UNESCO-IHE
Institute for Water Education

P.W. Gerbens-Leenes
A.Y. Hoekstra

June 2010

Burning water:

The water footprint of biofuel-based transport

Value of Water
Research Report Series No. 44

BURNING WATER:

THE WATER FOOTPRINT OF BIOFUEL-BASED TRANSPORT

P.W. GERBENS-LEENES[1]
A.Y. HOEKSTRA[1,2]

JUNE 2010

VALUE OF WATER RESEARCH REPORT SERIES NO. 44

[1] Dept. of Water Engineering and Management, University of Twente, Enschede, The Netherlands
[2] Contact author: Arjen Hoekstra, a.y.hoekstra@utwente.nl

The Value of Water Research Report Series is published by
UNESCO-IHE Institute for Water Education, Delft, the Netherlands
in collaboration with
University of Twente, Enschede, the Netherlands, and
Delft University of Technology, Delft, the Netherlands

Contents

Summary

The trend towards substitution of conventional transport fuels by biofuels requires additional water. The EU aims to replace 10 percent of total transport fuels by biofuels by 2020. This study calculates the water footprint (WF) of different transport modes using bio-ethanol, biodiesel or bio-electricity and of European transport if 10 percent of transport fuels is replaced by bio-ethanol. We compare results for Europe with similar goals for other regions (Africa, Asia, Latin America, the former USSR, Australia and North America). In order to provide a context, we compare results with WFs of food and cotton.

In general, it is more efficient to use bio-electricity and bio-ethanol than biodiesel. Transport per train or electric car using bio-electricity (8-19 and 11-13 litres per passenger km) is more water efficient than transport by car driven by bio-ethanol (36-212) or by airplane using bio-ethanol (65-136 litres per passenger km). For cars, we find a range of a factor of ten between the most water-efficient car using bio-ethanol and the least efficient car using biodiesel. When using bio-energy, freight can be transported in the most water-efficient way by ship or train; airplanes are the least water efficient.

The European goal to have 10 percent biofuel in transport in 2020 will result in a water footprint of 62 Gm^3 per year. This is equal to about 10% of the current European water footprint of food and cotton consumption. Differences in per capita energy use for transport among European countries, together with differences in production systems, result in a broad range of transport-related WFs: from 60 m^3 per year per capita in Bulgaria to 500 m^3 per year per capita in Finland. If the same 10% biofuel target would be applied in all other regions of the world as well, the additional water footprint of China would be equivalent to 5% of the water footprint related to food and cotton consumption, in the rest of Asia 3%, in Africa 4%, in Latin America 10%, in the former USSR 22% and both in North America and Australia 52%. The global water consumption related to biofuel-based transport in this scenario would be 9% of the current global water consumption for food and cotton. The results show that a trend towards the increased application of biofuels in transport will substantially enhance the competition for fresh water resources.

1. Introduction

In western societies, transport requires about one third of total energy use (Blok, 2006; IEA, 2009) and contributes substantially to greenhouse gas emissions. Energy for transport in transition countries, such as Romania and Bulgaria, and in developing countries, such as China and India, is still relatively small (IEA, 2009). It can be expected that along with economic growth in these countries, transport will also grow, increasing the need for transport fuels. In many countries, policy goals aim at a gradual introduction of renewable transport biofuels, such as biodiesel and bio-ethanol. For example, India promotes the introduction of biodiesel and aims to replace 20 percent of petrodiesel by biodiesel (Government of India, 2008), in China the National Development and Reform Commission promotes the production of biofuels and aims for a share of 15 percent of biofuel for transport in 2020 (Yang et al., 2009). Based on energy use in 2006, the United States aims to replace 15 percent of gasoline by biofuels in 2022 (Dominguez-Faus et al., 2009). The European Union aims to replace 10 percent of transport fuels by renewable biofuels in 2020 (European Commission, 2009). Replacing traditional transport fuels, made from crude oil, by biofuels, made from agricultural crops, will take large efforts. Biofuels need to be produced in agriculture and have, among other things, large water requirements.

An important challenge for the 21st century is to provide enough water along with the protection of the ecological quality of freshwater systems (Postel, 2000). Worldwide, humans already use more than half of the accessible runoff of water (Postel et al., 1996). At present, agriculture accounts for 86 percent of all human freshwater consumption (Hoekstra and Chapagain, 2007; 2008). Biofuels for transport (e.g. bio-ethanol from sugar cane or maize and biodiesel from rapeseed) promoted to decrease greenhouse gas emissions, need substantial amounts of water, because they are produced using the same agricultural system as is needed for food. Biofuels produced using irrigated crops could significantly strain global water resources (Hughes et al., 2007) so that efforts to decrease greenhouse gas emissions related to transport put an additional claim on the global freshwater resources. Increasing use of freshwater makes it necessary to apply less accessible resources, often requiring more and more energy. In California, for example, 19 percent of total electricity use is needed to supply drinking water (Krebs, 2007).

Many studies have addressed the advantages of renewable energy (e.g. De Vries et al., 2006). At present, however, there is a polarized global debate over biofuels. Popular press reports present biofuels as a commodity feeding fuel-hungry Northern cars instead of food-hungry Southerners. For the scientific community, biofuels can be conceived as a technological system encompassing complex interactions at local, national and global levels between positive claims, addressing rural poverty and economic development (Government of India, 2008) and competing negative counter-claims linked to land use changes (Fischer et al., 2009; Yang et al., 2009), increasing food prices (FAO, 2008) and increased water use. Several studies (e.g. Hoekstra and Hung, 2005; Hoekstra and Chapagain, 2007; 2008) have shown the large WF of agriculture, the phenomenon of ‘water dependency’ of countries, the relation between local disturbances of water systems and global markets, and the critical situation of freshwater availability in the context of global climate change. It has also been shown that the WF of bio-energy is much larger than the WF of fossil fuels (King and Webber, 2008; Gerbens-Leenes et al., 2009a). Berndes (2002) and De Fraiture et al. (2008) show that increased use of bio-energy at global scale will lead to a substantial increase in global water use in agriculture, increasing the competition for water. Yang et al. (2009) demonstrated that Chinese government goals for biofuels would increase water use needing the annual discharge of the Yellow River. Galan-del-Castillo and Velazquez (2010) calculated that Spain's water footprint would increase substantially if the goal for biofuels of 5.83 percent of gasoline and diesel consumption is met. Dominguez-Faust et al. (2009) showed the large water requirement for biofuels in the US and its impact on aquifers such as the Ogallala Aquifer. Chiu et al. (2009) showed the large variation in irrigation water requirements for ethanol produced in the US. King and Webber (2008) calculated the large water intensity (gallon water/mile) of ethanol and biodiesel. A more recent study (King et al., 2010) showed the large water requirement related to biofuel use for transport in the US in 2030. Van der Velde et al. (2009) showed the large variety in water use efficiencies for rapeseed, a crop commonly used for biodiesel, in Europe. In an earlier study (Gerbens-Leenes et al., 2009b), we have assessed the water footprint (WF) of biofuels, including bio-ethanol, biodiesel and bio-electricity for the main producing countries, also showing the large variety among WFs.

The WF of biofuel-based transport, expressed in litres of water per passenger km or per 1,000 kg of freight per km, is a function of the energy requirement of transport (MJ/km) and the WF of the specific form of bio-energy applied (litre/MJ). The energy requirement per kilometre varies depending on the mode of transport (e.g. road, rail or air transport) and the type of fuel applied. In addition, large differences can occur within one specific transport mode. For example, energy use per passenger km of small cars is much lower than for large cars (RDW, 2010).

This study aims to quantify the water footprint of biofuel-based transport. First, we calculate the water footprint (WF) for different modes of passenger and freight transport, distinguishing between the use of biodiesel, bio-ethanol and bio-electricity. Second, we calculate, for the European countries, the WF related to the use of biofuels in transport in the case that biofuels take a share of 10 percent of all fuels used in transport, the EU goal for 2020. Third, we compare, for each European country, the WF related to 10 percent biofuel use in transport with the WF of food and cotton. Finally, we compare results with 10 percent replacements in other regions (Africa, Asia, Latin America, the former USSR, Australia and North America).

