Global Environmental Change 22 (2012) 764–775

Contents lists available at SciVerse ScienceDirect

Global Environmental Change

journal homepage: www.elsevier.com/locate/gloenvcha

Biofuel scenarios in a water perspective: The global blue and green water footprint of road transport in 2030

P.W. Gerbens-Leenes [a,*], A.R. van Lienden [a,b], A.Y. Hoekstra [a], Th.H. van der Meer [b]

[a] Dept. of Water Engineering and Management, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands
[b] Dept. of Thermal Engineering, University of Twente, Enschede, The Netherlands

ARTICLE INFO

Article history:
Received 14 September 2010
Received in revised form 27 March 2012
Accepted 5 April 2012
Available online 5 May 2012

Keywords:
Biofuels
Energy
Water footprint

ABSTRACT

Concerns over energy security and climate change stimulate developments towards renewable energy. Transport is expected to switch from fossil fuel use to the use of fuel mixtures with a larger fraction of biofuels, e.g. bio-ethanol and biodiesel. Growing biomass for biofuels requires water, a scarce resource. Existing scenarios on freshwater use usually consider changes in food and livestock production, and industrial and domestic activities. This research assesses global water use changes related to increasing biofuel use for road transport in 2030 and evaluates the potential contribution to water scarcity. To investigate water demand changes related to a transition to biofuels in road transport, the study combines data from water footprint (WF) analyses with information from the IEA APS energy scenario for 2030. It includes first-generation biofuels, bio-ethanol from sugar cane, sugar beet, sweet sorghum, wheat and maize, and biodiesel from soybean, rapeseed, jatropha and oil palm. Under the IEA APS scenario, the global biofuel WF will increase more than tenfold in the period 2005–2030. The USA, China and Brazil together will contribute half of the global biofuel WF. In many countries, blue biofuel WFs significantly contribute to blue water scarcity. The research provides a first exploration of the potential contribution of transport biofuel use to blue water scarcity. In 2030, the global blue biofuel WF might have grown to 5.5% of the totally available blue water for humans, causing extra pressure on fresh water resources. When biofuel use continues to expand after 2030, countries should therefore consider the water factor when investigating the extent to which biofuels can satisfy future transport energy demand.

1. Introduction

In the 21st century, important global issues include diminishing non-renewable energy resources, CO_2 emissions, food security and water scarcity. The need to find more efficient, cleaner and sustainable fuels drives transitions in the energy sector. The use of bioenergy, such as biofuels for transport, is seen as an alternative with many of these characteristics. With the largest share of all renewables (IEA, 2006), bioenergy has a prominent role in energy scenarios. Bioenergy includes the first-generation biofuels, which are based on the starch, sugar or oil fraction in the crop and second-generation bioenergy, which is based on the cellulosic fraction of crops or other biomass (e.g. wastes). Biomass production, however, is the greatest global water consumer (e.g. Berndes, 2002; De Fraiture et al., 2008; Varis, 2007; Hoekstra & Chapagain, 2008). Numerous studies have investigated the potential of biomass for bioenergy in the light of land availability, agricultural technology, biodiversity and economic development (e.g. Fischer & Schrattenholzer, 2001; Berndes et al., 2003; Hoogwijk et al., 2003; Smeets et al., 2007; Dornburg et al., 2008; Fischer et al., 2009). The competition between crops for food or energy purposes, as well as the carbon dioxide neutrality of bioenergy have received much attention. Much attention has also been paid to the risks of depending on fossil and nuclear fuels (e.g. Sørenson, 1991; IPCC, 2008b), giving an impulse to the development of renewables, such as energy from wind, water, sunlight and biomass. The IPCC expects a robust mix of energy sources, including fossil, renewable and nuclear energy, combined with improved end-use efficiency to meet the growing demand for energy services (Sims et al., 2007). There are few studies that analyze the impact of bioenergy on the water system. Research on water use of crops for bioenergy exists (e.g. Chiu et al., 2009; Dominguez-Faus et al., 2009; Gerbens-Leenes et al., 2009a), as does research about regional water systems and stresses exerted on them (UNESCO, 2006; IPCC, 2008a). Scenarios on the use of water resources (e.g. Alcamo et al., 2003) consider changes in food and livestock production, industry and domestic activity. However, all our activities can be associated with the consumption of water, including a shift to greater bioenergy use.

To gain insight in what the future may look like, scenarios based on assumptions about driving forces and the relations between them are an useful instrument. Disagreement on the number of

* Corresponding author. Tel.: +31 53 489 2080; fax: +31 53 489 5377.
E-mail address: p.w.gerbens-leenes@utwente.nl (P.W. Gerbens-Leenes).

0959-3780/$ – see front matter
http://dx.doi.org/10.1016/j.gloenvcha.2012.04.001

forces and their exact effects results in the construction of alternative scenarios. There are several energy scenarios regarding the contribution of renewables. Generally, it is expected that in 2030 biomass will have the largest share of all renewables (IEA, 2006; World Energy Council, 2007; IPCC, 2008b; Shell, 2008). Especially in the transport sector, there is great interest in biofuels, such as bio-ethanol and biodiesel (we use the term biofuels exclusively for liquid fuels derived from biomass that can be used for transport purposes. Some studies use the term more broadly to cover all types of fuels derived from biomass used in different sectors). Many governments believe that biofuels can replace substantial volumes of imported oil with (indigenously produced) renewable biofuels and that they will play a key role in diversifying the sources of energy supply in the coming decades (IEA, 2006). All energy scenarios indicate an absolute increase of total energy demand (US Department of Energy, 2010; IEA, 2006). The increased energy demand will be supplied by increased fossil fuel supply, especially coal, and additional supply of renewables, dominated by biomass. The scenarios cover different periods, for example the Alternative Policy Scenario (APS) of the International Energy Agency (IEA) gives a projection for the period 2008–2030 (IEA, 2006), while for example the IIASA/WEC scenarios (Nakicenovic et al., 1998) cover the period 1990–2100. The first study that was done into the relationship between water availability and future biomass use concluded that large-scale bioenergy production in 2100 doubles global evapotranspiration from cropland compared to 1990 (Berndes, 2002). That study also found that the leading energy scenarios did not take water into account when estimating future biomass use. Gerbens-Leenes et al. (2009b) have shown that the WF of energy from biomass is nearly 70 to 700 times larger than that of fossil fuels. A recent study (Gerbens-Leenes and Hoekstra, 2011) assessed the water footprint of biofuel based transport showing large differences among WFs of different transport modes. That study also assessed the additional water requirement of the European transport sector related to the EU policy target to replace 10% of transport fuels by renewables in 2020. Based on energy use in 2005 and smallest WFs for biofuels per country, i.e. the use of the most favourable crop for ethanol, the EU water footprint would increase by 10%. Future research should take restrictions from water availability and competing demand for water into account (Berndes, 2002, 2008). In order to better understand the relation between various commodities that we use and underlying water requirements, Hoekstra (2003) has introduced the concept of the 'water footprint' (WF), referring to the direct and indirect water use over the entire supply chain (Hoekstra et al., 2011). The WF methodology provides a useful tool to investigate the relationship between human activities and water consumption.

To supply a country with sufficient energy and to decrease carbon dioxide emissions to comply to international agreements, countries need to make decisions on the selection of energy carriers. For example, China aims to produce the majority of renewable electricity in 2030 from hydropower (US Department of Energy, 2010). The European Union aims to replace 10% of transport fuels by renewables (biofuels, electricity from biomass, wind, solar energy and/or hydrogen) in 2020 (European Commission and Renewable Energies, 2009). This also requires a choice on which renewable energy source to apply. A choice for bioenergy does not require large system changes, because it can easily be stored, co-fired in electricity plants or applied in the form of biofuels in the transport sector. The European transport sector is dominated by road transport (European Environment Agency, 2010) that can easily shift to biofuels without large system changes. A shift to electricity or hydrogen, however, would mean a change of the system requiring large efforts. To support policy to make the right decisions, it is needed to analyse the energy scenarios more closely to estimate if the projections for biomass supply are possible from a water perspective. Berndes (2002) has shown that global evapotranspiration from energy crops will increase, especially between 2030 and 2100. In western societies, road transport contributes about one third to total energy use (IEA, 2006). This great energy use, in combination with the introduction of biofuels with large WFs in the transport sector, asks for insight in the effects of biofuel introduction on freshwater resources and hence on the plausibility of some leading energy scenarios.

This research assesses the possibilities from a water perspective for the global introduction of presently available first-generation biofuels as an energy source for an important sector of the economy, transport, for the year 2030. The objective of this research is to assess the change in water footprints (WFs) related to the adoption of biofuels for road transport in 2030 for the main regions and ten largest biofuel consuming countries and to evaluate the potential contribution to freshwater scarcity in the light of increasing competition among economic sectors. Research questions are: (i) what is the change in the blue and green WF related to the adoption of biofuels for road transport? (ii) Does the change in the blue WF of biofuels for road transport lead to increased blue water scarcity in the top-ten biofuel consuming countries? To answer question (i), we formulated the following subquestions: Which biofuels will be used for road transport in 2030? Which feedstocks will be used to produce these biofuels? How much water is needed for the production of these feedstocks? To answer question (ii), we formulated the following subquestions: how much blue water is available for biofuels in the top-ten biofuel consuming countries? Is the available volume of blue water exceeded as a result of the WF of the 2030 biofuel consumption? Are the top-ten biofuel consuming countries likely to experience blue water scarcity due to the consumption of biofuels in 2030?

