio-ethanol or biodiesel, biofuels that can displace fossil energy carriers in motor vehicles (Hughes et al. 2007).

At present, the production of biomass for food and fibre in agriculture requires about 86% of the worldwide freshwater use (Hoekstra and Chapagain 2007, 2008). In many parts of the world, the use of water for agriculture competes with other uses such as urban supply and industrial activities, 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 bio-energy 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 land and water use (Fresco 2006).

Globally, many countries explore options to replace gasoline by biofuels (Hughes et al. 2007). The EU and the US have set targets for the replacement. When agriculture grows crops for bio-energy, however, it needs additional water that cannot be used for food anymore. Large-scale cultivation of biomass for fossil fuels substitution influences future water demand (Berndes 2002). An important question is whether we should apply our freshwater resources for the production of bio-energy or food crops. The FAO estimates that in 2007 alone, before the food price crisis hit, 75 million more people have been pushed into undernourishment as a result of higher prices, bringing the total number of hungry people to 923 million (FAO 2008a). Moreover, the FAO reports biofuels increasing food insecurity (FAO 2008b). The World Bank recognizes biofuels production as a major factor driving food prices. It estimates that 75% of the increase of food prices in the period 2002–2008 was due to biofuels (Mitchel 2008).

The replacement of fossil energy by bio-energy generates the need for detailed information on water requirements of this new energy source. A tool for the calculation of water needs for consumer products is the concept of the water footprint (WF) (Hoekstra and Hung 2002; Hoekstra and Chapagain 2007, 2008), defined as the total annual volume of freshwater used to produce goods and services for consumption.

The objective of this chapter is to give a global overview of the WF per unit of bio-energy (m^3/GJ), including heat, electricity, bio-ethanol, and biodiesel. It covers the 12 main crops that together contribute to 80% of global crop production. In addition, the study includes jatropha, a plant species often mentioned in the context of bio-energy. Research questions are: (1) what are the green and blue WFs (m^3/GJ) for heat and electricity derived from the combustion of biomass per crop per country, and (2) what are the WFs (m^3/GJ) for transport fuels (bio-ethanol and biodiesel) per crop per country? The study excludes organic wastes, such as manure or crop residues, biogas, and energy from algae.

The study builds on two earlier studies: one that estimated the WFs of a large variety of food and fibre products (Hoekstra and Chapagain 2007, 2008) and one that estimated the WF of heat from biomass (Gerbens-Leenes et al. 2009). It refines the study of Hoekstra and Chapagain by taking precise production locations into account for the calculation of crop water requirements and by using local estimates for the start of the growing season based on an analysis of when weather conditions at specific locations are most favourable. An additional refinement is that the study differentiates between blue and green water. Next, it extends the study of Gerbens-Leenes et al.—which focussed on the water footprint of heat from biomass—to the water footprint of bio-electricity and biofuels.

BIO-ENERGY

Energy derived from biomass is termed bio-energy. The FAO defines biomass as material of organic origin, in nonfossilized 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 or feed (e.g., wheat, maize, sugar), materials (e.g., cotton, wood, paper), or for bio-energy (e.g., maize, sugar, jatropha). Figure 8-1 shows that biomass can provide different forms of bio-energy: heat, electricity, and biofuels like ethanol and biodiesel. First-generation biofuels concern presently available biofuels produced using conventional technology, i.e. fermentation of carbohydrates into ethanol, and extracting and processing oil from oil crops into biodiesel. Biomass not only contains starch, sugar, and oil that can be processed into biofuels, it also contains large amounts of cellulosic biomass. So far, the cellulosic fraction could be used for energy by burning it to provide heat and produce electricity. It is expected that these cellulosic fractions will form an attractive source for the production of next-generation biofuels. Next-generation biofuels concern future available biofuels produced using new technology under development that aims to also convert cellulosic fractions from crops into biofuels, e.g., ethanol (Worldwatch Institute 2007). In this way, the production of biofuel per unit of crop can increase substantially.

WATER FOOTPRINT

The WF of a product is defined as the volume of freshwater used for production at the place where it was actually produced (Hoekstra and Chapagain 2008). In general, actual water contents of products are negligible compared to their WF, and water use in product life cycles are dominated by the agricultural production stage. The WF consists of three components: the green, blue, and gray WF. The green WF refers to rainwater that evaporated during