Many governments have goals to replace traditional transport fuels by biofuels while at the same time economic growth stimulates the increase of transport itself. This study considers different types of biofuel, i.e. bio-ethanol, biodiesel and bio-electricity, for different types of transport and shows the most efficient ways of transport from a water perspective. The study provides information for the European countries about the increase of water use when the EU goals are met and puts the results in a global perspective by comparing EU results with results for other regions.

2. Method

2.1 Energy requirements for different modes of transport

Different transport modes, such as cars or airplanes, have different energy requirements. Differences originate from energy requirements of the transport mode itself, but also from factors like the load factor. For example, in 2000, the average passenger load factor for airplanes was 70 percent (Åkerman, 2005). Other factors include size and geography of the country, congestion, or urbanisation (IEA, 2007). For instance, mountainous countries have larger energy requirements for lorries. These factors cause differences in energy requirements for transport among countries. For the assessment of the average energy requirement per passenger km and per ton freight per km, a literature search was done.

We estimated the average energy requirement per passenger km for airplanes, buses and trains based on data from Åkerman (2005), IEA (2007), Jamin et al. (2004) and Scholl et al. (1996). For trains, direct energy requirements in the form of electricity were calculated adopting an efficiency of electric power generation of 59 percent from Gerbens-Leenes et al. (2009b). For electric cars, we adopted energy use per km from DeLuchi et al. (1989), Johansson and Mårtensson (2000) and Arar (2010). For fuel-based cars, we distinguished between petrol and diesel fuel use. The amount of different car types is very large. To make an estimate of the range of energy use for cars, we selected three different car types: cars with low, medium and high energy use (litre fuel per 100 km). Data were derived from the Dutch RDW (2010), which gives an overview of fuel use of cars available in the Netherlands. The higher heating values (HHV) of petrol (36.7 MJ/litre) and diesel (38.3 MJ/litre) were derived from SenterNovem (2007). To convert energy use of a car per km to energy use per passenger km, we adopted a load factor of 1.66 passengers per car (CBS and Kluwer Voertuigtechniek, 1996). For walking and biking, we calculated additional energy requirements for a person of 60 kg at a speed of 5 and 16 km per hour respectively, using data from Breedveld et al. (2010).

We calculated average energy requirements for freight transport using data from Davis et al. (2009), Gerbens-Leenes et al. (2003), IEA (2007), the SIMAPRO 7 database (Frischknecht and Suter, 1996) and Schipper et al. (1996). Table 1a gives an overview of the energy requirements of passenger transport modes. Table 1b gives a more detailed overview of energy requirements of cars. Table 2 gives the data for freight transport.

Table 1a. Overview of energy requirements for different modes of passenger transport.

Transport mode	Energy source	Energy (MJ/passenger km)
Airplane	Kerosene [a]	1.7-3.5
Car	Petrol	1.0-5.5
Car	Diesel	0.8-2.6
Bus	Diesel	0.8-1.1
Train	Electricity	0.2-0.6
Car	Electricity	0.3-0.4
Walking	Sugar	0.1
Bike	Sugar	0.1

[a] In the further analysis we assume that the energy requirement for airplanes using bio-ethanol or biodiesel are the same as the requirement for airplanes using kerosene.

Table 1b. Energy requirements for different car types using petrol or diesel.

		Car type	Energy (MJ/passenger km)
Petrol	Low energy use	Toyota IQ 1.o '99	1.0
		Nissan Pixo 1.0	1.0
		Smart	1.0
		Suzuki Alto 1.0	1.0
		Daihatsu Cuore 1.0	1.0
	Medium energy use	Peugeot 206 1.1 LHFXA	1.3
		Toyota Corolla 1.3 ‘133’	1.3
		Opel Astra 14-16v (Z14XEP) ‘146’	1.3
		Volkswagen Golf B 59 KW H5 149 32	1.4
		Ford Focus 1.4l 59kW	1.4
		Renault Megane 1.6 16V 100 (159)	1.5
	High energy use	Subaru legacy 30 spec	2.7
		Alfa 3.2 ITS	2.7
		Renault Espace	2.7
		Rolls Royce Phantom	3.5
		Jeep Grand Cherokee	3.6
		Bentley continental	3.7
		Bugatti Veyron 16.4	5.5
Diesel	Low energy use	Smart 451	0.8
		VW Polo	0.9
	Medium energy use	Ford focus 1.6TDCi 66kW cDPF	1.0
		Toyota Corolla 1.4 D-4D DPF ‘125’	1.1
		Opel Meriva A 1.3CDTi (Z1.3DTJ-DPF) ‘134’	1.2
	High energy use	Alfa 2.4 JTD	1.8
		Dodge Nitro	2.1
		Land Rover Discovery 3	2.4
		Land Rover Discovery sport	2.6

Table 2. Overview of energy requirements for different modes of freight transport.

Transport mode	Energy source	Energy (MJ per 1,000 kg/km)
Airplane	Kerosene	6.90-9.00
Lorry	Diesel	1.70-2.90
Ship (inland shipping)	Diesel	0.40-0.80
Ship (sea, bulk)	Diesel	0.09-0.10
Train	Electricity	0.18-0.35[a]

[a] Based on the use of electricity. For comparison of energy use with other transport modes, the efficiency to convert primary energy into electricity has to be taken into account.

2.2 The water footprint of biofuel-based transport in litres per kilometre

The WF of bio-energy depends on the crop used and the circumstances under which the crop is grown, both climate and agricultural practice (Gerbens-Leenes at al., 2008). For biodiesel we considered rapeseed, the most water-efficient crop for that purpose in Europe. For bio-ethanol and sugar, we focused on sugar beet and for bio-electricity on maize. Per bio-energy type, we assessed the weighted average WF in the European Union (litres per MJ). The calculation was done for the European countries that make a substantial contribution to global agricultural production. These countries were: the Czech republic, Denmark, France, Germany and the United Kingdom (for rapeseed); Austria, Belarus, Belgium-Luxembourg, Czech republic, Denmark, France, Germany, Greece, Hungary, Ireland, Italy, Moldova, the Netherlands, Poland, Romania, Serbia and Montenegro, Slovakia, Sweden and the United Kingdom (for sugar beet); and France, Germany, Italy, Romania and Spain (for maize). Data on national average WFs per crop were obtained from Gerbens-Leenes et al. (2008).

The water footprint of a certain mode of passenger transport was calculated based on the weighted average water footprint (litre/MJ) for the fuel of that transport mode and the energy requirement for the transport mode:

$$WF^{*}\left[m,e,c\right]=E\left[m,e\right]\times\sum_{n=1}^{i}\frac{P\left[n,c\right]*WF\left[n,e,c\right]}{\sum_{n=1}^{i}P\left[n,c\right]}$$

in which $WF^{*}[m,e,c]$ is the weighted average water footprint of transport mode m based on energy source e from crop c (litre/passenger km), $E[m,e]$ the energy requirement of transport mode m based on energy source e (MJ/passenger km), $P[n,c]$ the production in country n of crop c (tons/year) and $WF[n,e,c]$ the water footprint in country n of the energy source e derived from crop c (litre/MJ). In our calculation, we assumed that energy requirements for transport using biofuels are the same as for transport using the traditional fuels. For biking and walking, we assumed that the required additional nutritional energy is obtained from sugar from sugar beet.

Freight can be transported in several ways. In general, transport of bulk freight by large sea container shipping requires less energy per unit of freight than transport by airplane (IEA, 2007). For the calculation of the WFs of freight, this study combined information on energy requirements of freight (MJ per 1,000 kg/km) with data on WFs of bio-energy from Gerbens-Leenes et al. (2008). We assumed that ships and lorries use biodiesel as a renewable fuel. For airplanes, calculations were done for biodiesel as well as for bio-ethanol, for trains for bio-electricity. The WF of freight transport was calculated in a similar way as in the case of passenger transport.