We provide information on how a transition to more biofuels in road transport will translate in increased water consumption and on the impact of the WF of biofuels in road transport on fresh water resources. The study builds on earlier research on the relation between energy and water (e.g. Gerbens-Leenes et al., 2009a,b,c; Gerbens-Leenes and Hoekstra, 2011) and extends earlier research into the WF for transport based on existing energy use and most favourable crop choice to future energy use in 2030 and most likely crop choice, giving an indication where fresh water scarcity might occur. It aims to raise awareness on the water scarcity issue, as well as provide insight into options for change. Earlier research has shown that water requirements for bioenergy will increase, especially between 2030 and 2100 (Berndes, 2002). This research focuses on part of the bioenergy demand, biofuels for transport, in the year 2030 when bioenergy use is still relatively small. For policy, it is important to know the sustainability impacts of specific choices related to changes in the transportation sector. A choice could be to stimulate changes in the transport system itself and promote, for example, biking, public transport or electric cars with smaller energy use and water footprints per passenger kilometer (Gerbens-Leenes and Hoekstra, 2011). Another choice could be to increase efficiency in agriculture decreasing water footprints per unit of biofuel or stimulate the introduction of second generation biofuels from wastes. Results of this study give insight where water scarcity might occur and can support policy decisions in which direction to make investments for renewable energy and system changes.

2. The water footprint

Major threats to the world's freshwater ecosystems include the key issues water abstraction, water pollution, and the physical modification of water bodies (e.g. dams, draining of wetlands) (L'vovich and White, 1990). The water footprint (WF) is an indicator of freshwater appropriation that includes direct and indirect water use along product supply chains (Hoekstra, 2003; Hoekstra and Chapagain, 2008; Hoekstra et al., 2011). The WF is a multi-dimensional indicator, giving water consumption volumes by source and polluted volumes by type of pollution. The tool distinguishes between green, blue and grey water and in this way gives a comprehensive and complete overview of freshwater use and pollution. The *green* WF refers to the rainwater consumed; the *blue* WF refers to surface and groundwater volumes consumed (evaporated) as a result of the production of a good. The *grey* WF of a product refers to the volume of freshwater required to assimilate the load of pollutants based on existing ambient water quality standards. It has appeared to be instrumental in analyzing water use along supply chains and in identifying hotspots and priority areas for action.

WF studies serve two discourses in water resources management. First, data on WFs of products, consumers and producers inform about sustainable, equitable and efficient freshwater use and allocation. Freshwater is scarce; its annual availability is limited. It is relevant to know who receives which portion and how water is allocated over various purposes. We included the green WF of biofuels, because WF accounts show water allocation in volumetric terms. Rainwater used for biofuels cannot be utilised for food. Second, WF accounts help to estimate local environmental, social and economic impacts. In this study, we include an environmental impact assessment by comparing the blue WF component to available runoff minus environmental flow requirements.

Recently, Galli et al. (2011) have identified four weaknesses of the WF: (i) the WF only tracks human demand on freshwater; (ii) the WF relies on local data that are often unavailable; (iii) although uncertainty is significant, there are no uncertainty studies; and (iv) grey water assessments are not based on measurements. In addition, from the life cycle assessment community, it has been suggested to multiply each blue WF component by a water-stress index in order to get a measure of local environmental impact and to neglect green WFs, because impacts would be negligible (Pfister et al., 2009). From a water resources point of view, however, the main issue is the allocation of scarce freshwater resources, which is essentially about the allocation of limitedly available blue and green water volumes, so that a weighted water footprint index would be little meaningful. Therefore we follow the standard methodology as defined in Hoekstra et al. (2011) and nowadays widely adopted in water management studies (e.g. Chapagain and Hoekstra, 2007; Chapagain and Orr, 2009; Ercin et al., 2011; Fader et al., 2011; Feng et al., 2011; Mekonnen and Hoekstra, 2011; Romaguera et al., 2010). However, we focused on water consumption by looking at both green and blue WFs and excluded the pollution-related grey WF from this study.

3. Method

3.1. Biofuels for road transport in energy scenarios

The International Energy Agency (IEA) is an intergovernmental organisation giving energy policy advises to its twenty eight member countries and information on global energy trends in energy scenarios (IEA, 2006). These scenarios provide data about energy use in a large number of regions and individual countries and contain information on different energy and transport fuel types. The Alternative Policy Scenario (APS), for example, gives a bioenergy share of 11% in global energy consumption, which is about the average value provided in other scenarios (Lienden van et al., 2008). Developments in the global energy sector between 2006 and 2009 are reflected well by the APS storyline. For example, the implementation of policy plans by many governments concerning energy security, efficiency and carbon dioxide emissions (e.g. the European Union Greenhouse Gas Emission Trading Scheme).

For the assessment of the WF of biofuels for road transport in 2030, we selected an energy scenario according to the following criteria: (i) the scenario contains all the necessary data for the calculations; (ii) it is geographically explicit; and (iii) it includes information about fuel types. For these reasons, we selected the APS of the IEA. Where data on individual countries were lacking, we complemented the dataset by data from regional scenarios that share a similar storyline. For countries in Europe (EU27), we used the RSAT-CDM scenario, the European Commission proposal with clean development mechanisms (CDM) and without renewable energy sources (RES) trading (Capros et al., 2008). Key assumptions about policy implementation, technological development and energy efficiency in the region are similar to the ones underlying the APS and trends in energy consumption are also alike. For countries excluded in these scenarios, we estimated the 2030 biofuel consumption either by looking at planned future production capacity (e.g. by private initiatives) or by extrapolation from demand in base-year 2005. In the latter case, the total regional biofuel consumption in 2030, as projected by a scenario, is ascribed to the country according to the share it had in total biofuel consumption in 2005. We obtained consumption data from the IEA (2006), Eurostat (2009) and USDA FAS (2006a,b,c, 2007a,b, 2008a,b,c, 2009a,b).

3.2. Calculation of the biofuel water footprint

We assessed national biofuel WFs and analysed the transition to biofuel in the road transport sector per country, distinguishing between two types of biofuels: bio-ethanol and biodiesel. We assessed crop feedstock choice for each biofuel per country and linked this to water footprints (m^3/GJ), enabling the translation from biofuel consumption to water consumption (i.e. the annual national green and blue WF of biofuel). For the top-ten biofuel consuming countries, we compared the blue WF to blue water availability, making a balance of fresh water resources and uses, enabling the determination of the blue water volume available for bioenergy. The comparison allows a measure of water scarcity to be established corresponding to the expected biofuel consumption in 2030. Fig. 1 shows the six steps of the method.

3.2.1. Step 1: determine biofuel demand

The APS gives bioenergy demand for different purposes, such as transport, electricity, heat, industry, agriculture and residential services. We focused on transport biofuel use of motorised road vehicles. The World Energy Outlook (IEA, 2006) provides data about biofuel consumption according to the APS and gives energy

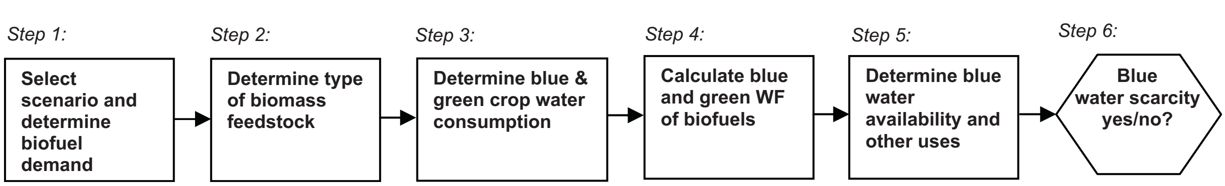

Fig. 1. Six steps of the research methodology.

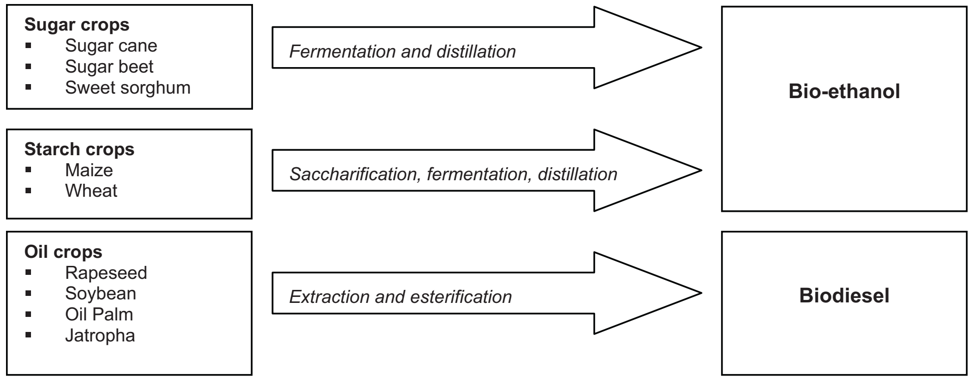

Fig. 2. Crops, conversion processes, and final energy carriers considered in this study.

balance tables for the main regions and six countries (USA, Japan, Russia, China, India and Brazil). It gives energy demand for the years 1990, 2004, 2015 and 2030 categorised in sectors, for example, for transport. However, the type of biofuel (i.e. biodiesel and/or bio-ethanol) is not specified in these tables. We distinguished between bio-ethanol and biodiesel using information and sector outlooks from the IEA (2004, 2006), the USDA FAS (2006a,b,c, 2007a,b, 2008a,b,c, 2009a,b), Dufey (2006), Eurostat (2009), Kleindorfer and Öktem (2007), Biofuels International (2007), EmBio (2008) and Capros et al. (2008).

The RSAT-CDM scenario (Capros et al., 2008) provides energy balances for twenty seven European countries, containing transport energy demand for different transport modes for 1990–2030: public road transport, private cars and motorcycles, trucks, rail, aviation and inland navigation. We considered public road transport, private cars, motorcycles and trucks. The RSAT-CDM scenario also provides an indicator for the expected national biofuel shares of transport diesel and gasoline. By multiplying the total diesel and gasoline consumption in 2030 with the projected 2030 biofuel share, we estimated total volumes of biodiesel and bio-ethanol demand per country in 2030.