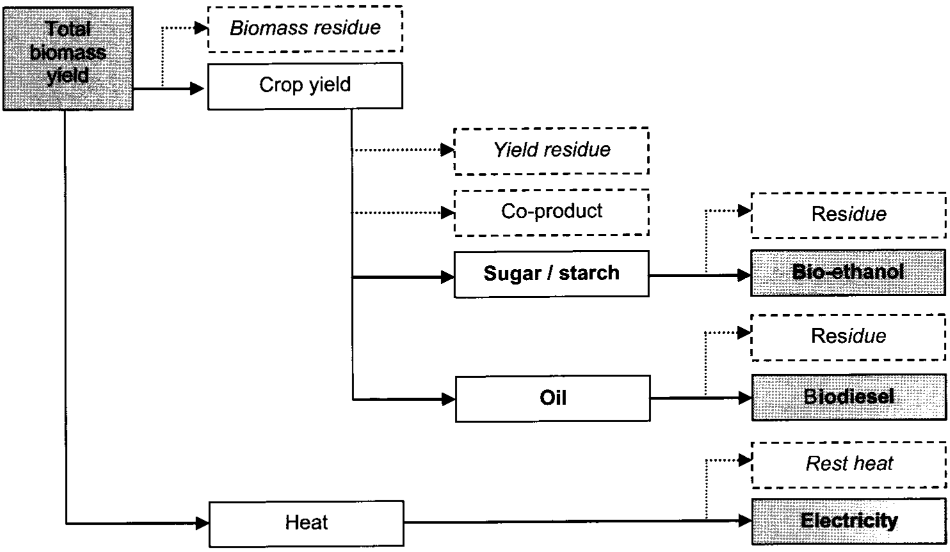

Figure 8-1. Total biomass yield can be converted into heat and subsequently into electricity. Alternatively, the crop yield, which is part of the total biomass, can be converted into bio-ethanol (in the case of starch and sugar crops) or biodiesel (in the case of oil crops). In every step in the production chain, residues or rest heat are generated.

production, mainly during crop growth. The blue WF refers to surface- and groundwater for irrigation evaporated during crop growth. The grey WF is the volume of water that becomes polluted during production, defined as the amount of water needed to dilute pollutants emitted to the natural water system to the extent that the quality of the ambient water remains beyond agreed water quality standards.

CROP COVERAGE

Globally, a limited number of crops determines total production. Theoretically, all crops can be applied for bio-energy. In practice, only some crops dominate production: sugar cane, sugar beet, maize, rapeseed, and soybean (Worldwatch Institute 2007). Since this study aims to provide a global overview of the WFs of the main crops that can be used for bio-energy, it included the 12 crops that contribute to 80% of total global crop production: sugar cane, maize, wheat, rice, potato, sugar beet, rye, cassava, soybean, barley, sorghum, and rapeseed. Additionally, the study included jatropha curcas, a tree species that provides oil from its seeds (Banerji et al. 1985).

The composition of biomass determines the availability of energy from a specific biomass type, resulting in differences in combustion energy and options for biofuel production. This study includes four categories of biomass: starch crops (cereals: barley, maize, rice, rye, sorghum, wheat; and tubers: cassava, potato,); sugar crops (sugar beet, sugar cane); oil crops (rapeseed, soybean); and trees (jatropha). For the assessment of the WF of bio-energy, it follows the method of Hoekstra and Chapagain (2008) to arrive at estimates of the WF of crops and the method of Gerbens-Leenes et al. (2009) to translate the WF of crops (m^3/ton) into a WF of bio-energy (m^3/GJ). Data were obtained from agricultural studies. Based on sugar or starch contents, we calculated the amount of energy that the crop could provide in the form of ethanol. For each oil crop, based on the oil content, we calculated the amount of energy that the crop could provide in the form of biodiesel.

METHOD

Calculation of the Water Footprint of Crops

For the calculation of the WF of crops, this study used the methodology from Hoekstra and Chapagain (2008). There is an extensive database that includes the WF of almost all crops produced worldwide (m^3/ton) based on average, national meteorological data (Chapagain and Hoekstra 2004). The current study, however, assessed the WFs of crops more specifically per production location. WF calculations are made by summing daily crop evapotranspiration (mm/day) over growing periods providing information on crop water requirements. The start of the growing season depends on climatic conditions, on the production location, and on individual choices of farmers. For the start of the growing season, the study considered the first option for sowing after winter or after a dry season, assuming that growing seasons start when mean monthly maximum temperatures are above 10°C and when sufficient rain and global radiation is available.

For the main producing countries, this study calculated crop water requirements for the 12 crops and for jatropha, distinguishing between the green and blue WF, but excluding the gray WF. Next, it selected the main producing countries. For jatropha, it considered production in Brazil, Guatemala, Indonesia, and Nicaragua, countries for which data were available (Daey Ouwens 2000). Next, it selected agricultural production locations. Information was derived from the Madison Center for Sustainability and the Global Environment at the University of Wisconsin (2008). For these areas, it selected weather stations providing climatic data that were used as input for the calculations. Data were derived from Müller and Hennings (2000).

The calculation of crop water requirements (mm/day) has been done per major production region, using the calculation model CROPWAT 4.3 (FAO 2007) based on the FAO Penman–Monteith method to estimate reference crop evapotranspiration (Allen et al. 1998), and a crop coefficient that corrects for the difference between actual and reference crops.