2.3 The water footprint of transport in the European Union

The European Union (EU) aims to reach a share of 20 percent of total energy supply from renewable sources in 2020 (European Commission, 2009). In order to reach this target, the EU also sets targets for various sectors in the economy, including the transport sector. It aims at 10 percent renewable energy for this sector in 2020. We calculated the effects on the WF of a shift towards a contribution of 10 percent renewable energy to total energy supply in the European transport sector for 25 countries of the EU (excluding Cyprus and Malta), and for Norway, Switzerland and Iceland. Assessments were based on energy use in 2005. The study combined data on energy consumption of the transport sector from the IEA (2009) with data on WFs of biofuels from Gerbens-Leenes et al. (2008). Currently, for biofuels countries mostly rely on national production (IEA, 2006). For the calculation of the water footprint of biofuel-based transport in a certain country, we quantified the water requirements assuming national production of the required crops. For each country, we selected the crop that has the lowest WF per unit of biofuel. For a few countries for which no data were available, we calculated and applied the weighted European average WF.

2.4 The water footprint of transport for the main global regions

In order to put results for Europe in a global perspective, we assessed the WF of transport for seven other world regions: Africa, Australia, Asia (excluding China), China, the former USSR, Latin America and North America. We assumed similar targets for renewable energy for these regions, i.e. 10 percent of total energy for transport. This was done using the method described above. The WF of biofuels in a specific region was calculated by assessing the weighted average number for the region. For all regions, bio-ethanol is the most water-efficient biofuel (Gerbens-Leenes et al., 2008). For the assessment of the WF of transport in the seven regions, we assumed that the most water-efficient biofuel, i.e. bio-ethanol, and the most water-efficient crop (different per region) is applied for biofuel production.

2.5 For comparison: the water footprint of food and cotton

In order to put results in an overall perspective, we compared national WFs of transport using 10 percent bio-energy to the WF of food and cotton consumption. We obtained data on the national WFs of food and cotton consumption from Hoekstra and Chapagain (2008). The regional WFs were calculated by adding the national WFs for the specific region. For all world regions, results were expressed as total annual WF per region as well as annual per capita WF.

3. Results

3.1 The water footprint of different transport modes using biofuels

Table 3 gives the average green, blue and total WF for biodiesel, bio-ethanol, bio-electricity and sugar (m^3 per GJ) in the EU. Per energy source, the most water-efficient crop has been taken. Bio-electricity obtained from maize has an average water footprint of 33 m^3/GJ. This can be used for trains and electric cars. Sugar from sugar beet (as an energy source for walking and biking) requires only little more water per unit of energy. Also bio-ethanol from sugar beet requires only little more. The most water-inefficient biofuel is biodiesel from rapeseed, with a total WF of four times the WF of bio-electricity. For biodiesel from rapeseed, the green WF is larger than the blue WF, but for bio-electricity from maize and bio-ethanol from sugar beet it is the other way around. In absolute numbers, however, the blue WFs of bio-electricity and bio-ethanol are smaller than the blue WF of biodiesel.

Table 3. Weighted average water footprint of four different sources of energy in the EU.

Energy source	Crop source	Average water footprint (m^3 per GJ or litres per MJ)		
		Green	Blue	Total
Biodiesel	Rapeseed	78	60	139
Bio-ethanol	Sugar beet	19	20	39
Sugar	Sugar beet	17	18	35
Bio-electricity	Maize	15	18	33

Table 4 gives the green, blue and total WFs per transport mode, energy source and crop source in litres per passenger km. When biking and walking are not considered, the train and electric car are the most water-efficient transport modes, airplanes using biodiesel the most water-inefficient. The table also shows the large variation in WFs caused by variation in energy requirements per passenger km. For airplanes, the difference between the lowest and the highest WF per passenger km is a factor 7.5. For cars the difference is even larger (factor 10). This is caused by the large variety in energy use of cars. Petrol use of small cars is about 4.3 litres of petrol per 100 km, whereas the use of a large car can be about 25 litres per 100 km (RDW, 2010). Although diesel cars are more efficient in terms of energy use than petrol cars, cars using biodiesel generally have a larger WF than cars driving on bio-ethanol, because biodiesel is less water-efficient than bio-ethanol. The WF of electric cars driving on bio-electricity is three to thirty times smaller than the WF of bio-fuelled conventional cars, depending on which conventional car is used for comparison.

Table 5 gives the average green, blue and total WF for freight transport in the EU. When depending on bio-energy, the most water-efficient way of transporting freight over long distances overseas is by ship using biodiesel; the most inefficient way is by airplane using biodiesel, with a difference of a factor of about 80. For transport over land, the electric train is the most water-efficient way of transport, about 35 times as efficient as a lorry driving on biodiesel or an airplane flying on bio-ethanol.

Table 4. Average WF for different modes of passenger transport in the EU.

Transport mode	Energy source	Crop source	WF (litre per passenger km)		
			Green	Blue	Total
Airplane	Biodiesel	Rapeseed	133-278	103-214	236-492
	Bio-ethanol	Sugar beet	32-66	34-71	65-136
Car	Biodiesel	Rapeseed	61-200	47-154	109-355
	Bio-ethanol	Sugar beet	18-102	19-111	36-212
Bus	Biodiesel	Rapeseed	63-87	48-67	111-154
	Bio-ethanol	Sugar beet	15-21	16-22	31-43
Train	Bio-electricity	Maize	3-9	4-10	8-19
Electric car	Bio-electricity	Maize	5-6	6-7	11-13
Walking	Sugar	Sugar beet	2.1	2.3	4.4
Bike	Sugar	Sugar beet	0.8	0.9	1.7

Table 5. Average WF for different modes of freight transport in the EU.

Transport mode	Energy source	Crop source	WF (litre per 1000 kg of freight per km)		
			Green	Blue	Total
Airplane	Biodiesel	Rapeseed	540-705	416-543	957-1248
	Bio-ethanol	Sugar beet	128-167	138-181	264-345
Lorry	Biodiesel	Rapeseed	133-227	103-175	236-402
Ship (inland)	Biodiesel	Rapeseed	31-62	24-48	56-111
Ship (sea, bulk)	Biodiesel	Rapeseed	7-8	5-6	13-14
Train	Bio-electricity	Maize	3-5	3-6	6-12

3.2 The WF of the European transport sector when 10 percent of fuels is bio-ethanol

Figure 1 shows the green and the blue WF for transport in the EU if 10 percent of all transport fuels derive from bio-ethanol. For Europe as a whole, the transport-related water footprint will be 62 Gm^3 per year (48% green, 52% blue). Differences among countries are large and depend on total energy use for transport per country and on the WF of the transport fuel. Germany, Italy and the United Kingdom show the largest WFs, followed by France, Spain and Poland. Although total energy use for transport in Germany is 50 percent larger than in Italy, the WF is similar. This is caused by differences in the WF of the bio-ethanol. In Italy, the most favourable crop for bio-ethanol production in terms of water is sugar beet (WF bio-ethanol 50 m^3 /GJ), in Germany potato (WF bio-ethanol 35 m^3 /GJ). Poland also has a relatively large WF. Although total energy use for transport is 1/3 of the use in Spain, the WF of bio-ethanol is twice the value of the WF of bio-ethanol in Spain. Slovenia, Latvia, Estonia and Iceland have the lowest WF for transport, mainly due to small energy use of their transport sector.