3.2.2. Step 2: determine type of biomass feedstock

For bio-ethanol and biodiesel, we considered the dominant, first-generation feedstocks. For bio-ethanol, these are sugar cane, sugar beet, sweet sorghum, maize and wheat. For biodiesel, rapeseed, soybean, oil palm and jatropha. Fig. 2 gives an overview of the crops and their conversion into biofuels. We obtained data on crop choice per country from Dufey (2006), USDA FAS (2006a,b,c), FAO (2009a), Konrad (2006), BioWanze (2008), Breyerová (2007), Kautola et al. (in press), SEI (2004), NOVEM (2003), Müllerová & Mikulík (2007), Biofuels Platform (2009), Içöz et al. (2008), Kleindorfer and Öktem (2007), BBN (2008), Ministry of Agriculture Latvia (2006), NV Consultants (2007), Reuters (2006), ENERO (2005), Vassilieva (in press) and Solsten (1991). If information about national crop choice is unavailable, we assumed the country uses the same crops as its neighbours. We assumed that in 2030 countries still rely on the same crops they used for bioenergy in base-year 2005 and that they are self-sufficient in their biofuel production.

3.2.3. Step 3: determine blue and green crop water consumption

We derived data on WFs of biofuels from Gerbens-Leenes et al. (2008). For the countries not covered in that study, we first calculated crop water requirements (CWRs) using the same approach. We determined national crop growing locations using Agro-MAPS (FAO, 2009c). If no data were available, we assumed that the crop location is in the area with most agricultural activity in Google Earth aerial images. If unsure, we chose the country capital. For each location, we selected a representative weather station from CLIMWAT 2.0 (FAO, 2009d). Based on the climatic data, we estimated crop planting dates using data from Chapagain & Hoekstra (2004). The information is used as input for the CROPWAT 4.3 model.

In Malaysia, Indonesia, Thailand and the Philippines, oil palm (*Elaeis guineensis*) is the sole feedstock for biodiesel production with the Tenera variety commonly used, because of superior oil yields (Gerritsma & Wessel, 1997; Poku, 2002). Palm oil is obtained from the fruit of the oil palm. The fruit contains two oil-rich components: the kernel (nut) and the mesocarp (pulp) that surrounds it. Although both oils are distinct in their chemical and physical properties, they can both be used for biofuel (Bora et al., 2003). In addition, we calculated the CWR of oil palm.

3.2.4. Step 4: calculate blue and green WF of biofuel

We calculated the WF_c of crop c in country z (m^3/ton) based on the CWR (m^3/ha) and crop yield Y (ton/ha):

$$WF_c(z) = \frac{CWR(z)}{Y_c(z)} \tag{1}$$

We assumed that CWRs are actually met. For the WF of biodiesel from oil palm and the WF of biofuels in countries excluded in Gerbens-Leenes et al. (2008, 2009a), we obtained crop yields from Chapagain & Hoekstra (2004) and the FAO (2009e). We calculated blue WFs based on blue CWRs (i.e. irrigation requirements) and green WFs as the minimum of the total CWR and effective precipitation. Dividing the WF_c (z) by the amount of biofuel (in energy terms) obtained from the sugar, starch or oil fraction E_c (GJ/ton) results in the biofuel WF_e (m^3/GJ):

$$WF_e(z) = \frac{WF_c(z)}{E_c} \tag{2}$$

Table 1 shows energy contents of different crops as assumed in this study. It also shows that oil palm has a relatively high biodiesel yield of 16.3 MJ per kilogram of oil palm fruit.

To calculate the annual green and blue biofuel WF for road transport in country z (km^3/year), we combined data on WFs per unit of bioenergy (m^3/GJ) with annual biofuel consumption (GJ/year) per country and feedstock:

$$WF(z) = \left[\sum_{i=1}^{5} \alpha_i(z) WF_{e,i}(z)\right] E(z) + \left[\sum_{j=1}^{4} \beta_j(z) WF_{e,j}(z)\right] D(z) \tag{3}$$

where E is the annual ethanol consumption; D the annual biodiesel consumption; α_i the ratio of ethanol from crop i to total ethanol consumption; and β_j the ratio of biodiesel from crop j to total biodiesel consumption. The numerator i refers to: (1) sugar cane, (2) sugar beet, (3) sweet sorghum, (4) maize and (5) wheat; j refers to: (1) rapeseed, (2) soybean, (3) oil palm and (4) Jatropha.

Table 1
Bio-energy provided by energy crops.

Crop	Energy content	
	Bio-ethanol (GJ/ton fresh weight crop)	Biodiesel (GJ/ton fresh weight crop)
Wheat	10.2[a]	
Maize	10.0[a]	
Sorghum	10.0[a]	
Sugar beet	2.6[a]	
Sugarcane	2.3[a]	
Soybean	–	6.4[a]
Rapeseed	–	11.7[a]
Oil Palm fruit	–	16.3[b]
Jatropha	–	12.8[a]

[a] Gerbens-Leenes et al. (2009a).
[b] Calculated in this study.

3.2.5. Step 5: determine blue water availability and other uses

Internal renewable fresh water resources (IRWR in km^3/year) indicate the amount of surface runoff and groundwater recharge generated within a country. The volume of blue water available for humans (WA_{blue}) is equal to the IRWR minus the so-called 'environmental flow requirements' (EFR). Flows entering a country from neighbouring countries are external renewable water resources, ERWR. To calculate volumes of blue water available for blue biofuel WFs, we made a supply and demand balance for the ten main producing countries using data from AQUASTAT (FAO, 2008). To prevent double counting, we excluded ERWR.

Since the 1970s, the environmental flow science community has put efforts in making standards for environmental flow protection. The recent publication of the 'Ecological Limits of Hydrologic Alteration (ELOHA)', proposed by the leading experts in this field, gives a framework for assessing environmental flow requirements (Poff et al., 2010). The method is not applied for most rivers yet, so that a simplified approach is needed. Recent publications, Richter et al. (2011) and Hoekstra et al. (2011), propose a presumptive standard for EFRs of 80% of runoff. We adopted this precautionary default EFR of 80%, so that 20% of the IRWR is available for human use. We ignored future change in water supply and derived long-term average IRWR data from AQUASTAT, assuming that these will not change significantly in the coming years.

Research in the beginning of the 21st century has shown that climate change will lead to shifts in the spatial and temporal patterns of precipitation (IPCC, 2001; Lehner et al., 2001). The absolute numbers and locations of people affected by climate change and climate policy vary considerably between climate model patterns, however. Recently, Arnell et al. (2011) have shown that by the 2050s, a 'Mitigation scenario' avoids between 16% and 30% of the change in runoff under a 'Reference scenario'. However, at the same time, the Mitigation scenario also reduces the positive impacts of climate change on water scarcity in other areas. Sulser et al. (2010) show that climate change causes irrigation water demand increase. We recognise that climate change may lead to shifts in global precipitation patterns, affecting the IRWRs, but this fell outside the scope of this research.

To put results in a context, we compared the estimated blue WF of biofuels with water withdrawals of industry, households and agriculture. We obtained data from AQUASTAT. Future changes in blue water withdrawals are incorporated in this study based on Alcamo et al. (2003). That study has estimated water withdrawals by all sectors for 200 countries in 2025, 2055 and 2075 based on changes in population, economy and technology according to the A2 and B2 IPCC scenarios (IPCC, 2000). The B2 scenario emphasises environmental values and assumes substantially lower emissions in the future, which matches the intentions behind the Alternative Policy Scenario. Climate change was also considered in their numbers (reflected in irrigation requirements), using two different climate models (HadCM3 and ECHAM4). The HadCM3 climate model results in a slightly higher total global irrigation requirement, but regional differences are not very large. We adopted the results from the B2 scenario and the HadCM3 model combination. Linear interpolation between 2025 and 2055 is done to determine the expected water withdrawals for 2030.

3.2.6. Step 6: determine blue water scarcity

For road transport, we explored water scarcity for the ten main bio-ethanol and biodiesel producing countries. We limited the study to scarcity of blue water resources because knowledge about green water demands in other sectors (e.g. related to green urban or industrial areas, or to forestry) and in the environment is poor. The evaluation of blue water scarcity creates awareness and can help to make an informed choice about changes in the energy system that have an impact on water resources. We included the contribution of the blue biofuel WF in country z in the blue water withdrawals in the other sectors (i.e. industry, domestic and agriculture) and compared the withdrawals with available internal renewable blue water and environmental flows. We recognise that the estimated blue WF of biofuels will be smaller than the total water withdrawal that will be necessary (because the blue WF measures consumptive water use, which is generally smaller than the total water withdrawal due to return flows). Therefore, adding the blue WF of biofuels to the water withdrawals for other purposes underestimates the increase in water withdrawals.

4. Results

4.1. Biofuel consumption

In 2005, bio-ethanol contributed 5% to the total bioenergy production and biodiesel 1% (IEA, 2006). In 2030 under the IEA APS scenario, bio-ethanol contributes 7% and biodiesel 3% to total bioenergy demand, increasing the relative share of biodiesel. Figs. 3 and 4 show the ten countries with the largest bio-ethanol and biodiesel consumption in 2030.