Calculations for green and blue WFs (m^3/ton) have been done using the method of Hoekstra and Chapagain (2008). Green water use (m^3/ha) over the length of the growing period is calculated as the sum of daily volumes of rainwater evapotranspiration. The latter is equal to the crop water requirement except if effective precipitation is less than the requirement. In that case, rainwater evapotranspiration is equal to effective precipitation. Blue water use (m^3/ha) over the length of the growing period is calculated as the sum of daily volumes of irrigation–water evapotranspiration. The latter is equal to the irrigation requirement if this requirement is actually met, and otherwise it is equal to actual effective irrigation. The irrigation requirement is defined as the crop water requirement minus effective precipitation. In the calculation, it has been assumed that irrigation requirements are actually met. The green WF of a crop (m^3/ton) is the total green water use over the length of the growing period (m^3/ha) divided by the crop yield (ton/ha). The blue WF (m^3/ton) is the total blue water use over the length of the growing period (m^3/ha) divided by the crop yield (ton/ha). In general, yields show variation among years. The study therefore calculated average yields over five production years (1997–2001) using data from the FAO.

Calculation of the WF of Heat and Electricity from Biomass

The energy content of biomass is expressed in terms of combustion values. Energy analysis defines the energy content of a substance as the amount of heat 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. For the calculation of the WF of heat from biomass, the study has followed the method of Gerbens-Leenes et al. (2009) that calculates the energy yield of a crop (GJ/ton) by combining data on the heat of combustion of plant components with information on composition, harvest index, and dry mass fraction of a crop as shown in Table 8-1.

$$E_{\text{heat}}(c) = HI(c) \times DMF_y(c) \times \sum_{i=1}^{5} \left(f_{y,i} \times HHV_i\right) + \left(1 - HI(c)\right) \times DMF_r(c) \times \sum_{i=1}^{5} \left(f_{r,i} \times HHV_i\right)$$

Eq. 8-1

$E_{\text{heat}}(c)$ is the energy yield of crop c in the form of heat (GJ/ton), $HI(c)$ is the harvest index of crop c (gram/gram), $DMF_y(c)$ is the dry mass fraction of the crop yield (gram/gram), $DMF_r(c)$ is the dry mass fraction in the rest fraction (i.e., in the residue biomass), $f_{y,i}$ is the fraction of component i in the dry mass of the crop yield (gram/gram), $f_{r,i}$ is the fraction of component i in the dry mass of the rest fraction (gram/gram), and HHV_i is the higher heating value of component i (kJ/gram).

For the generation of electricity from biomass, industry can apply the heat that becomes available from the combustion of total biomass. The energy in the form of electricity from crop c (GJ/ton) depends on the efficiency with which energy in the form of biomass heat can be transformed into electricity:

$$E_{\text{electr}}(c) = \eta \times E_{\text{heat}}(c) \qquad \text{Eq. 8-2}$$

For the value of the efficiency η, the study applied a value of 59%, based on the maximum efficiency based on Carnot and the technology of Biomass-fired Integrated Gasifier Combined Cycle (BIG/CC) operated at a temperature of 720 K (Blok 2006, Faay 1997).

The WF of heat from a crop c (m^3/GJ) is calculated by dividing the WF of the crop (m^3/ton) by the heat content of the crop (GJ/ton). The WF of biomass electricity from a crop c (m^3/GJ) is calculated by dividing the WF of the crop (m^3/ton) by the electricity output per crop unit (GJ/ton):

$$WF_{\text{heat}}(c) = \frac{WF(c)}{E_{\text{heat}}(c)}; \quad WF_{\text{electr}}(c) = \frac{WF(c)}{E_{\text{electr}}(c)} \qquad \text{Eq. 8-3}$$

Calculation of the Wf of First-Generation Biofuels

At present, bio-ethanol is produced from sugars from sugar cane or sugar beet, or from starch hydrolysed into sugars derived from maize, wheat, or cassava (Worldwatch Institute 2007). Under anaerobic conditions, sugar naturally ferments into acids and alcohols (mainly ethanol). For thousands of years, people have applied yeasts to enhance fermentation. The main metabolic pathway involved in ethanol fermentation is glycolysis through which one molecule of glucose is metabolized and two molecules of pyruvate are produced (Verkerk et al. 1986; Bai et al. 2008). Under anaerobic conditions, pyruvate is further reduced to ethanol