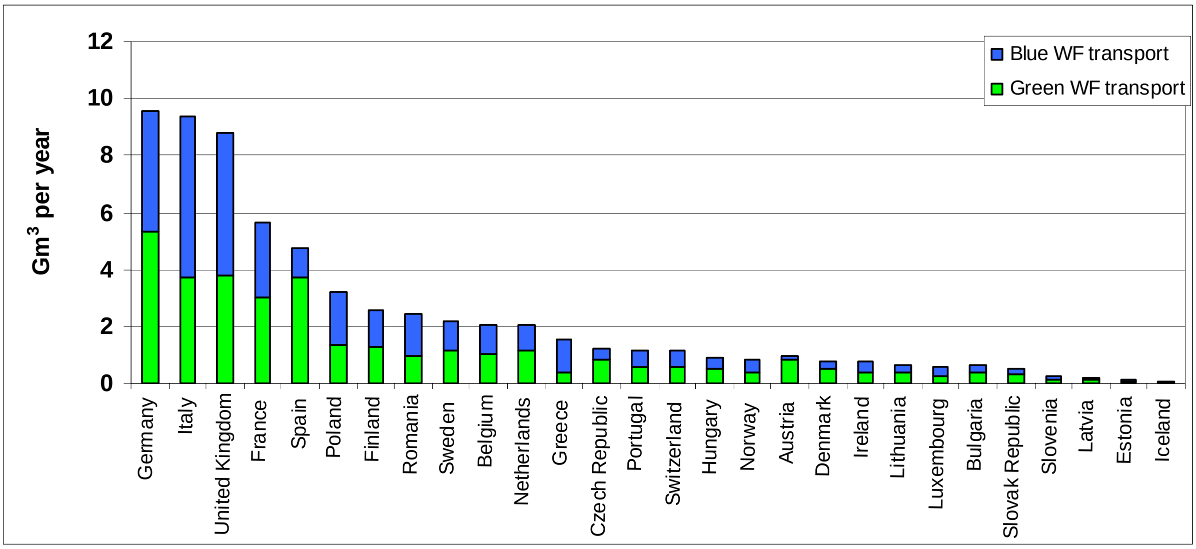

Figure 1. The WF of the European transport sector when 10 percent of all transport fuels derive from bio-ethanol

Figure 2 gives per capita green and blue WFs for transport in the EU if 10 percent of all transport fuels derive from bio-ethanol. Most countries show WFs between 60 and 200 m^3 per capita per year. Differences are caused by differences in energy use and specific WFs of bio-ethanol. For example, Switzerland, Denmark, Spain and Austria combine relatively large per capita energy use for transport (42-43 GJ per capita per year) with small WFs for bio-ethanol (24-28 m^3/GJ), whereas Romania combines small energy use (8 GJ per capita per year) with a large WF for bio-ethanol (133 m^3/GJ). Results for Luxembourg differ from results for the other countries, mainly caused by very large per capita energy use compared to other countries.

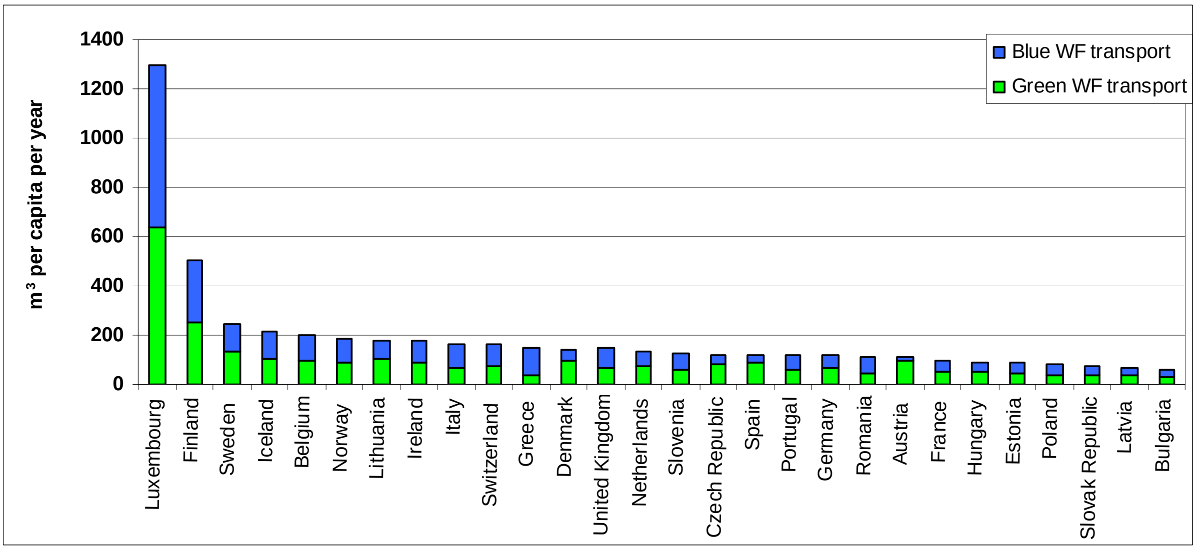

Figure 2. WF per capita related to consumption of biofuels when in each European country 10 percent of all transport fuels are derived from bio-ethanol

3.3 The WF of European transport compared to the WF of European consumption of food and cotton

Figure 3 shows for the European countries the per capita WF of food and cotton consumption together with the per capita WF of transport when based on 10 percent bio-ethanol. In average, the European water footprint related to transport when 10% of the fuels come from bio-ethanol is 10% of the current European water footprint of food and cotton consumption. As one can see from the figure, there are substantial differences across countries, however.

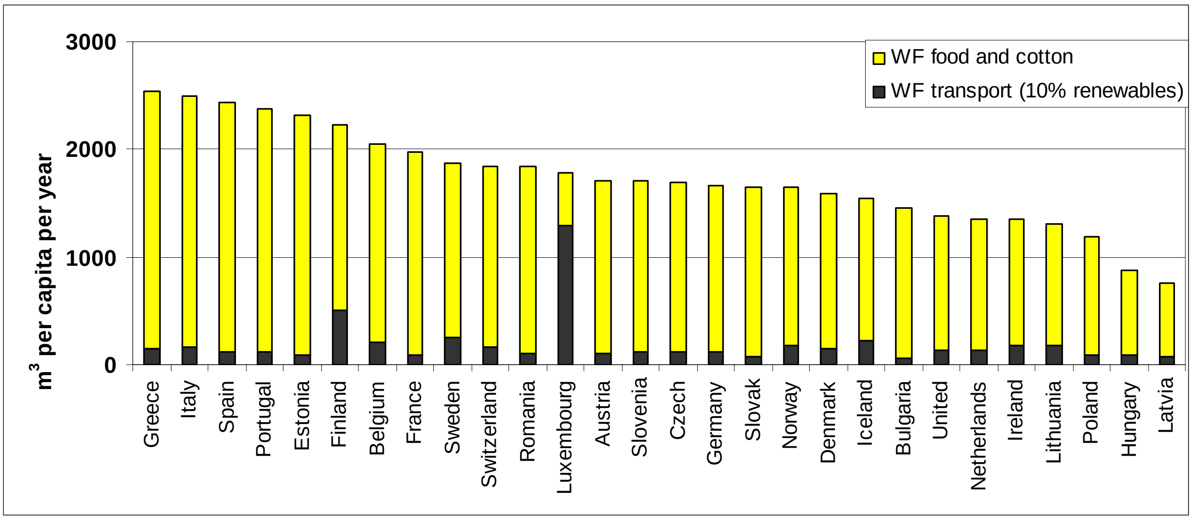

Figure 3. WF per capita for the European countries related to transport when based on 10 percent bio-ethanol compared to the WF of food and cotton consumption.

3.4 The water footprint of Europe compared to other regions

Table 6 gives the most favourable crops from a water footprint point of view for bio-ethanol production for eight world regions including the weighted average WF. Total WFs range from 38 m^3/GJ for Europe to 163 m^3/GJ for the former USSR. The blue WF is particularly large for bio-ethanol obtained from sugar beet in the former USSR and for bio-ethanol obtained from sugar cane in Asia (excluding China). The green WF of bio-ethanol is especially large for bio-ethanol from cassava grown in Africa; the blue WF in Africa is relatively small.

Figure 4 shows the global green and blue WF of transport per world region for the situation that 10 percent of transport energy derives from bio-ethanol. If 10 percent of biofuels for transport derives from the most efficient transport fuel in terms of water, that is bio-ethanol, this requires globally 300 Gm^3 per year of green water and an additional 300 Gm^3 of blue water. Differences among regions are large. The difference between North America and the EU is a factor four, while energy for transport in the EU is only half of the value of North America. The difference is due to the difference between the WF of bio-ethanol made from maize in North America (78 m^3/GJ) and the WF of bio-ethanol made from sugar beet in the EU (38 m^3/GJ). The WF in the former USSR is relatively large given its energy use for transport, which is only half of energy use in the EU. This is caused by the disadvantageous WF of bio-ethanol produced in the former countries of the USSR.