In North America, the USA is the largest consumer of bio-ethanol (1500 PJ) and biodiesel (250 PJ). In Europe, Germany (225 PJ), Italy (215 PJ), France (170 PJ) and the United Kingdom (150 PJ) consume most bio-ethanol; France (180 PJ), Italy (120 PJ), Germany (110 PJ), Spain (90 PJ) and the United Kingdom (85 PJ) the most biodiesel. Countries in the Pacific region just fall outside the top-ten for both fuels. In Asia, China has the largest bio-ethanol demand (360 PJ); Malaysia (350 PJ) has the largest demand for biodiesel. The Middle East consumes little biofuels. In Africa, most bio-ethanol is consumed by South Africa (150 PJ). In Latin America, Brazil, the world's second bio-ethanol consumer (820 PJ), also shows a large consumption of biodiesel (140 PJ). For the production of biodiesel, North and South America and Asia use predominantly soybean; Europe, the Former USSR and Australia mainly rapeseed. In the dryer regions, jatropha is commonly used and around the equator ($\pm 15^{\circ}$) oil palm. For bio-ethanol, Latin America, Africa and Asia use sugar cane, Europe and the former USSR mainly sugar beet and wheat, North America and the Pacific region maize.

4.2. The biofuel water footprint

Larger biofuel consumption causes increasing WFs. Figs. 5 and 6 display the change in annual green and blue WFs for bio-ethanol and biodiesel per region between 2005 and 2030 under the IEA APS scenario.

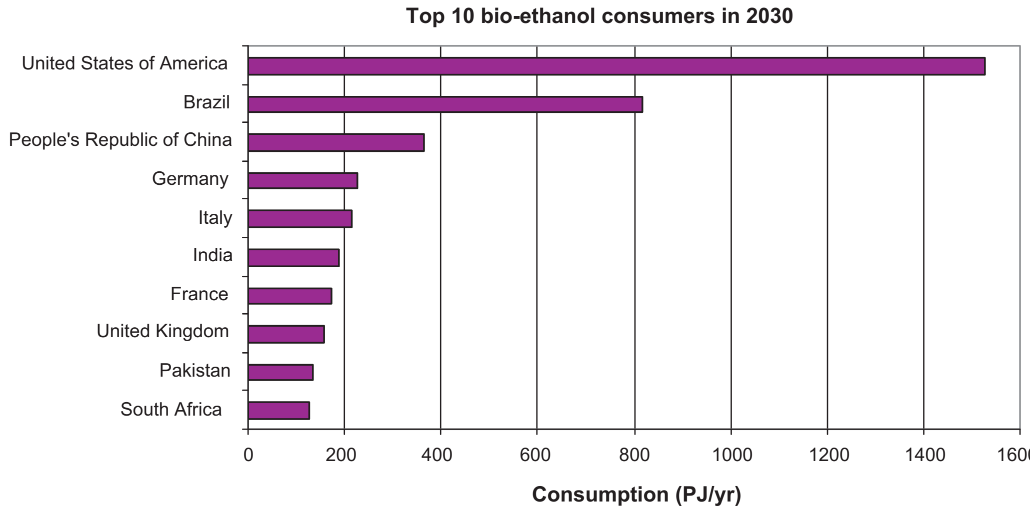

Fig. 3. Top-ten of bio-ethanol consumers in 2030 under the IEA APS scenario.

In all regions, the WF increase is a combined effect of the growth of the transport sector and the greater biofuel share in transport fuels. The WF of biodiesel consumption is largest in Europe, the WF of bio-ethanol in North America. The order of regions according to their WF size is equivalent to their ranking in biofuel consumption. However, some interesting differences appear when comparing the relative sizes of biofuel consumption and WF. For example, in 2030 biodiesel consumption in Europe and North America constitute approximately 42% and 13% of the world total consumption. Corresponding WFs, however, represent 31% and 23% of the world total biodiesel WF. In other words, the biodiesel WF of North America is relatively large compared to the European one. Other differences are the relative magnitudes of the green and blue WFs in each region.

The production of crops for biodiesel in Latin America, the Middle East and Africa depends greatly on blue water and relatively little on green water. Fig. 6 shows that Developing Asia, Africa, the former USSR and Balkans depend relatively strongly on blue water for bio-ethanol crops. Globally, under the IEA APS scenario, the blue biofuels WF represent 48% (466 km^3/year) of the total biofuel WF in 2030 (968 km^3/year). In 2005 its share was 45% (42 km^3/year) of the total WF (93 km^3/year).

Fig. 7 gives the top-ten country ranking according to the annual blue biofuel WF in 2030 under the IEA APS scenario. It shows, for example, that China and France have relatively large blue biodiesel WFs. Fig. 8 shows the top-ten green biofuel WFs in 2030.

Some countries depend more on blue water and others on green. For both blue and green biofuel WFs, the USA, China and Brazil have the largest WFs. In 2030, they account for half the global biofuel WF. The crop types for biofuel, in combination with different growing conditions, cause differences in annual biofuel WFs. The USA uses soybean for biodiesel, Europe rapeseed. The WF (in m^3/GJ) of biodiesel from USA soybean is much larger than that of European rapeseed, because it requires relatively large amounts of irrigation in combination with smaller biodiesel yields per unit of crop.

4.3. Biofuels and blue water scarcity

The increase of biofuel use for transport has consequences for national water resources. Globally, under the IEA APS scenario, we expect the blue biofuel WF to rise from 0.5% of the available blue water in 2005 to 5.5% in 2030. Fig. 9 puts the projected blue WFs of biofuels for the four largest biofuel consuming countries – India,

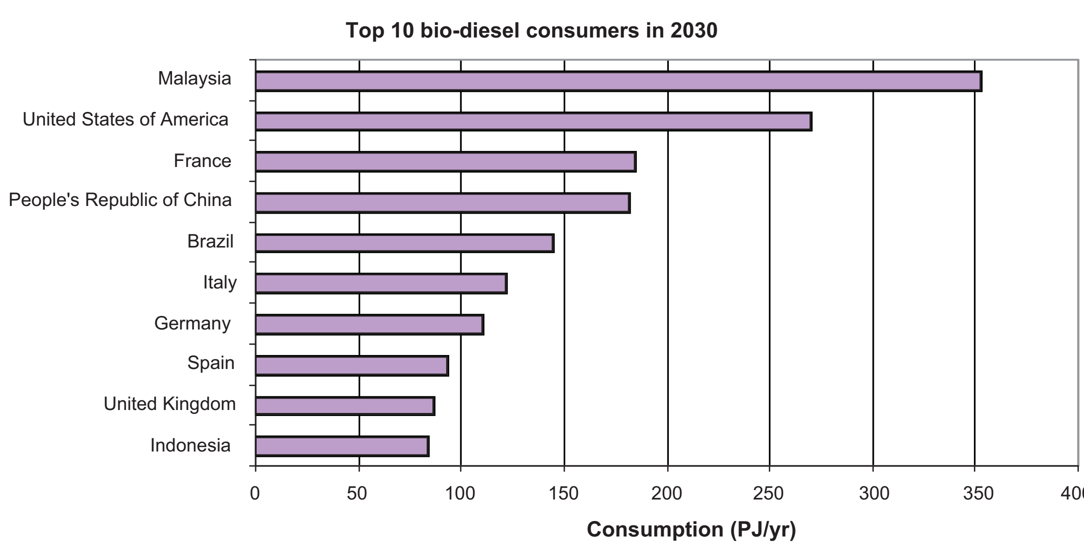

Fig. 4. Top-ten of biodiesel consumers in 2030 under the IEA APS scenario.

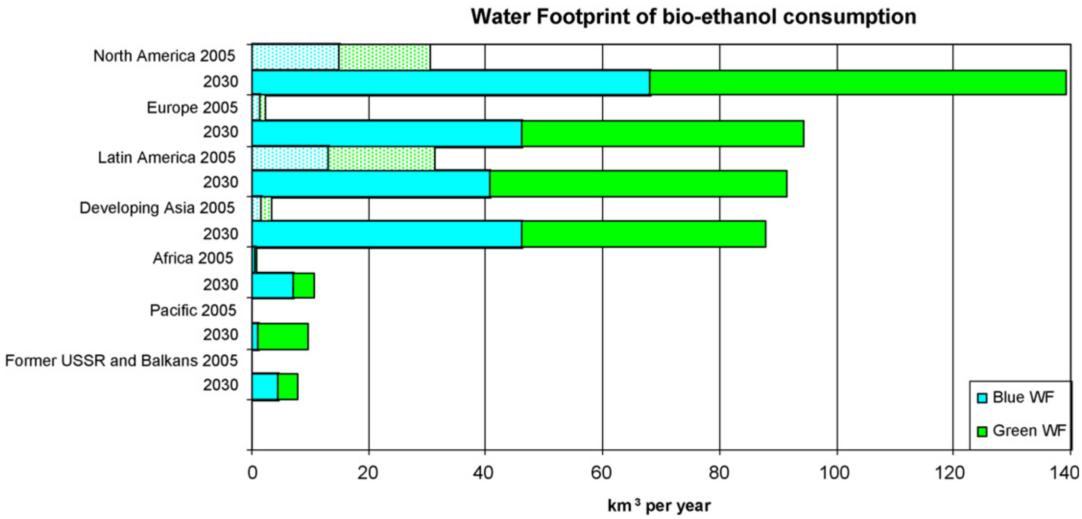

Fig. 5. Change in water footprint of bio-ethanol consumption in road transport between 2005 and 2030 under the IEA APS scenario.

the USA, China and Brazil – in the context of blue water availability and blue water withdrawals for other purposes.