Table 8-1. Main characteristics of twelve crops

	Cassava	Barley	Maize	Paddy Rice	Potato	Rapeseed	Rye	Sorghum	Soybean	Sugar Cane	Sugar Beet	Wheat
Harvest Index	0.70[a]	0.42[a]	0.45[a]	0.42	0.70[a]	0.32[a]	0.42	0.42	0.40[a]	0.60[a]	0.66[a]	0.42[a]
Economic yield	Tuber[b]	Ear + Grain[b]	Whole Tops[b]	Inflor + Grain	Tuber[b]	Inflor + Seed[d]	Ear + Grain[b]	Ear + Grain[b]	Beans[a]	Whole Tops[a]	Beet[a]	Ear + Grain[b]
Dry mass[b]	0.38	0.85	0.85	0.85	0.25	0.74	0.85	0.85	0.92	0.27	0.21	0.85
Composition dry mass (g /100 g)[c]												
Carbohydrates	87	76	75	76	78	7	76	76	29	57	82	76
Proteins	3	12	8	8	9	22	12	12	37	7	5	12
Fats	1	2	4	2	0	42	2	2	18	2	0	2
Lignin	3	6	11	12	3	2	6	6	6	22	5	6
Organic acids	3	2	1	1	5	1	2	2	5	6	4	2
Minerals (K, Ca, P, S)	3	2	1	1	5	26	2	2	5	6	4	2
Rest fraction	Leaves	Shells	Stems	Stems	Leaves	Leaves	Stems	Stems	Leaves	Stems	Leaves	Stems
Dry mass[b]	0.38	0.85	0.85	0.85	0.13	0.13	0.85	0.85	0.15	0.27	0.21	0.85
Composition dry mass (g /100 g)[c]												
Carbohydrates	52	62	62	62	52	52	62	62	52	62	52	62
Proteins	25	10	10	10	25	25	10	10	25	10	25	10
Fats	5	2	2	2	5	5	2	2	5	2	5	2
Lignin	5	20	20	20	5	5	20	20	5	20	5	20
Organic acids	5	2	2	2	5	5	2	2	5	2	5	2
Minerals (K, Ca, P, S)	8	4	4	4	8	8	4	4	8	4	8	4

Data 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: Akthar (2004)

with the release of CO_2. The overall reaction is $C_6H_{12}O_6 \lozenge 2C_2H_5OH + 2CO_2$. Theoretically, the maximum yield of ethanol is 511 g of ethanol and 489 g of carbon dioxide per kg of glucose metabolized (or 530 g of ethanol per kg of starch). Often, various by-products are also produced, for example, glycerol (Bai et al. 2008). During ethanol fermentation, yeast cells suffer from stresses such as ethanol accumulation inhibiting yeast cell growth and ethanol production. The final ethanol concentration is about 10–12% (Bai et al. 2008, Catsberg et al. 1997). The fermentation industry, therefore, applies a tanks-in-series system to alleviate product inhibition. Today, it can reach a yield of 90–93% of the theoretical value of glucose to ethanol (Rosillo-Calle et al. 2007).

Oilseed crops, such as rapeseed, soybean, and jatropha, are used to produce straight vegetable oil or biodiesel. Straight vegetable oil is oil extracted from an oilseed crop and directly applied for energy purposes (Worldwatch Institute 2007). An example is olive oil for lighting. Due to its chemical properties, such as the high viscosity at low temperatures, it is often difficult to use straight vegetable oil as a biofuel in diesel engines. In countries with warm climates, the relatively high temperatures prevent the oil from thickening and the straight vegetable oil is a viable fuel. In countries with temperate climates, the oil needs additional treatment to manufacture a biodiesel less sensitive to lower temperatures. Biodiesel is manufactured in a chemical reaction termed transesterification in which oil reacts with an alcohol resulting in an alkyl ester of the fatty acid with glycerine molecules as the primary co-product. In Europe, rapeseed oil is the dominant feedstock for biodiesel, with some sunflower oil also used. In the US, the main feedstock is soybean oil; in tropical and subtropical countries, palm, coconut, and jatropha oil is used (Worldwatch Institute 2007).

When calculating natural resource use, the whole life cycle of a product should be taken into account. The use of water, however, is dominated by the first link of the production chain—agriculture. Ethanol production, for example, requires about 21 litres of water per litre of ethanol. Moreover, this water is often reused (Institute for Agriculture and Trade Policy 2007). This study therefore only took water requirements in agriculture into account and neglected water use in industrial links of the production chain.

The ethanol-energy yield of a crop (in GJ/ton) has been calculated as follows:

$$E_{\text{ethanol}}(c) = DMF_y(c) \times f_{\text{carbohydr}}(c) \times f_{\text{ethanol}} \times HHV_{\text{ethanol}} \qquad \text{Eq. 8-4}$$

where $DMF_y(c)$ is the dry mass fraction in the crop yield (gram/gram), $f_{\text{carbohydr}}(c)$ the fraction of carbohydrates in the dry mass of the crop yield (gram/gram), f_{ethanol} the amount of ethanol obtained per unit of carbohydrate (gram/gram), and HHV_{ethanol} the higher heating value of ethanol (kJ/gram). For the amount of ethanol per unit of sugar, we assumed the theoretical maximum value of 0.51 g/g; for starch, 0.53 g/g (Bai et al. 2008).