Table 6. Most favourable crops for bio-ethanol production for eight world regions including the weighted average WF.

Region	Crop for bio-ethanol	Weighted average WF bio-ethanol (m^3/GJ)		
		Green	Blue	Total
Europe	Sugar beet	19	20	38
Australia	Sugar cane	38	32	70
North America	Maize	41	37	78
China	Sugar cane	58	25	83
Latin America	Sugar cane	56	48	104
Asia (excluding China)	Sugar cane	42	77	119
Africa	Cassava	124	17	141
Former USSR	Sugar beet	43	120	163

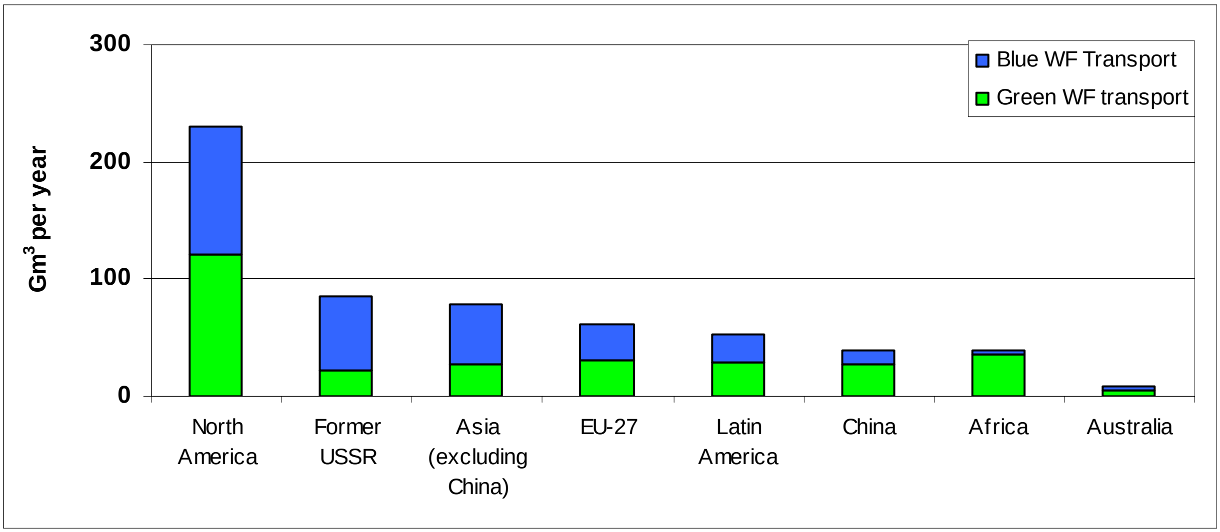

Figure 4. Green and blue WF per world region related to the consumption of biofuels in the transport sector for the situation that 10 percent of transport fuels are derived from bio-ethanol.

Figure 5 gives the total WFs for the eight world regions including both the WF of food and cotton consumption and the WF of transport for the situation that 10 percent of biofuels in transport is derived from bio-ethanol. The figure shows that when 10 percent of transport biofuels consists of bio-ethanol, 'food and cotton' is still the main water user, about 90 percent of total water use. The fraction of water for transport is much larger however, for North America, Australia and the former USSR. In Asia and Africa, the fraction of water for transport is substantially smaller than the global average. Figure 6 shows the same data as Figure 5, but now per capita. The per capita WF for North America is the largest in the world, first because the people in the region have an affluent consumption pattern and second because the region has a large energy intensity. The latter translates to a very significant contribution to the WF per capita when 10% of transport fuels are sourced from biomass.

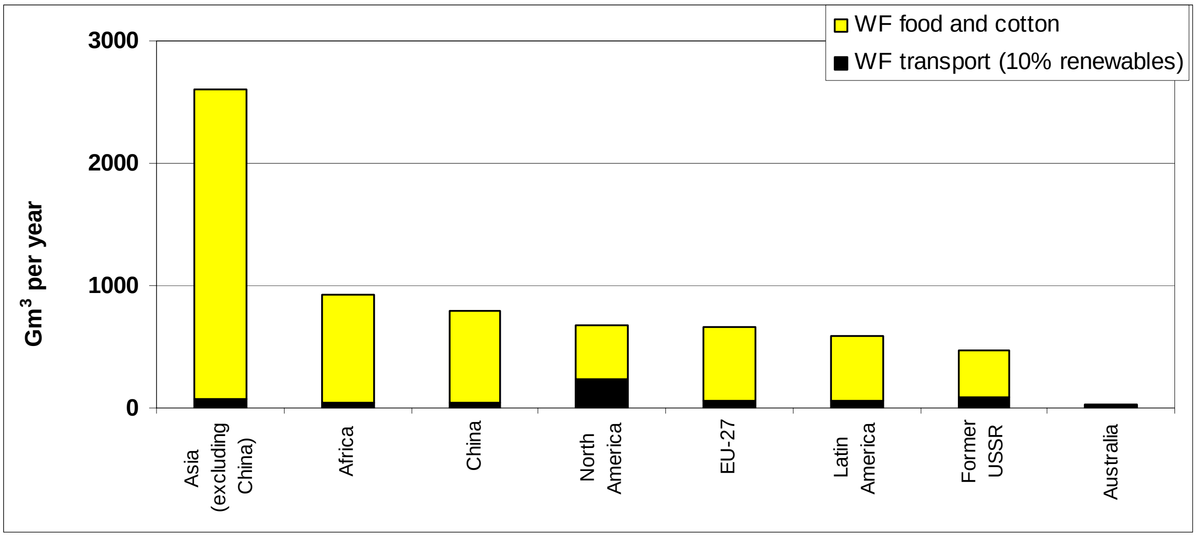

Figure 5. The total WF per world region related to the consumption of food and cotton plus the WF related to transport for the situation that 10 percent of transport fuels are derived from bio-ethanol.

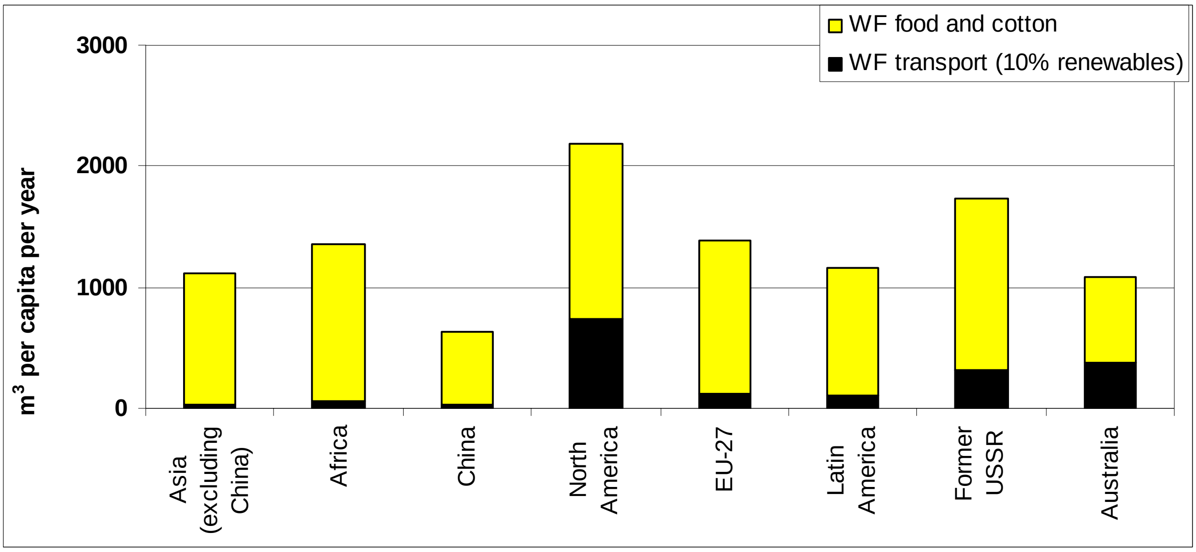

Figure 6. The WF per capita per world region related to the consumption of food and cotton plus the WF per capita related to transport for the situation that 10 percent of transport fuels are derived from bio-ethanol.