Available internal renewable blue water is largest in Brazil. Here, the withdrawals in 2030 are much smaller than available water. China has less available water than Brazil, while withdrawals are larger. In 2030, withdrawals exceed available water, mainly withdrawals for agriculture (without biofuels), households and industry. Withdrawals for biofuels are relatively small. In the

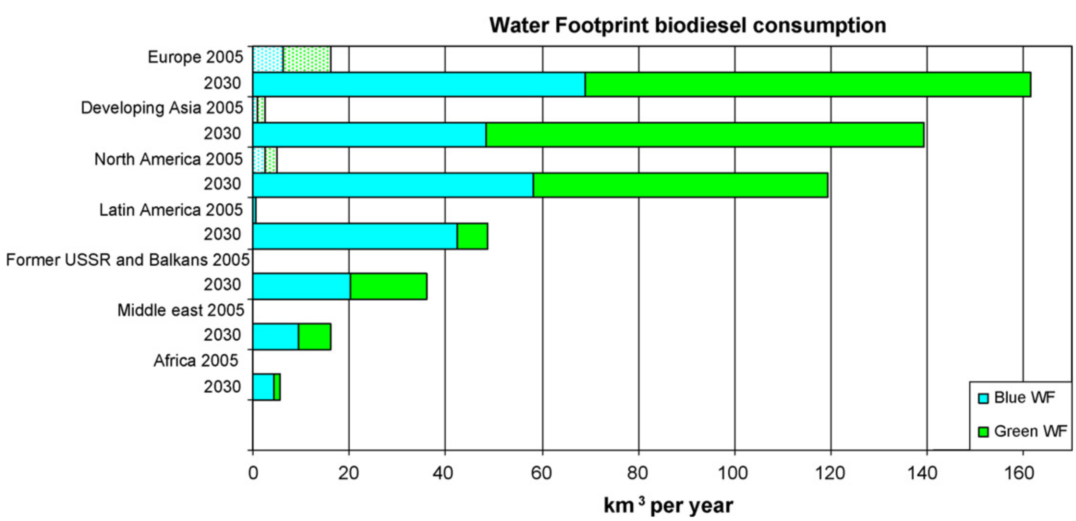

Fig. 6. Change in water footprint of biodiesel consumption in road transport between 2005 and 2030 under the IEA APS scenario.

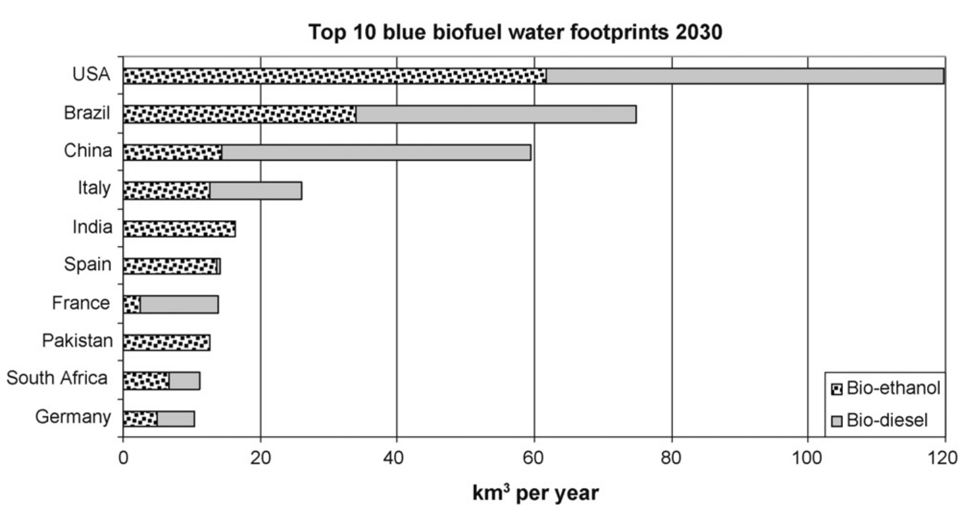

Fig. 7. Ranking of countries according to their annual blue biofuel water footprint in 2030 under the IEA APS scenario.

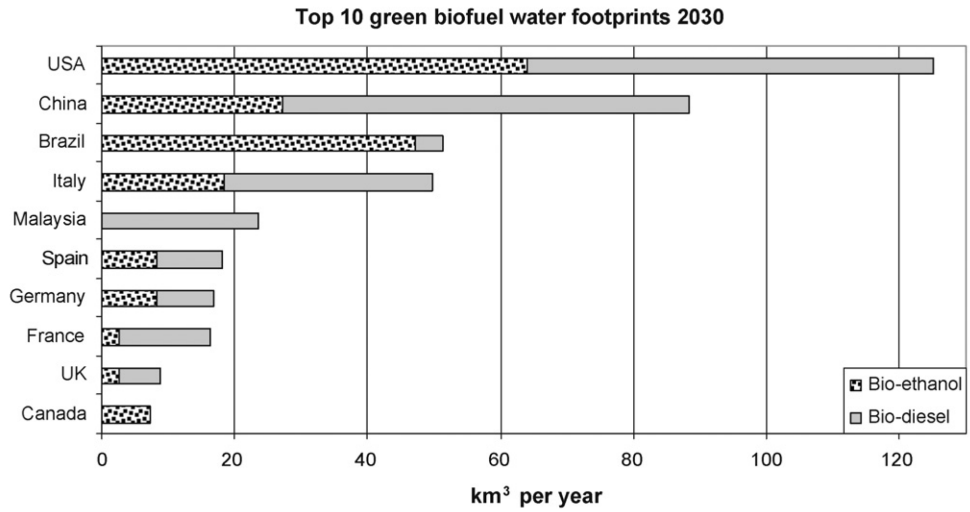

Fig. 8. Ranking of countries according to their annual green biofuel water footprint in 2030 under the IEA APS scenario.

USA, withdrawals are dominated by industry and agriculture (without biofuels), withdrawals for households are relatively small. In 2030, the USA withdraws all its available water. In India, withdrawals are dominated by agricultural water, water for biofuels is small. Water withdrawals in the country exceed available resources by far.

Fig. 10 shows a comparison between national blue water demands and availability in 2030 for the top six largest biofuel consuming countries after the USA, China, Brazil and India. These countries are: South Africa, Pakistan, Germany, Spain, France and Italy.

All six countries have withdrawals that exceed available water resources and use environmental flows. Especially withdrawals in Pakistan are large and are mainly dominated by agriculture. Blue water demands will likely exceed the available internal blue water resources by about 28 times, causing a high degree of water scarcity. Pakistan uses more water than internally available, applying external renewable water resources that were excluded in this study to prevent double counting. However, the WF of biofuels contributes only 4% to total water demand. All countries, except Pakistan, have a substantial water withdrawal for biofuels contributing to overextraction. In Europe, especially in Italy, France, Spain and Germany, the biofuel WF will contribute significantly to water scarcity, but also in South Africa the biofuel WF will take a large share.

5. Discussion

5.1. Scenarios

We based our results on compiled scenario data, with the APS (IEA, 2006) as the base scenario, which we supplemented by similar region-specific scenarios and extrapolated historic data. The fact remains that these results are merely based on a particular view of the future. Although this is a reasonable, established projection, it does not mean that the future will actually unfold this way. These results should merely be used to get an idea of what the consequences might be if we will follow the storyline of the scenarios. It should also be noted that the scenarios we used in this research reflect an average biofuel transition. The biomass amounts projected in the scenarios, however, are very similar across different scenarios. For example, the IEA gives 69 EJ for biomass used in 2030 in the reference scenario and 71 EJ for the APS; for Shell, the average of the Scramble and Blueprints scenario is 75.5 EJ; the WEC gives values of 57, 77, 102, 59 and 65 (average 74 EJ). Greenpeace gives an average for 2030 of 74.5 of the

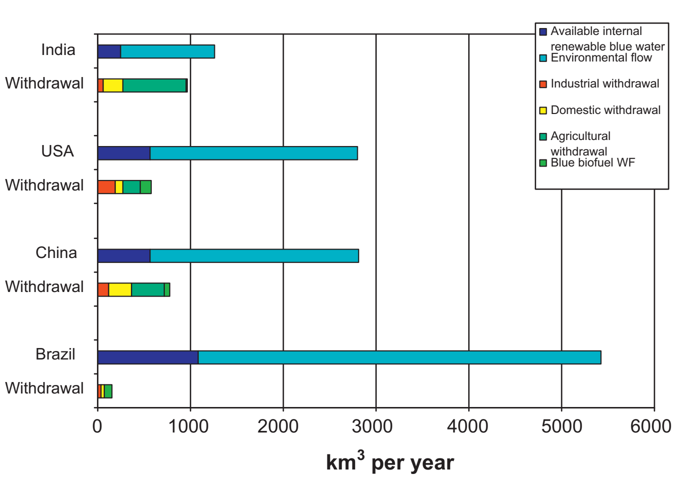

Fig. 9. Comparison of blue water demands under the IEA APS scenario and available internal renewable blue water resources in the four largest biofuel consuming countries.

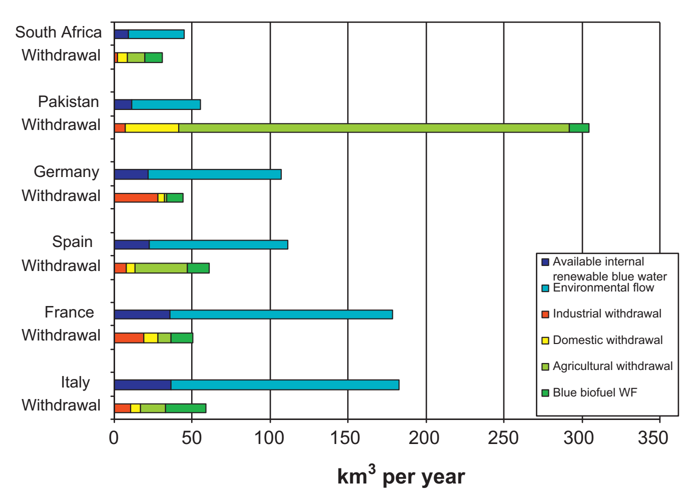

Fig. 10. Comparison of blue water demands under the IEA APS scenario and available internal renewable blue water resources in South Africa, Pakistan, Germany, Spain, France and Italy.

reference (66) and revolution scenario (83). The average of the IPCC A1 (85) and B2 (61) is also 73 EJ. The greenest scenarios, e.g. the Greenpeace revolution scenario (Greenpeace, 2008) and EREC AIP (104 EJ) (EREC, 2007), are 'greener' and project a larger contribution of biofuels. In the Greenpeace scenario, the blue biofuel WF in 2030 is 17% larger than the 2030 biofuel WF as projected in this study for the IEA APS scenario. In the EREC AIP scenario, this it would be 46% larger, while the Shell blueprints scenario would result in a 17% smaller water footprint.