The biodiesel-energy yield of a crop (in GJ/ton) has been calculated as follows:

$$E_{\text{diesel}}(c) = DMF_y(c) \times f_{\text{fat}}(c) \times f_{\text{diesel}} \times HHV_{\text{diesel}} \qquad \text{Eq. 8-5}$$

where $DMF_y(c)$ is the dry mass fraction in the crop yield (gram/gram), $f_{\text{fat}}(c)$ the fraction of fats in the dry mass of the crop yield (gram/gram), f_{diesel} the amount of biodiesel obtained per unit of fat (gram/gram), and HHV_{diesel} the higher heating value of biodiesel (kJ/g). For the fraction biodiesel per fat weight, we assumed the value 1. The fractions of carbohydrates and fats in the dry mass of crop yields are given in Table 8-1. The higher heating value for ethanol is 29.7 kJ/g and for biodiesel, 37.7 kJ/g.

The WF of ethanol energy from a crop c (m^3/GJ) is calculated by dividing the WF of the crop (m^3/ton) by the ethanol-energy yield of the crop (GJ/ton). The WF of biodiesel energy from a crop c (m^3/GJ) is calculated in a similar way:

$$WF_{\text{ethanol}}(c) = \frac{WF(c)}{E_{\text{ethanol}}(c)}; \qquad WF_{\text{diesel}}(c) = \frac{WF(c)}{E_{\text{diesel}}(c)} \qquad \text{Eq. 8-6}$$

For the calculation of the WF of first-generation biofuels, this study fully allocated the WF of the crop to the biofuels derived, assuming that the value of the residues of production is much lower than the value of the biofuel.

Calculation of the WF of Next-Generation Biofuels

Biomass not only contains starch, sugar, and oil that can be processed into biofuels, it also contains large amounts of cellulosic biomass. So far, the cellulosic fraction could be used for energy by burning it to provide heat and produce electricity. It is expected that these cellulosic fractions will form an attractive source for the production of liquid, next-generation biofuels. For next-generation biofuels, industry can apply total biomass, including wastes. It is not yet clear what efficiency will be achieved in converting total biomass into biofuel. It is safe to assume that the WF of next-generation biofuels will never be lower than the WF of the crop (m^3/ton) divided by the energy content of the crop (GJ/ton), where the latter is expressed in terms of its higher heating value (HHV).

THE WATER FOOTPRINT OF BIO-ELECTRICITY AND BIOFUELS

Crop Production, Crop Water Requirements, and Irrigation Requirements

Some countries have a large contribution to global production. For example, Brazil produces 27% of globally available sugar cane; the United States almost half of global soybean production, 40% of the maize, and one-quarter of the sorghum; China 18% of all wheat, one-third of the paddy rice, one-fifth of the potatoes, and 27% of the rapeseed. Half of the global production of rye takes place in Russia and Germany, while Nigeria shows the largest contribution to cassava production. For other crops, such as sugar beet and barley, production is distributed more evenly.

On almost every crop location, irrigation is required. Exceptions are sugar beet grown in Japan; maize from South Africa; wheat from Australia; cassava from Nigeria, Angola, Benin, Guinea, the Philippines, Vietnam, and India; potato from Bangladesh, Peru, and Japan; sorghum from Nigeria, Ethiopia, Chad, and Venezuela; and rapeseed from Bangladesh. In some countries, crop water requirements are completely or almost completely covered with irrigation water. These crops and countries are: sugar cane from Argentina (96%) and Egypt (92%); wheat from Argentina (100%), Kazakhstan (98%), and Uzbekistan (98%); potato and barley from Kazakhstan (100%); sorghum from Yemen (100%); and soybean from Brazil (95%). For the other crops and production locations, irrigation requirements find themselves in between the two extremes.

The WF of Biomass

The WFs of biomass (m^3/ton) show large variations among crops. For each specific crop, WFs vary among countries, dependent on agricultural production systems applied and climate conditions. Most WFs show a variation of a factor of 4 to 15, with two exceptions. These are the values for wheat and sorghum, with a difference of a factor of 20 and 47, respectively.

The WF of Heat and Electricity from Biomass

Table 8-2 shows the total weighted global average WF for 13 crops providing electricity. It is assumed that not only crop yields, but total biomass yields are applied for the generation. The largest difference is found between jatropha and sugar beet: beets are 10 times more water efficient. The WF of heat is always 59% of the WF of electricity, as shown in the table, based on the energy efficiency assumed in this study.

The WF of First-Generation Biofuels

Biofuel Energy Production per Crop Unit

Table 8-3 shows energy provided by ethanol (HHV ethanol in MJ/kg fresh weight of the crop) from two sugar- and eight starch-providing crops included in this study. It shows three categories: sugar-providing crops and one starch-providing crop with relatively low values for energy provided by ethanol (sugar beet, sugar cane, and potato); the category of starch-

Table 8-2. Total weighted global average water footprint for 13 crops providing electricity (m^3/GJ). It is assumed that not only crop yields, but total biomass yields are applied for the generation of electricity.