4. Discussion

4.1 Assumptions

The calculations have been based on a number of assumptions: (1) energy requirements of transport (MJ/km) remain constant when switching from fossil fuels to biofuels; (2) we considered current volumes of fuel needed for transport; (3) all countries and regions have similar goals for renewable energy for transport; (4) transport fuels are produced in the most water-efficient way; (5) agricultural water productivities remain constant; (6) for estimating the biofuel-related water footprint per country and region we have taken the agricultural water productivities as in the country or region considered, implicitly assuming that the biomass is grown domestically; and (7) biofuels have a substantially higher WF per unit of energy than fossil fuels, so that the WF of the latter can be ignored compared to the former.

Ad (1) Currently, biofuels give the same energy efficiency (km/MJ) only when added in relatively marginal amounts to fossil fuels. This means that the calculated water footprints per km may be at the conservative side.

Ad (2) Taking the current volumes of fuels used in the transport sector while the expectation is that energy use will actually grow, implies that we underestimate the 2020 conditions.

Ad (3) For the comparison, the study has taken a goal of 10 percent biofuels in transport for all countries and regions, but actual goals may differ of course. Countries with high potential for bio-ethanol may have other goals for adopting biofuels than countries without potentials. For example, the Brazilian Alcohol Program aimed to produce bio-ethanol from sugarcane, was already established during the 1970s with the intention to reduce oil imports (Goldemberg et al., 2004). The USA also stimulates bio-ethanol for transport (US Congress, 2005).

Ad (4) The study has taken optimistic assumptions by either taking theoretical minimum values or values that refer to the best available technology. The study has assumed that countries apply the most water-efficient biofuel, which means that the resulting water footprint figures are conservative. Gerbens-Leenes et al. (2008) have shown that, at present, bio-ethanol is the most water-efficient biofuel for cars. Some countries, for example Germany, promote biodiesel from rapeseed (Die Bundesregierung, 2008), a fuel with a relatively large WF. For Germany, the WF of biodiesel from rapeseed is 130 m^3/GJ, whereas the WF of bio-ethanol from sugar beet amounts 40 m^3/GJ.

Ad (5) With respect to agricultural systems, data for WFs of bio-ethanol are based on actual yields, which in many cases can be increased in the future without increasing water use per hectare. This means that in some cases water footprints per unit of energy can be lowered.

Ad (6) Today, most countries are mostly self-sufficient in biofuels. When demand increases, this situation may change because countries with few opportunities will have to import biofuels from other countries. In this case, the water footprint will press in the other countries and water productivity data as in the other countries will have to be applied when estimating the biofuel-related water footprints of the importing countries.

Ad (7) Gerbens-Leenes et al. (2009a) have shown that the WF of bio-energy is indeed much larger than the WF of fossil energy.

Data used for this study are based on rough estimates of freshwater requirements in crop production and on theoretical maximum conversion efficiencies in the production of biofuels. Data on the WF of biofuels are based on information from several sources, each of which adds a degree of uncertainty. Crop water requirements, for example, are sensitive to input of climatic data and assumptions concerning the start of the growing season. This means that results presented in this study are indicative and show directions of change.

4.2 Comparison with other studies

Although methods of calculation, assumptions and scenarios among studies that have estimated the relation between biofuels and freshwater differ, all studies agree that the expansion of crop production for biofuels leads to a large increase of freshwater use along with an increase of water stressed situations in some countries. Compared to the study of Berndes (2002) our results are conservative. We only considered the transport sector, assumed a constant energy use for transport of 90 EJ per year as in 2005, 10 percent renewable energy use and the most favourable biofuel in terms of water, bio-ethanol produced from the most water-efficient crop, and arrived at a global WF of 600 Gm^3/yr, compared to 6400 Gm^3/yr for food and cotton (Hoekstra and Chapagain, 2008). Based on a bio-energy use of 300 EJ in 2100, Berndes (2002) has arrived at a doubling of evapotranspiration from global croplands from 6,800 to 13,600 Gm^3 that could even increase with 370 Gm^3 if irrigation is applied. De Fraiture et al. (2008) estimate for 2030 a total evapotranspiration from croplands for biofuel production of 262 Gm^3/yr, based on a much more modest expectation of biofuel growth.

For China, we assumed that energy use for transport is 0.5 EJ, where Yang et al. (2009) have estimated the use of 10 million tons of bio-ethanol and 2 million tons of biodiesel in 2000 (0.4 EJ) and have arrived at a water requirement between 31.9 and 71.7 Gm^3/yr. Based on the most water-efficient crop, sugar cane, we calculated a water footprint of 40 Gm^3/yr. For 0.4 EJ, this would require 32 Gm^3/yr, a result in line with the study of Yang et al. (2009). That study is also in line with our finding that in China sugar cane is the most favourable crop in terms of water and that rapeseed and soybean are unfavourable.

King and Webber (2008) have estimated the water requirement for light duty vehicles in the US using ethanol from maize and have arrived at 15 to 260 litre per km. That study only considered irrigation water (blue water) and expressed water requirements per km. We arrived at a blue WF per passenger km based on bio-ethanol from EU sugar beet between 19 and 111 litre per passenger km (32-184 litre per km). When also the larger blue WF of ethanol from US maize (37 m^3 per GJ) compared to the average EU value of 20 m^3 per GJ is taken into account, our results fall in the range found by King and Webber (2008). Our analysis is in line with King et al. (2010) if it comes to the conclusion that water use in the USA for producing biofuels is very substantial if compared to total water consumption. We agree with King et al. (2010) who conclude that is important to understand the full life cycle of transport and not only the fuel. At present, energy use in the transport sector is heavily dominated by cars. Our study has shown that there are large differences among WFs per passenger km of cars, especially electric cars have low WFs. This result gives options to use water in the most efficient way. Also a shift from transport using cars to trains is more favourable in terms of water.

The study of Galan-del-Castillo and Velazquez (2010) into the WF of transport in Spain also shows the large impact of differences in crops used for biofuels on WFs. In the case of self sufficiency, a target of 5.58 percent of biofuel use and a mix of ethanol from wheat and barley and biodiesel from sunflower and rapeseed, Spanish transport requires 600 m^3 per capita per year. Importing biofuels based on more water-efficient crops from elsewhere could substantially reduce the water footprint of biofuels in Spanish transport. Our study showed a favourable WF of 120 m^3 per capita per year in Spain, based on the use of bio-ethanol from Spanish potato. These comparisons show that differences in biofuel type (bio-ethanol or biodiesel), crop type and country of origin have a large impact on the final results.

5. Conclusions

The WF of transport per passenger km shows differences among transport modes and depends on the transport fuel. In general, it is more efficient to use bio-electricity or bio-ethanol than biodiesel. Transport per train based on bio-electricity (8-19 litres per passenger km) is more water-efficient than transport by car using bio-ethanol (36-212) or airplane using bio-ethanol (65-136 litres per passenger km). For cars, WFs have large differences. A small car using bio-ethanol has a ten times smaller WF than a large car using biodiesel (36 versus 355 litres per passenger km). Based on a load factor of 1.66 passenger per car, an electric car fed by bio-electricity is a favourable alternative using 11-13 litres of water per passenger km. Freight can be transported in the most water-efficient way by ship or train, while the airplane is the most water-inefficient way of transport.

The European goal of 10 percent biofuel in the transport sector in 2020 means that the transport-related WF will grow to 62 Gm^3 per year. This is a conservative estimate, assuming that the most water-efficient crops for making bio-ethanol are used. The volume is to be compared with the current WF of European consumption of food and cotton of about 600 Gm^3 per year. If a mix of biodiesel and bio-ethanol is used or if fuels are imported from outside the EU, the transport-related WF will be larger.