The same goes for the data we used for the water balances. Future water withdrawals are based on one particular scenario and model, and although obtained from a reliable, renowned source (Alcamo et al., 2003), they remain just one interpretation of the future. Furthermore, no account is taken of possible changes in temperature and precipitation due to climate change. Another point for discussion is the assumption that the blue water used for agriculture as taken from Alcamo et al. (2003) is solely applied for the production of crops for food, feed and seed. According to the FAO food balance sheets, the quantity of crop used for other purposes besides food, feed and seed (e.g. biofuels) is relatively small. In the USA, for example, the amount of maize used for other purposes, mainly bio-ethanol, constitutes only 3% of the total domestic maize production (FAO, 2009b). We assumed that the agricultural water demand projections for 2030 based on Alcamo et al. (2003) exclude the increase of water use in agriculture for producing biofuels.

Internationally, there is a growing awareness of the sustainability issues related to the increased use of biofuels. For example, the European Union outlined sustainability criteria for biofuels in the European Renewable Energy Directive (European Parliament and the council of the European Union, 2009). These criteria now enter into national laws. The criteria, however, focus on nature protection and on greenhouse gas savings and exclude water. Water is mentioned in the Dutch Cramer criteria for biofuels that state that competition for water should be avoided and include an indicator that aims to improve the quantity and quality of surface and groundwater (Cramer, 2007). Industry in the Netherlands has recently adopted these criteria. Water footprint research has recently formulated criteria for the sustainable use of freshwater that are related to the geographic context and the characteristics of the production process itself (Hoekstra et al., 2011). A WF is unsustainable when the process is located in a so termed hotspot, a catchment where during a certain period of the year the total WF is unsustainable. For the evaluation of hotspots, it is assumed that environmental flow requirements are 80% of available water. When more water is withdrawn, this will affect nature. Agriculture can reduce green WFs by increasing the land productivity, blue WFs can be reduced by more efficient irrigation or the selection of other crops. We have shown the large differences in WFs among countries and among crops. Taking the water sustainability criteria into account might have an effect on the likelihood of the dominant energy scenarios being realised.

5.2. Use of average data

Spatial and temporal variability in water supply are not reflected in the water availability data. We used annual and country-average supply and demand data. Generally, both water demand and availability vary strongly throughout the year, with demands often greatest when availability is smallest, which means that the full potential of available fresh water cannot be used. Besides, water demand and availability patterns generally vary within countries, which can lead to mismatches that do not show in aggregated country comparisons. Furthermore, we only considered the water resources generated within a country, not the external flows. For these reasons, actual water availability in a particular country, e.g. in Pakistan, may deviate from the figures presented in this study.

5.3. Environmental flow requirements

The statements about blue water scarcity are very sensitive to the amount of flow allocated to the environment. We assumed a precautionary default EFR of 80% of IRWR for all countries, representing a threshold for potential concern. The actual EFR in a country may deviate. A further limitation is that we did not analyse green water scarcity. It is yet difficult to estimate green EFR (Hoekstra et al., 2011) and projections of future green water demands by other sectors are not available. It should nonetheless be realised that the green WF of biofuels would also have a significant impact on future water allocations. Moreover, we excluded the grey biofuel WF, i.e. the amount of water needed to assimilate pollution to an accepted standard. The reason is that the available data were not satisfactory for global coverage. Gerbens-Leenes et al. (2009c) have calculated the grey bio-ethanol WF on a smaller scale and found that the grey WF constitutes a minor part of the total WF, on average about 10%. Thus, the biofuel WF could be about 10% greater than presented in this study.

5.4. Assumptions and uncertainties

The study has been based on the assumption that agricultural yields and water footprints of crops in m^3/kg remain constant. This is not necessarily true. On the one hand, the necessary expansion of agricultural lands may result in a move into marginal lands with lower yield potential, but on the other hand, over a period of 25 years, yields may increase as a result of improving farming practices. Further, in assessing water footprints it was assumed that crop water requirements are always met, which is not necessarily the case and therefore gives an overestimate of water consumption, in particular blue water consumption. The results from this study could be improved by considering actual irrigation patterns and estimates at a higher spatial resolution as was recently shown by Mekonnen and Hoekstra (2010, 2011). Further, we did not take changes in crop choice into account. Changes in crop choice, new crop varieties or new agricultural technology may make it possible to get the same yields with less irrigation, or higher yields using the same amount of water. Switching to more water-efficient crops will also have an effect on the WF. For example, the blue WF of biodiesel from soybean in the US is about 200 m^3/GJ, the blue WF of biodiesel from rapeseed in Germany only 50 m^3/GJ.

The study has assumed that all biofuels derive from first-generation biofuels, which are based on the starch, sugar or oil fraction in the crop. Water footprints of second-generation crops, which are based on the cellulosic fraction of crops or other biomass, are much lower then the water footprints of first-generation biofuels (Gerbens-Leenes et al., 2009a). Depending on the speed with which second-generation biofuels will become economically feasible and replace first-generation biofuels, this will lower the total WF related to biofuels. Moreover, countries may choose to use waste oils, fish oils or algae to produce biodiesel, produce biogas, or apply electricity from wind or sun for transport. These developments will all have an effect on the annual WF of biofuels.

Finally, the research explores a self-sufficiency scenario regarding biofuels. A recent IPCC report shows that at present international trade in biofuels is still small, about 6–9% of total biofuels (IPCC, 2011). When countries start importing, they generate an external WF. The size depends on the production circumstances in the exporting countries. Only Brazil has sufficient available water resources to meet its targets for 2030. The other three large producers, the USA, India and China all suffer water shortages. In the top-ten of large biofuel producers, Pakistan shows extreme water stress. Italy and France have sufficient water, if no biofuels are grown. South Africa, Spain and Germany even have water shortage without biofuel production (although the picture for Germany is a bit distorted by the exclusion of external water resources in the estimate of water availability). In South Africa the greatest withdrawals are for agriculture, including biofuels, in Spain for agriculture and in Germany for industry. This could indicate that it is unlikely that these countries will produce their own biofuels, as we principally assumed. In this way, we show that water forms a constraint for the leading energy scenarios and that the biomass needs to be produced in the water abundant countries, e.g. in Canada, Russia or in Brazil.

6. Conclusions

Energy scenarios project an increase in biofuel consumption in the future. The APS scenario of the IEA shows a biomass energy use of 71 EJ in 2030, compared to 69 EJ for the IEA reference scenario. In 2030, under the IEA APS scenario, bio-ethanol contributes to 7% and biodiesel to 3% of total bioenergy demand, increasing the relative share of biodiesel. Europe and North America continue to play an important role, but towards 2030 Developing Asia catches up and becomes the second largest biodiesel consumer in the world. The ten countries that contribute most to global biodiesel consumption in 2030 are: Malaysia, the USA, France, China, Brazil, Italy, Germany, Spain, the UK and Indonesia. The ten countries that will consume most bio-ethanol are: the USA, Brazil, China, Germany, Italy, India, France, the UK, Pakistan and South Africa.

The transition to biofuels requires the production of more crops. Depending on the location, countries chose different crops. For biodiesel, North America and northern Asia predominantly grow soybean. In the tropical regions of Latin America and southern Asia, farmers grow palm oil; in Europe, the former USSR and Balkans and the Pacific region rapeseed. In the dryer regions, farmers commonly choose jatropha. For bio-ethanol, farmers in Latin America, Africa and Asia often use sugar cane; in Europe and the former USSR mainly sugar beet and wheat, and in North America and the Pacific region maize.

The production of crops for bioenergy involves large fresh water demands. Crops use precipitation stored in the soil (green water) and irrigation water (blue water). Depending on the location and growing conditions, the crop water requirements and yields vary significantly, resulting in different biofuel WFs per country.

Overall, the transition to biofuels will lead to a larger WF for the global transport sector. Under the IEA APS scenario, it is expected that the global annual biofuel WF will increase more than tenfold, from about 90 km^3/year in 2005 to 970 km^3/year in 2030. In 2030, the USA, China and Brazil contribute most, together half of the global biofuel WF. These findings are derived from the no-trade assumption. When countries start importing, they generate an external WF. The size depends on the production circumstances in the exporting countries. Under the IEA APS scenario, the blue biofuel WF is expected to represent 48% of the total biofuel WF in 2030. On a global level, the blue biofuel WF is expected to grow to 5.5% of the total available blue water for humans in 2030, thus causing extra pressure on our fresh water resources.

Several studies have analysed biofuel scenarios in the context of land availability, food production, biodiversity and the carbon dioxide balance. We have looked at the scenarios for 2030, when bioenergy use is still relatively small compared to 2100, from a water perspective. We show the repercussion of extensive biofuel consumption on our fresh water resources and advocate that countries should consider the water factor thoroughly when investigating the extent to which biofuels can satisfy the future energy demand in the transport sector. Energy transitions will only improve our standards of living and productivity if all impacts are taken into account.