	Total Water Footprint	Blue Water Footprint	Green Water Footprint
Crop	**m^3 per GJ Electricity**		
Sugar beet	46	27	19
Maize	50	20	30
Sugar cane	50	27	23
Barley	70	39	31
Rye	77	36	42
Paddy rice	85	31	54
Wheat	93	54	39
Potato	105	47	58
Cassava	148	21	127
Soybean	173	95	78
Sorghum	180	78	102
Rapeseed	383	229	154
Jatrophaa	396	231	165

[a]Average numbers for five countries (India, Indonesia, Nicaragua, Brazil, and Guatemala).

Table 8-3. Energy provided by ethanol from the two sugar- and 10 starch-providing crops that were included in this study, as well as the energy provided by oil from the three oil providing crops.

Crop	MJ of Biofuel per kg Fresh Weight Crop
Ethanol from sugar	
Sugar cane	2.3
Sugar beet	2.6
Ethanol from starch	
Potato	3.1
Cassava	5.2
Sorghum	10.0
Maize	10.0
Wheat	10.2
Barley	10.2
Paddy rice	10.5
Rye	10.5
Biodiesel from oil	
Soybean	6.4
Rapeseed	11.7
Jatropha	12.8

providing crops with relatively large values for energy provided by ethanol (sorghum, maize, wheat, barley, paddy rice, and rye); and one category in between (cassava). These differences are caused by differences in the water contents of the crops, where a large water content relates to relatively low energy values provided by ethanol. Table 8-3 also shows the energy provided by oil from the three oil-providing crops included in this study. The HHV of oil from soybean is smallest, about half the value of rapeseed or jatropha.

The WF of Bio-ethanol

Figure 8-2 shows the lowest value, the highest value, and the weighted average global value of the WF for energy for 10 crops providing ethanol showing the enormous variation in the total WF among crops. Especially sorghum shows large variation, mainly caused by unfavourable conditions in Niger and high production efficiency in Egypt. Figure 8-3 shows weighted global average green and blue WFs for 10 crops providing ethanol. It shows that differences among crops are large.

At present, sugar beet is the most favourable crop, sorghum the most unfavourable with a difference of a factor of seven. When data for the two main ethanol- producing countries, Brazil and the United States are compared, in Brazil ethanol from sugar cane is more efficient than maize (99 versus 140 m^3/GJ ethanol), while in the United States, maize is more attractive than sugarcane (78 versus 104 m^3/GJ ethanol). Figure 8-3 shows the distinction between green and blue water. As a global average, the blue WF of cassava is smallest. Other favourable crops are sugar beet, potato, maize, and sugar cane. In terms of blue water, sorghum is unfavourable.

Table 8-4 shows the total weighted global average WF for 10 crops providing ethanol, as well as the blue and green WF. The table also shows the amount of water needed for a specific crop to produce one litre of ethanol.

On average, it takes 1,400 L of water to produce 1 L of ethanol from sugar beet, 2,400 L for 1 L of ethanol from potato, 2,500 L from sugar cane, and 2,600 L from maize. Sorghum is the most inefficient crop, 9,800 L for 1 L ethanol. Irrigation is smallest for cassava, 400 L of blue water for 1 L of ethanol, followed by 800 L for sugar beet, and 1,000 L for maize. Sorghum is the crop showing the largest WF, 4,250 L per litre ethanol. As one can see from Tables 8-2 and 8-4, sugar beet is most efficient in terms of ethanol and electricity. The other crops show a different order for the efficiency in which electricity and ethanol are produced. In general, the production of ethanol of only part of the crop is less water efficient than the production of electricity from total biomass.

The WF of Biodiesel

The WF of biodiesel derived from soybean, rapeseed, and jatropha shows differences among the main producing countries. For rapeseed, western Europe shows the smallest WFs, Asia the largest. Especially in India, rapeseed has a large blue WF. For soybean, Italy, Paraguay, and Argentina have the smallest WFs, India the largest. Biodiesel from jatropha is produced in the most water efficient way in Brazil, and inefficiently in India. Table 8-4 shows the total weighted global average WF for biodiesel (soybean and rapeseed) and the average WF for jatropha, as well as the blue and green WF. It also shows the amount of water needed to produce 1 L of biodiesel. On average, it takes 14,000 L of water to produce 1 L of biodiesel from soybean or rapeseed, and 20,000 L for 1 L of biodiesel from jatropha.