The per capita WF for renewable transport is a function of energy use and the WF of the transport fuel. Both show large differences. In Europe, there is a difference in per capita energy use for transport between the western European countries showing energy use above 40 GJ per capita per year (e.g. Austria 43 GJ, the UK 41 GJ, the Netherlands 41 GJ) and the eastern countries with energy use below 25 GJ per capita per year (e.g. Bulgaria 15 GJ, Romania 8 GJ). WFs of transport fuels also differ. Currently, the western European countries generally have the lowest WF per unit of bio-ethanol and the eastern European countries the highest. Differences in per capita energy use for transport among European countries, together with differences in production systems, result in a broad range of transport-related WFs: from 60 m^3 per year per capita in Bulgaria to 500 m^3 per year per capita in Finland (assuming 10% biofuels in transport).

If 10 percent of the fuel used in the transport sector is replaced by bio-ethanol, biofuel-based transport in Europe will require a water volume that is equal to about 10% of the European water footprint of food and cotton consumption. If the same biofuel target would be applied in all other regions of the world as well, the additional water consumption in China would be equivalent to 5% of the water footprint for food and cotton consumption, in the rest of Asia 3%, in Africa 4%, in Latin America 10%, in the former USSR 22% and both in North America and Australia 52%. The global water consumption related to biofuel-based transport in this scenario would be 9% of the current global water consumption for food and cotton. In regions where water is limited and where energy use in the transport sector is large, the trend towards biofuels is a significant factor for total water use in agriculture and increases the competition for fresh water resources.

References

Åkerman, J., 2005. Sustainable air transport-on track in 2050. Transport Research Part D 10: 111-126.

Arar, J.I., 2010. New directions: The electric car and carbon emissions in the US. Atmospheric Environment 44: 733–734.

Berndes, G., 2002. Bio-energy and water-the implications of large-scale bio-energy production for water use and supply. Global Environmental Change 12:253-271.

Blok, K., 2006. Introduction to energy analysis. Techne Press, Amsterdam, the Netherlands.

Bouwman, M.E., Moll, H.C., 2002. Environmental analyses of land transport systems in The Netherlands. Transport Research Part D 7, 331-345.

Breedveld, B.C., Hammink, J. and Van Oosten, H.M. (eds), 1998. Nederlandse Voedingsmiddelentabel. Voedingscentrum, The Hague, the Netherlands.

CBS and Kluwer Voertuigtechniek, 1996. Auto's in Nederland. Heerlen/Deventer, Centraal Bureau voor de Statistiek en Kluwer BedrijfsInformatiebeheer.

Chiu, Y., Walseth, B., Suh, S., 2009. Water embodied in bioethanol in the United States. Environmental Science and Technology 43, 2688-2692.

Davis, S.C.; Diegel, S.W., Boundy, R.G., 2009. Transport Energy Data Book: Edition 28. US Department of Energy. pp. Table 2.12. ORNL-6984 (Edition 28 of ORNL-5198). http://cta.ornl.gov/data/. Retrieved 2009-07-12.

De Fraiture, C., Giordano, M. and Liao, Y.S., 2008. Biofuels and implications for agricultural water use: blue impacts of green energy. Water Policy 10: 67-81.

DeLuchi, M., Wang, Q., Sperling, D., 1989. Electric vehicles: performance, life-cycle costs, emissions, and recharging requirement. Transpn.Res.-A, 23A(3): 255-278.

De Vries, B.J.M., Van Vuuren, D.P., Hoogwijk, M.M., 2006. Renewable energy sources: their global potential for the first half of the 21st century at a global level: an integrated approach. Energy Policy 35: 2590-2610.

Die Bundesregierung, 2008. Regierungonline-Energie vom Acker. http://www.bundesregierung.de/nn_501404/Content/DE/Artikel/2008/04/2008-04-01-hightech-serie-pflanzen-energie-vom-acker.html

Dominguez-Faus, R., Powers, S.E., Burken, J.G., Alvarez, P.J., 2009. The water footprint of biofuels: a drink or drive issue. Environmental Science and Technology 43 (9): 3005-3010.

EcoInvent 2000, 2007. Ökoinventare von Energiesystemen, Transporten und Grundmaterialien, Version 2.0

European Commission, 2009. Renewable energies. http://ec.europa.eu/energy/renewables/index_en.htm

Fischer, G., Hizsnyik, E., Prieler, S., Shah, M., Van Velthuizen, H., 2009. Biofuels and food security. International Institute for Applied Systems Analysis, Laxenburg, Austria.

Frischknecht, R., Suter, P., 1996. Őko-inventare von Energiesystemen, third ed. www.energieforschung.ch

Galan-del-Castillo, E., Velasquez, E., 2010. From water to Energy: The virtual water content and water footprint of biofuel consumption in Spain. Energy Policy, 38, 1345-1352.

Gerbens-Leenes, P.W., Moll, H.C., Schoot Uiterkamp, A.J.M., 2003. Design and development of a measuring method for environmental sustainability in food production systems. Ecological Economics, 46: 231-248.

Gerbens-Leenes, P.W., Hoekstra, A.Y., Th.H. van der Meer, 2008. The water footprint of bio-energy: global water use for bio-ethanol, biodiesel, heat and Electricity. Value of Water Research Report Series No.34, UNESCO-IHE, Delft, The Netherlands.

Gerbens-Leenes, P.W., Hoekstra, A.Y., Th.H. van der Meer, 2009a. The water footprint of energy from biomass: A quantitative assessment and consequences of an increasing share of bio-energy supply. Ecological Economics 68(4): 1052-1060.

Gerbens-Leenes, W., Hoekstra, A.Y. and Van der Meer, T.H. (2009b) The water footprint of bio-energy, Proceedings of the National Academy of Sciences, 106 (25): 10219-10223

Goldemberg, J., Teixeira Coelho, S, Oswaldo Lucon, O., 2004. How adequate policies can push renewables. Energy Policy 32: 1141–1146.

Government of India, Ministry of New&Renewable energy, 2008. National Policy on Biofuels. http://mnes.nic.in/policy.biofuel-policy.pdf (Accessed January 5, 2010).

Hoekstra, A.Y., Chapagain, A.K., 2007. Water footprints of nations: Water use by people as a function of their consumption pattern. Water Resources Management 21: 35-48.

Hoekstra, A.Y., Chapagain, A.K., 2008. Globalization of Water. Sharing the planet’s freshwater resources. Blackwell Publishing, Oxford, UK.

Hoekstra, A.Y., Hung, P.Q., 2005. Globalisation of water resources: international virtual water flows in relation to crop trade. Global Environmental Change 15 (1): 45-56.

Hughes, S., Partzsch, Gaskell, J., 2007. The development of biofuels within the context of the global water crisis. Sustainable Development Law & Policy, Spring 2007: 58-62.

IEA, 2006. World energy outlook 2006. OECD/International Energy Agency, Paris, France.

IEA, 2007. Energy use in the new millennium. Trends in IEA countries. OECD/International Energy Agency, Paris, France.

IEA, 2009. Energy balances 2005. International Energy Agency, Paris, France.

Jamin, S., Schäfer, A., Ben-Akiva, M.E., Waitz, I.A., 2004. Aviation emissions and abatement policies in the United States: a city-pair analysis. Transport Research Part D 9, 295-317.

Johansson, B., A. Mårtensson, A., 2000. Energy and environmental costs for electric vehicles using CO2 neutral electricity in Sweden. Energy 25, 777–792.

King, C.W., Webber, M.E., 2008. Water intensity of transportation. Environmental Science and Technology 42 (21): 7866-7872.

King, C.W., Webber, M.E., Duncan, I.J., 2010. The water needs for LDV transportation in the United States. Energy Policy 33: 1157-1167.

Kok, R., Benders, R.M.J., Moll, H.C., 2001. Energie-intensiteiten van de Nederlandse consumptieve bestedingen anno 1996. Center for energy and environmental Studies (IVEM), IVEM-onderzoeksrapport 105. Groningen, the Netherlands.

Krebs, M., 2007. Water-Related Energy Use in California. Public Interest Energy Research Program, California Energy Commission.

Postel, S.L., Daily, G.C., Ehrlich, P.R., 1996. Human appropriation of renewable freshwater. Science 271(9 February): 785-788.

Postel, S.L., 2000. Entering an era of water scarcity: the challenges ahead. Ecological applications 10(4): 941-948.