References

Alcamo, J., Märker, M., Flörke, M., Vassolo, S., 2003. Water and climate: a global perspective. Center for Environmental Systems Research (CESR), University of Kassel. Germany. www.usf.uni-kassel.de/watclim/.

Arnell, N.W., Van Vuuren, D.P., Isaac, M., 2011. The implications of climate policy for the impacts of climate change on global water resources. Global Environmental Change 21 (2), 592–603.

BBN, 2008. Minister Estonia could produce biofuel from grain. Article by S. Taimre. www.balticbusinessnews.com/Default2.aspx?ArticleID=354d71d0-e15b-4dc9-832e-85437ad84623.

Berndes, G., 2002. Bioenergy and water: the implications of large-scale bioenergy production for water use and supply. Global Environmental Change 12 (4), 253–271.

Berndes, G., Hoogwijk, M., Van den Broek, R., 2003. The contribution of biomass in the future global energy supply: a review of 17 studies. Biomass and Bioenergy 25 (1), 1–28.

Biofuels International, 2007. Driving the market forward Biofuels International 4 (1).

Biofuels Platform, 2009. Situation of biofuels in Switzerland. ENERS Energy Concept Lausanne. www.biofuels-platform.ch/en/infos/ch-situation.php.

BioWanze, 2008. Grondstoffen. www.biowanze.be/nl/Grondstoffen/.

Bora, P.S., Rocha, R.V.M., Narain, N., Moreira-Monteiro, A.C., Moreira, R.A., 2003. Characterisation of principal nutritional components of Brazilian oil palm (*Eliaes guineensis*) fruits. Bioresource Technology 87 (1), 1–5.

Breyerová, P., 2007. Czech biofuel provision in effect. Renewable Development Initiative. European Bank for Reconstruction and Development (EBRD), www.ebrdrenewables.com/sites/renew/Lists/EBRD%20Master%20Spreadsheet/DispForm.aspx?ID=731.

Capros, P., Mantzos, L., Papandreou, V., Tasios, N., 2008. Model-based analysis of the 2008. EU policy package on climate change and renewables. June 2008. Report to the European Commission–DG ENV.

Chapagain, A.K., Hoekstra, A.Y., 2004. Water footprints of Nations. Value of Water Research Report Series No. 16. UNESCO-IHE. Delft.

Chapagain, A.K., Hoekstra, A.Y., 2007. The water footprint of coffee and tea consumption in The Netherlands. Ecological Economics 64 (1), 109–118.

Chapagain, A.K., Orr, S., 2009. An improved water footprint methodology linking global consumption to local water resources: A case of Spanish tomatoes. Journal of Environmental Management 90, 1219–1228 (2009).

Chiu, Y.W., Walseth, B., Suh, S., 2009. Water embodied in bioethanol in the United States. Environmental Science & Technology 43 (8), 2688–2692.

Cramer, J., 2007. Toetsingskader voor duurzame biomassa. Eindrapport van de projectgroep Duurzame productie van biomassa in opdracht van de Interdepartementale Programma Directie Energietransitie. Rijksoverheid 414066MEZ-brochure.indd. (Criteria for sustainable biomass. Final report of the projectgroup Sustainable production of biomass. Dutch government Brochure 414066MEZ).

De Fraiture, C., Giordano, M., Yongsong, L., 2008. Biofuels and implications for agricultural water use: blue impacts of green energy. Water Policy 1 (Suppl. (10)), 67–81.

Dornburg, V., Faaij, A., Verweij, P., Langeveld, H., Van de Ven, G., Wester, F., Van Keulen, H., Van Diepen, K., Meeusen, M., Banse, M., Ros, J., Van Vuuren, D., Van den Born, G.J., Van Oorschot, M., Smout, F., Van Vliet, J., Aiking, H., Londo, M., Mozaffarian, H., Smekens, K., 2008. Assessment of global biomass potentials and their links to food, water, biodiversity, energy demand and economy. Main Report. WAB Climate Change.

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 & Technology 43 (9), 3005–3010.

Dufey, A., 2006. Biofuels Production, Trade, and Sustainable Development: Emerging Issues September 2006. Environmental Economics Programme/Sustainable Markets Group, London.

EmBio, 2008. Company website of Emirates Biodiesel LLC.UAE.

ENERO, 2005. Strategies for increased biofuels use in Romania. Bio-East Project. July 2005.

Ercin, A.E., Aldaya, M.M., Hoekstra, A.Y., 2011. Corporate water footprint accounting and impact assessment: The case of the water footprint of a sugar-containing carbonated beverage. Water Resources Management 25 (2), 721–741.

European Commission, Renewable Energies, 2009. http://ec.europa.eu/energy/renewables/index_en.htm, accessed January 5 2010.

European Environment Agency, 2010. The European environment–state and outlook 2010.

European Parliament and the council of the European Union, 2009. Directive 2009/28/EC of the European Parliament and of the council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending a subsequently repealing Directives 2001/77/EC and 2003/30/EC.

European Renewable Energy Council (EREC), 2007. Renewable energy scenarios to 2040. EREC Brussels.

Eurostat, 2009. European energy statistics. http://epp.eurostat.ec.europa.eu/portal/page/portal/energy/data/database.

Fader, M., Gerten, D., Thammer, M., Heinke, J., Lotze-Campen, H., Lucht, W., Cramer, W., 2011. Internal and external green-blue agricultural water footprints of