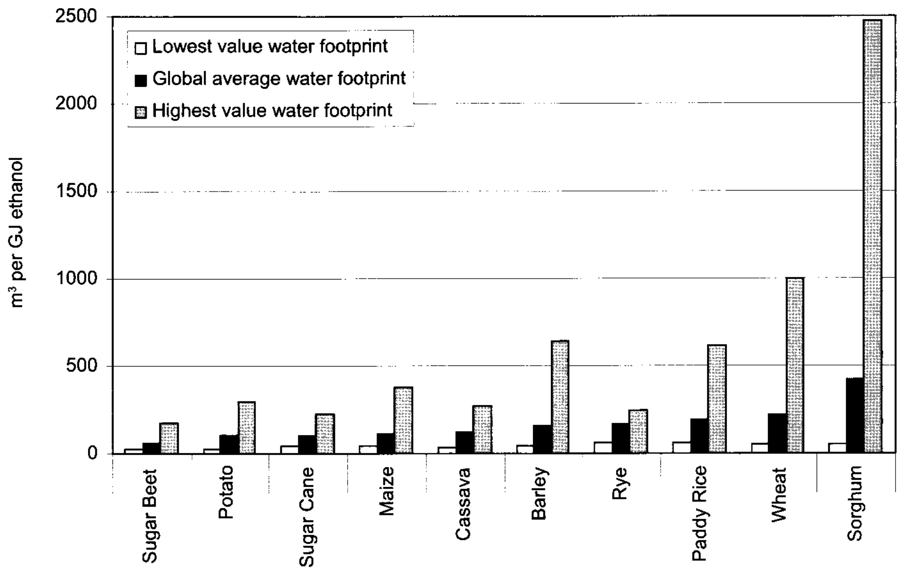

Figure 8-2. Lowest value, highest value, and weighted average global value of the water footprint for energy for 10 crops providing ethanol

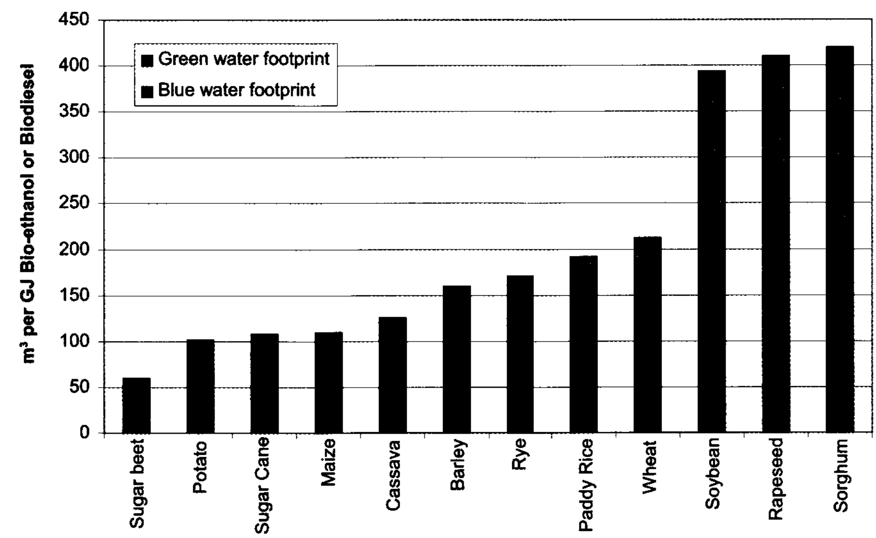

Figure 8-3. The weighted global average water footprint for 10 crops providing ethanol and for two crops providing oil for biodiesel

The WF of Next-Generation Biofuels

For next-generation biofuels, total biomass of a crop can be applied. When we optimistically assume that the production of next-generation biofuels will be as efficient as the productionof electricity from biomass (in terms of GJ/ton), the results shown in Table 8-2 form a lower limit for the WF of these next-generation biofuels.

Table 8-4. Global average water footprint for 10 crops providing ethanol and three crops providing biodiesel, expressed both in terms of m^3/GJ and in terms of litres of water per litre of biofuel

Crop	Total Water Footprint (m^3/GJ)	Blue Water Footprint (m^3/GJ)	Green Water Footprint (m^3/GJ)	Total Water (L/L)	Blue Water (L/L)	Green Water (L/L)
Ethanol	m^3 per GJ ethanol			litres water per litre ethanol		
Sugar beet	59	35	24	1,388	822	566
Potato	103	46	56	2,399	1,078	1,321
Sugar cane	108	58	49	2,516	1,364	1,152
Maize	110	43	67	2,570	1,013	1,557
Cassava	125	18	107	2,926	420	2,506
Barley	159	89	70	3,727	2,083	1,644
Rye	171	79	92	3,990	1,846	2,143
Paddy rice	191	70	121	4,476	1,641	2,835
Wheat	211	123	89	4,946	2,873	2,073
Sorghum	419	182	238	9,812	4,254	5,558
Biodiesel	m^3 per GJ Biodiesel			Litres Water per Litre Biodiesel		
Soybean	394	217	177	13,676	7,521	6,155
Rapeseed	409	245	165	14,201	8,487	5,714
Jatropha[a]	574	335	239	19,924	11,636	8288

[a] average numbers for five countries (India, Indonesia, Nicaragua, Brazil, and Guatemala).