RDW, 2010. Brandstofverbruiksboekje januari 2010. ANWB, Den Haag, the Netherlands.

Schipper, L., Scholl, L., Price, L., 1997. Energy use and carbon emissions from freight in 10 industrialized countries: an analysis of trends from 1973 to 1992. Transport Research Part D 2 (1): 57-76.

SenterNovem, 2007. Handreiking verbredingsthema's. Bijlage. Onderbouwing energiekentallen, www.senternovem.nl/mmfiles/Bijlage_onderbouwing_energiekentallen_tcm24-204104.pdf .

Scholl, L., Schipper, L., Kiang, N., 1996. CO_2 emissions from passenger transport. A comparison of international trends from 1973 to 1992. Energy Policy 24(1): 17-30.

US Congress, 2005. Energy Policy Act of 2005. Available from:www.epa.gov/OUST/fedlaws/publ_109-058.pdf.p. 109–58.

Van der Velde, M., Bouraoui, F., Aloe, A., 2009. Pan-European regional-scale modelling of water and N efficiencies of rapeseed cultivation for biodiesel production. Global Change Biology 15(1): 24-37.

Yang, H., Zhou, Y., Liu, J., 2009. Land and water requirements of biofuels and implications for food supply and the environment in China. Energy Policy 37(5): 1876-1885.

Value of Water Research Report Series

1. Exploring methods to assess the value of water: A case study on the Zambezi basin.
   A.K. Chapagain – February 2000
2. Water value flows: A case study on the Zambezi basin.
   A.Y. Hoekstra, H.H.G. Savenije and A.K. Chapagain – March 2000
3. The water value-flow concept.
   I.M. Seyam and A.Y. Hoekstra – December 2000
4. The value of irrigation water in Nyanyadzi smallholder irrigation scheme, Zimbabwe.
   G.T. Pazvakawambwa and P. van der Zaag – January 2001
5. The economic valuation of water: Principles and methods
   J.I. Agudelo – August 2001
6. The economic valuation of water for agriculture: A simple method applied to the eight Zambezi basin countries
   J.I. Agudelo and A.Y. Hoekstra – August 2001
7. The value of freshwater wetlands in the Zambezi basin
   I.M. Seyam, A.Y. Hoekstra, G.S. Ngabirano and H.H.G. Savenije – August 2001
8. ‘Demand management’ and ‘Water as an economic good’: Paradigms with pitfalls
   H.H.G. Savenije and P. van der Zaag – October 2001
9. Why water is not an ordinary economic good
   H.H.G. Savenije – October 2001
10. Calculation methods to assess the value of upstream water flows and storage as a function of downstream benefits
    I.M. Seyam, A.Y. Hoekstra and H.H.G. Savenije – October 2001
11. Virtual water trade: A quantification of virtual water flows between nations in relation to international crop trade
    A.Y. Hoekstra and P.Q. Hung – September 2002
12. Virtual water trade: Proceedings of the international expert meeting on virtual water trade
    A.Y. Hoekstra (ed.) – February 2003
13. Virtual water flows between nations in relation to trade in livestock and livestock products
    A.K. Chapagain and A.Y. Hoekstra – July 2003
14. The water needed to have the Dutch drink coffee
    A.K. Chapagain and A.Y. Hoekstra – August 2003
15. The water needed to have the Dutch drink tea
    A.K. Chapagain and A.Y. Hoekstra – August 2003
16. Water footprints of nations, Volume 1: Main Report, Volume 2: Appendices
    A.K. Chapagain and A.Y. Hoekstra – November 2004
17. Saving water through global trade
    A.K. Chapagain, A.Y. Hoekstra and H.H.G. Savenije – September 2005
18. The water footprint of cotton consumption
    A.K. Chapagain, A.Y. Hoekstra, H.H.G. Savenije and R. Gautam – September 2005
19. Water as an economic good: the value of pricing and the failure of markets
    P. van der Zaag and H.H.G. Savenije – July 2006
20. The global dimension of water governance: Nine reasons for global arrangements in order to cope with local water problems
    A.Y. Hoekstra – July 2006
21. The water footprints of Morocco and the Netherlands
    A.Y. Hoekstra and A.K. Chapagain – July 2006
22. Water’s vulnerable value in Africa
    P. van der Zaag – July 2006
23. Human appropriation of natural capital: Comparing ecological footprint and water footprint analysis
    A.Y. Hoekstra – July 2007
24. A river basin as a common-pool resource: A case study for the Jaguaribe basin in Brazil
    P.R. van Oel, M.S. Krol and A.Y. Hoekstra – July 2007
25. Strategic importance of green water in international crop trade
    M.M. Aldaya, A.Y. Hoekstra and J.A. Allan – March 2008

26. Global water governance: Conceptual design of global institutional arrangements
    M.P. Verkerk, A.Y. Hoekstra and P.W. Gerbens-Leenes – March 2008
27. Business water footprint accounting: A tool to assess how production of goods and services impact on freshwater resources worldwide
    P.W. Gerbens-Leenes and A.Y. Hoekstra – March 2008
28. Water neutral: reducing and offsetting the impacts of water footprints
    A.Y. Hoekstra – March 2008
29. Water footprint of bio-energy and other primary energy carriers
    P.W. Gerbens-Leenes, A.Y. Hoekstra and Th.H. van der Meer – March 2008
30. Food consumption patterns and their effect on water requirement in China
    J. Liu and H.H.G. Savenije – March 2008
31. Going against the flow: A critical analysis of virtual water trade in the context of India's National River Linking Programme
    S. Verma, D.A. Kampman, P. van der Zaag and A.Y. Hoekstra – March 2008
32. The water footprint of India
    D.A. Kampman, A.Y. Hoekstra and M.S. Krol – May 2008
33. The external water footprint of the Netherlands: Quantification and impact assessment
    P.R. van Oel, M.M. Mekonnen and A.Y. Hoekstra – May 2008
34. The water footprint of bio-energy: Global water use for bio-ethanol, bio-diesel, heat and electricity
    P.W. Gerbens-Leenes, A.Y. Hoekstra and Th.H. van der Meer – August 2008
35. Water footprint analysis for the Guadiana river basin
    M.M. Aldaya and M.R. Llamas – November 2008
36. The water needed to have Italians eat pasta and pizza
    M.M. Aldaya and A.Y. Hoekstra – May 2009
37. The water footprint of Indonesian provinces related to the consumption of crop products
    F. Bulsink, A.Y. Hoekstra and M.J. Booij – May 2009
38. The water footprint of sweeteners and bio-ethanol from sugar cane, sugar beet and maize
    P.W. Gerbens-Leenes and A.Y. Hoekstra – November 2009
39. A pilot in corporate water footprint accounting and impact assessment: The water footprint of a sugar-containing carbonated beverage
    A.E. Ercin, M.M. Aldaya and A.Y. Hoekstra – November 2009
40. The blue, green and grey water footprint of rice from both a production and consumption perspective
    A.K. Chapagain and A.Y. Hoekstra – March 2010
41. Water footprint of cotton, wheat and rice production in Central Asia
    M.M. Aldaya, G. Muñoz and A.Y. Hoekstra – March 2010
42. A global and high-resolution assessment of the green, blue and grey water footprint of wheat
    M.M. Mekonnen and A.Y. Hoekstra – April 2010
43. Biofuel scenarios in a water perspective: The global blue and green water footprint of road transport in 2030
    A.R. van Lienden, P.W. Gerbens-Leenes, A.Y. Hoekstra and Th.H. van der Meer – April 2010
44. Burning water: The water footprint of biofuel-based transport
    P.W. Gerbens-Leenes and A.Y. Hoekstra – June 2010

Reports can be downloaded from:
www.waterfootprint.org
www.unesco-ihe.org/value-of-water-research-report-series

UNESCO-IHE
P.O. Box 3015
2601 DA Delft
The Netherlands

Website www.unesco-ihe.org
Phone +31 15 2151715

UNESCO-IHE
Institute for Water Education

University of Twente

University of Twente
The Netherlands

Delft University of Technology

TU Delft
Delft University of Technology