nations, and related water and land savings through trade. Hydrology and Earth System Sciences 15 (5), 1641–1660.
FAO, 2008. Aquastat: information system on water and agriculture Food and Agriculture Organisation, Rome, www. fao. org/nr/water/aquastat/main/index. stm.
FAO, 2009a. FAOSTAT food balance sheets. Food and Agriculture Organisation, Rome, http://faostat.fao.org/site/368/default.aspx.
FAO, 2009b. FAOSTAT forestry database – ForestSTAT. Food and Agriculture Organisation, Rome, http://faostat.fao.org/site/626/default.aspx#ancor.
FAO, 2009c. Agro-MAPS: global spatial database of agricultural land-use statistics, version 2.5. Food and Agriculture Organisation, Rome, www.fao.org/landandwater/agll/agromaps/interactive/page.jspx.
FAO, 2009d. CLIMWAT 2.0 database, Food and Agriculture Organisation, Rome, www.fao.org/nr/water/infores_databases_climwat.html.
FAO, 2009e. FAOSTAT-Food and agriculture database. Food and Agriculture Organisation, Rome, http://faostat.fao.org/site/567/default.aspx#ancor.
Feng, K., Hubacek, K., Minx, J., Siu, Y.L., Chapagain, A., Yu, Y., Guan, D., Barrett, J., 2011. Spatially explicit analysis of water footprints in the UK. Water 3 (1), 47–63.
Fischer, G., Schrattenholzer, L., 2001. Global bioenergy potentials through 2050. Biomass and Bioenergy 20 (3), 151–159.
Fischer, G., Hizsnyik, E., Prieler, S., Shah, M., Van Velthuizen, H., 2009. Biofuels and Food Security. International Institute for Applied Systems Analysis, Laxenburg, Austria.
Galli, A., Wiedman, T., Ercin, E., Knoblauch, D., Ewing, B., Giljum, S., 2011. Integrating ecological, carbon and water footprint into a Footprint Family of indicators: definition and role in tracking human pressure on the planet. Ecological Indicators, http://dx.doi.org/10.1016/j.ecolind.2011.06.017.
Gerbens-Leenes, P.W., Hoekstra, A.Y., Van der Meer, Th.H., 2008. The water footprint of bioenergy: global water use for bio-ethanol, biodiesel, heat and electricity. Value of Water Research Report Series No. 34. UNESCO-IHE. Delft.
Gerbens-Leenes, P.W., Hoekstra, A.Y., Van der Meer, Th.H., 2009a. The water footprint of bioenergy. Proceedings of the National Academy of Science 106 (25), 10219–10223.
Gerbens-Leenes, P.W., Hoekstra, A.Y., Van der Meer, Th.H., 2009b. The water footprint of energy from biomass: a quantitative assessment and consequences of an increasing share of bioenergy in energy supply. Ecological Economics 68 (4), 1052–1060.
Gerbens-Leenes, P.W., Hoekstra, A.Y., Scholten, W., 2009c. The water footprint of sweeteners and bio-ethanol from sugar cane, sugar beet and maize. Value of Water Research Report Series No. 38. UNESCO-IHE. Delft.
Gerbens-Leenes, P.W., Hoekstra, A.Y., 2011. The water footprint of biofuel-based transport. Energy & Environmental Science 4, 2658–2668.
Gerritsma, W., Wessel, M., 1997. Oil palm: domestication achieved? Netherlands Journal of Agricultural Science 45, 463–475.
Greenpeace, 2008. Energy revolution – a sustainable global energy outlook. Greenpeace International and EREC.
Hoekstra, A.Y., 2003.In: Virtual water trade: Proceedings of the International Expert Meeting on Virtual Water Trade Value of Water Research Report Series No.12 IHE Delft The Netherlands, Delft, The Netherlands 12–13 December 2002.
Hoekstra, A.Y., Chapagain, A.K., 2008. Globalisation of water. Sharing the Planet's Freshwater Resources. Blackwell Publishing, UK.
Hoekstra, A.Y., Chapagain, A.K., Aldaya, M.M., Mekonnen, M.M., 2011. The water footprint assessment manual setting the global standard. Earthscan, London.
Hoogwijk, M., Faaij, A., Van den Broek, R., Berndes, G., Gielen, D., Turkenburg, W., 2003. Exploration of the ranges of the global potential of biomass for energy. Biomass and Bioenergy 25 (2), 119–133.
Içöz, E., Tuğrul, K.M., Saral, A., İçöz, E, 2008. Research on ethanol production and use from sugar beet in Turkey. Ankara University Agricultural Faculties and Turkish Sugar Factories Corporation. Ankara.
IEA (International Energy Agency), 2004. Biofuels for transport—an International Perspective. OECD/IEA. Paris.
IEA, 2006. World energy outlook 2006. OECD/IEA. Paris.
IPCC, (Intergovernmental Panel on Climate Change), 2000. IPCC special report emissions scenarios – Summary for policymakers. IPCC Working Group III. Geneva.
IPCC, (Intergovernmental Panel on Climate Change), 2001. Climate Change 2001: Impacts, Adaptation, and Vulnerability – A Report of Working Group II of the IPCC.
IPCC, (Intergovernmental Panel on Climate Change), 2008a. Climate change and water. IPCC Technical Paper VI. Chapter 5. Analysing regional aspects of climate change and water resources, pp 77-115. June 2008. IPCC Working Group II. Geneva.
IPCC, (Intergovernmental Panel on Climate Change), 2008b. Proceedings of IPCC scoping meeting on renewable energy sources. IPCC Working Group III. Geneva.
IPCC, (Intergovernmental Panel on Climate Change), 2011. IPCC special report on renewable energy sources and climate change mitigation, pp 28. IPCC Working Group III. Geneva.
Kautola H., Cárdenas P., Kymäläinen M., Tokeensuu L., Alatalo T., Siukola K., Näsi J. Bioethanol from different Finnish agricultural carbon sources. Collaborative research from the HAMK University of Applied Sciences, Universidad Central del Ecuador, and Suomen Biojalostus Oy, in press.
Kleindorfer, P.R., Öktem, Ü.G., 2007. Economic and Business Challenges for Biodiesel Production in Turkey. Wharton School of University of Pennsylvania, USA.
Konrad, A., 2006. Bioethanol production for fuel use in Austria. Research Institute for Managing Sustainability – on behalf of the Austrian Ministry of Agriculture, Forestry, Environment and Water Management.
Lehner, B., Henrichs, T., Döll, P., Alcamo, J., 2001. EuroWasser. Model-based assessment of European water resources and hydrology in the face of global change. Kassel World Water Series 5. Center for Environmental Systems Research. University of Kassel, Kurt-Wolters-Strasse 3, 34109 Kassel, Germany.
Lienden van, A.R., Gerbens-Leenes, P.W., Hoekstra, A.Y., Van der Meer, Th.H., 2008. Biofuel scenarios in a water perspective. The global blue and green water footprint of road transport in 2030. Value of Water Research Report Series No. 43. UNESCO-IHE. Delft.
L'vovich, M.I., White, G.G., 1990. Use and transformation of terrestrial water systems. In: Turner, I.I., Clark, B.L., Kates, W.C., Richards, R.W., Mathews, J.F., Meyer, J.T.W.B. (Eds.), The earth as transformed by human action, global and regional changes in the biosphere over the past 300 years. Cambridge University Press, Cambridge.
Mekonnen, M.M., Hoekstra, A.Y., 2010. The green, blue and grey water footprint of crops and derived crop products, Value of Water Research Report Series No.47, UNESCO-IHE, Delft.
Mekonnen, M.M., Hoekstra, A.Y., 2011. The green, blue and grey water footprint of crops and derived crop products. Hydrology and Earth System Sciences 15 (5), 1577–1600.
Ministry of Agriculture Latvia, 2006. Situation of biofuel in Latvia Presentation by the Ministry of Agriculture, www. agri. ee/public/juurkataloog/BIOENERGEETIKA/Situation%20on%20biofuels%20in%20Latvia%20(Zane%20L%C4%ABde). ppt.
Müllerová, J., Mikulík, M., 2007. Production and utilisation of bio-fuels in conditions of the Slovak Republic. University of Žilina, Žilina.
Nakicenovic, N., Grübler, A., McDonald, A., 1998. Global Energy Perspectives. In: International Institute for Applied Systems Analysis/World Energy Council, Cambridge University press, Cambridge, UK.
NOVEM, 2003. Biofuels in the Dutch market: a fact-finding study. Report number 2GAVE-03.12. November 2003. NOVEM. Utrecht.
NV Consultants, 2007. Renewable energy resource assessment – Slovenia. Renewable Development Initiative. European Bank for Reconstruction and Development (EBRD), www.ebrdrenewables.com/sites/renew/countries/Slovenia/default.aspx#latest.
Pfister, S., Koehler, A., Hellweg, S., 2009. Assessing the environmental impacts of freshwater consumption in LCA. Environmental Science and Technology 43, 4098–4104.
Poku, K., 2002. Small-scale palm oil processing in Africa. FAO Agricultural Services Bulletin, 148. Food and Agriculture Organisation, Rome, www.fao.org/docrep/005/Y4355E/y4355e00.HTM.
Poff, N.L., Richter, B.D., Aarthington, A.H., Bunn, S.E., Naiman, R.J., Kendy, E., Acreman, M., Apse, C., Bledsoe, B.P., Freeman, M.C., Henriksen, J., Jacobson, R.B., Kennen, J.G., Merritt, D.M., O'Keeffe, J.H., Olden, J.D., Rogers, K., Tharme, R.E., Warner, A., 2010. The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. Freshwater Biology 55 (1), 147–170.
Reuters, 2006. Biofuel plants planned in Eastern Europe. Russian Biofuels Association, www.biofuels.ru/bioethanol/news/453/.
Richter, B.D., Davis, M.M., Apse, C., Konrad, C., 2011. A presumptive standard for environmental flow protection. River Research and Applications, http://dx.doi.org/10.1002/rra.1511 wileyonlinelibrary.com.
Romaguera, M., Hoekstra, A.Y., Su, Z., Krol, M.S., Salama, M.S., 2010. Potential of using remote sensing techniques for global assessment of water footprint of crops. Remote Sensing 2 (4), 1177–1196.
SEI, 2004 Liquid biofuels strategy study for Ireland. Report prepared for Sustainable Energy Ireland.
Shell, 2008. Shell energy scenarios to 2050. Shell International BV. The Hague.
Sims, R.E.H., Schock, R.N., Adegbululgbe, A., Fenhann, J., Konstantinaviciute, I., Moomaw, W., Nimir, H.B., Schlamadinger, B., Torres-Martínez, J., Turner, C., Uchiyama, Y., Vuori, S.J.V., Wamukonya, N., Zhang, X., 2007. Energy supply. In: Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A. (Eds.), Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, USA.
Smeets, E.M.W., Faaij, A.P.C., Lewandowski, I.M., Turkenburg, W.C., 2007. A bottom-up assessment and review of global bioenergy potentials to 2050. Progress in Energy and Combustion Science 33 (1), 56–106.
Solsten, E., 1991. Cyprus: A country study. GPO for the Library of Congress. Washington, http://countrystudies.us/cyprus/41.htm.
Sørenson, B., 1991. A history of renewable energy technology. Renewables Series. Butterworth-Heinemann Ltd..
Sulser, T.B., Ringler, C., Zhu, T., Msangi, S., Bryan, E., Rosegrant, M., 2010. Green and blue water accounting in the Ganges and Nile basins: implications for food and agricultural policy. Journal of Hydrology 384, 276–291.
UNESCO, 2006. The state of the resource – chapter 4. 2nd UN World Water Development Report. March 2006. UNESCO/Berghahn Books.
USDA FAS, 2006a. Global agriculture information network reports on bio-fuels. GAIN Report CH6049. Washington DC, www.fas.usda.gov/scriptsw/attacherep/default.asp.
USDA FAS, 2006b. Global agriculture information network reports on bio-fuels. GAIN Report IN6047. Washington DC, www.fas.usda.gov/scriptsw/attacherep/default.asp.
USDA FAS, 2006c. Global agriculture information network reports on bio-fuels. GAIN Report BR6008. Washington DC, www.fas.usda.gov/scriptsw/attacherep/default.asp.

USDA FAS, 2007a. Global agriculture information network reports on bio-fuels. GAIN Report PA7004. Washington DC, www.fas.usda.gov/scriptsw/attacherep/default.asp.
USDA FAS, 2007b. Global agriculture information network reports on bio-fuels. GAIN Report UY8004. Washington DC, www.fas.usda.gov/scriptsw/attacherep/default.asp.
USDA FAS, 2008a. Global agriculture information network reports on bio-fuels. GAIN Report PK8033. Washington DC, www.fas.usda.gov/scriptsw/attacherep/default.asp.
USDA FAS, 2008b. Global agriculture information network reports on bio-fuels. GAIN Report AR8027. Washington DC, www.fas.usda.gov/scriptsw/attacherep/default.asp.
USDA FAS, 2008c Global agriculture information network reports on bio-fuels. GAIN Report HO9006. Washington DC, www.fas.usda.gov/scriptsw/attacherep/default.asp.
USDA FAS, (2009a. Global agriculture information network reports on bio-fuels. GAIN Report MY9026. Washington DC, www.fas.usda.gov/scriptsw/attacherep/default.asp.
USDA FAS, 2009b. Global agriculture information network reports on bio-fuels. GAIN Report RP9019. Washington DC, www.fas.usda.gov/scriptsw/attacherep/default.asp.
US Department of Energy, International Energy Outlook 2010.
Varis, O., 2007. Water demands of bioenergy production. International Journal of Water Resources Development 23 (3), 519–535.
Vassilieva, Y. Corn and manioc starch duties increased. Russian Biofuels Association, www.biofuels.ru/bioethanol/news/corn_and_manioc_starch_duties_increased/, in press.
World Energy Council, 2007. Deciding the future: energy policy scenarios to 2050. World Energy Council, United Kingdom.