DISCUSSION

Similar to earlier studies (Hoekstra and Chapagain 2007, 2008), the calculations have been based on the assumption that crop water use is equal to crop water requirements. When actual water availability is lower and water stress occurs, the study overestimates actual crop water use. With respect to agricultural yields, we have taken actual yields, which in many cases can be increased in the future without increasing water use per unit of product. This means that in some cases water footprints per unit of energy can be significantly lowered. For the efficiency of obtaining electricity or biofuels from biomass, we have taken optimistic assumptions by taking theoretic maximum values or values that refer to the best available technology. This means that the resulting water footprint figures are conservative.

The results of this study are based on rough estimates of freshwater requirements in crop production and on theoretically maximum conversion efficiencies in the production of bio-electricity and biofuels. For the assessment of the WF of bio-energy, the study integrated data from several sources, each of which adds a degree of uncertainty. For example, the calculations using the CROPWAT model (FAO 2007) required input of meteorological data that are averages over several years rather than data for a specific year. The data presented do thus not reflect annual variations. Estimated crop water requirements are sensitive to the input of climatic data and assumptions concerning the start of the growing season. In the most extreme cases, this study found crop water requirements that were a factor two different from earlier studies (Hoekstra and Chapagain 2007, 2008). Other times results were similar. The factors mentioned imply that results presented here are indicative. However, the differences in calculated WFs are so large that general conclusions with respect to the water footprint of bio-ethanol versus the water footprint of biodiesel can be drawn, and that also conclusions can be drawn about the relative water footprints of different crops.

There is a distinction between gross and net production of bio-energy (Giampietro and Ulgiati 2005, Pimentel and Patzek 2005). In assessing the WF of heat, electricity, and fuels from biomass, we looked at the WF of the gross energy output from crops. We did not study energy inputs in the production chain, like energy requirements in the agricultural system (e.g., energy use for the production of fertilizers and pesticides) or the energy use during the industrial production of the biofuel. This means that this study underestimates the WF of bio-energy, especially in cases in which agricultural systems have a relatively large energy input. As an example, in a case where energy input equals 50% of the energy output – a case common in bio-energy production systems (Pimentel and Patzek 2005)—the water footprint of the net bio-energy production would be twice the water footprint of gross energy production.

CONCLUSIONS

The water footprint of bio-energy is large if compared to other forms of energy. In general, it is more efficient to use total biomass, including stems and leaves, and generate electricity than producing a biofuel. For most crops, the WF of bio-electricity is about a factor of two smaller than for bio-ethanol or biodiesel. The difference is caused by the crop fraction that can be applied. For electricity, total biomass can be used; for bio-ethanol or biodiesel, only the starch or oil fraction of the yield. In general, the WF of bio-ethanol is smaller than of biodiesel. The WF of bio-energy shows a large variation, depending on three factors: (1) the crop used, (2) the climate at the location of production, and (3) the agricultural practice.

For electricity generation, sugar beet, maize, and sugar cane with WFs of about 50 m^3/GJ are the most favourable crops, followed by barley, rye, and rice with WFs of about 70–80 m^3/GJ. Rapeseed and jatropha, typical energy crops, showing WFs of about 400 m^3/GJ are the most unfavourable crops. For the production of ethanol, two crops grown in a temperate climate, sugar beet and potato, with WFs of 60 and 100 m^3/GJ, respectively, are most favourable, followed by a crop typical for a warm climate, sugar cane, also showing a WF of about 110 m^3/GJ. Values for maize and cassava show the same order of magnitude. With a WF of 400 m^3/GJ, sorghum is by far the most unfavourable crop. For biodiesel production, soybean and rapeseed, crops mainly grown for food, show the most favourable WF of 400 m^3/GJ; jatropha has the most unfavourable WF of about 600 m^3/GJ.

Results show large differences in crop water requirements among countries caused by differences in climate. The crop water requirement of sugar beet grown in Iran, for example, is twice the weighted global average value.

Agricultural practice determines yields and thus differences among WFs of crops even in cases with a similar climate. When yield levels are relatively low, WFs are high and vice versa. For example, in Kazakhstan, yields of barley, potato, and wheat are relatively low. In combination with unfavourable climatic factors, this results in high values for the WFs. Conditions in Denmark are favourable, resulting in relatively low crop water requirements for wheat.

Theoretically, all crops can be applied for energy, including crops like rice and rye that are currently mainly applied for food. Water use for a specific crop does not depend on whether the crop is applied for energy or for food. Some food crops, including rice, are more water efficient in producing a unit of ethanol, biodiesel, or electricity than some typical energy crops, such as rapeseed or jatropha. The ethical discussion whether food crops can be used for energy should be extended to the discussion whether we should apply our limited water resource base for food or for energy.

The scientific and the international political communities promote a shift toward renewable energy sources, such as biomass, to avoid emissions of greenhouse gases. This study has shown that biomass production goes along with large water requirements. Already 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. If a shift toward a larger contribution of bio-energy to total energy supply takes place, results of this study can be used to select the crops and countries that (under current production circumstances) produce bio-energy in the most water-efficient way.

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