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Bioenergy water footprints, comparing first, second and third generation feedstocks for bioenergy supply in 2040

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Abstract: Freshwater is important for energy. Energy scenarios show increasing energy use, combined with increasing bioenergy shares. Bioenergy derives from first (food crops), second (energy crops or agricultural residues) and third (algae) generation feedstocks. There is an ongoing debate about the competition between energy and food crops. Energy crops have no direct competition with food, but an indirect one, using the same natural resources, like water. Crop residues seem a good alternative for food or energy crops. This paper gives water footprints (WFs) of first, second and third generation bioenergy (m³/GJ). Next, it compares WFs of future energy demand using different bioenergy feedstocks. WFs of energy from residues is smallest, WFs of energy crops largest. Bioenergy from algae has the largest blue WF. From a resource-use point of view, impacts of green WFs on the environment are smaller than impacts of blue WFs. Comparing different bioenergy feedstocks, residues are most favorable. With increasing bioenergy production, impacts on freshwater also increase. It is expected that increased production of first generation biofuels heavily contributes to global water scarcity. For third generation bioenergy, the application of algae would substantially increase the global blue WF. Comparing IEA scenarios, the greenest scenarios have the largest WFs, due to large contribution of bioenergy (especially in the case of energy crops and algae). Feedstocks with a relatively small WF are crop residues. The potential is enormous, but large challenges remain concerning technical possibilities to convert residues into energy carriers in combination with the possibility that not all residues are available for bioenergy.

Key words: Water footprint; Bioenergy; First, second and third generation biofeedstocks

1. INTRODUCTION

Freshwater is an important resource to provide energy, especially bioenergy (Gerbens-Leenes et al., 2009; IEA, 2012). The most recent World Energy Outlook energy scenarios show an increase of total energy use, in combination with an increase of the share of renewables, especially of bioenergy (IEA, 2016). The IEA has developed three different energy scenarios for 2040 that all show an increase of total energy demand, but are based on different energy mixes (IEA, 2016). These scenarios are the current policies scenario (annual bioenergy use 77 EJ), the new policies scenario (annual bioenergy use 79 EJ) and the 450 scenario (annual bioenergy use 97 EJ). Bioenergy that derives from biomass needs large amounts of water in agriculture and forestry. Freshwater is a scarce resource, because most of the world’s water is saltwater, only 2.6% is freshwater of which the largest part is stored in ice (Speidel et al., 1988). Agriculture, industry and domestic supply, with different quality standards for freshwater, are the main users. In 2000, agriculture accounted for 70% of total water withdrawals, industry for 20% and domestic withdrawals for 10% (Shiklomanov, 2000). Humans influence surface water distribution, for example by building large dams (Pekel et al., 2016) for hydropower, water storage for irrigation in agriculture, or flood control. The impacts of agriculture on freshwater availability are very large, because that sector uses large amounts of freshwater.

Biomass is a renewable energy feedstock, providing bioenergy carriers, like the biofuels bioethanol or biodiesel that are mainly applied for transportation, but also electricity, when used in a power plant, or heat when burned in a stove. Bioenergy includes the so termed first, second and
third generation bioenergy (Gerbens-Leenes et al., 2014). *First generation bioenergy* is energy from food crops. There is an ongoing debate about the competition between crops for energy and crops for food. *Second generation bioenergy* is energy from either energy crops or from agricultural residues. When energy crops are applied for energy, there is no direct competition with food, but an indirect one over the natural resource input, like water. Crop residues, leftovers from agriculture, seem a good alternative for food or energy crops. *Third generation bioenergy* includes energy from algae. The aim of this paper is to give an overview of water footprints (WFs) of first, second and third generation bioenergy (m³ per GJ) and to show the consequences of a large scale introduction of bioenergy in the global energy system on water resources for 2040. The main research questions are:

- What is the average global consumptive (green, blue and grey) WF of first, second and third generation bioenergy types?
- What is the consumptive WF of the IEA 450 scenario for 2040 for first, second and third generation bioenergy types?

The next section, Section 2, gives the method and data sources applied for the assessment. Section 3 shows the main results. Section 4 provides a discussion on the limitations of the study. Finally, Section 5 concludes summarizing the main findings. This paper is based on earlier research into the WFs of first, second and third generation bioenergy. It compares WFs of different feedstocks from these earlier studies and the consequences for water if these feedstocks are applied on a global scale in the near future.

2. METHOD AND DATA

The six major crops that are relevant for biofuels are sugar cane, maize, cassava, oil palm, rape and soybean (Fischer et al., 2009). These crops use 338 million hectares of agricultural land or 22% of the total cultivated land area. Part of these crops is applied for biofuels, 25 million hectares of agricultural land or 1.6% of the total cultivated land area. Figure 1 shows the production chain of bioenergy. The biomass that forms the input for bioenergy includes food crops, residues from food crops, wood and other crops grown for energy purposes, such as miscanthus. Food crops, such as sugar cane, generate the so termed first generation bioenergy. The residues of food crops are the input for the so termed second generation bioenergy. The energy crops also generate second generation bioenergy. Algae form the input for third generation bioenergy. The bioenergy not only includes the biofuels, such as ethanol and biodiesel, but also electricity and heat.

For the overview of the WF of first, second and third generation bioenergy types, data on WFs of first generation biofuels were derived from Mekonnen and Hoekstra (2010). The most important crops that form the feedstock for bioethanol were included: sugar beet, sugar cane, potato, cassava, maize, barley, rye, paddy rice and wheat, as well as the main crops for biodiesel: palm oil, rapeseed and soybean. For second generation bioenergy, the study included residues from sugar beet, soybean, sugar cane, cassava, maize, wheat, paddy rice and rapeseed, as well as the energy crop miscanthus and the wood types pine and eucalyptus. Data on second generation bioenergy were derived from the study of Mathioudakis et al. (2017) into the WF of second generation bioenergy. The study also includes the WF of firewood. Data were derived from Mekonnen et al. (2015). For third generation bioenergy, bioenergy from algae, the study derived data on WFs of algae energy from Gerbens-Leenes et al. (2014).

When bioenergy is generated from food crops, carbohydrates or oils are extracted from the crop. These extraction yields can be used as food, or applied as the feedstock for the biofuels ethanol and biodiesel. The conversion is rather straightforward, because the crops already contain carbohydrates for ethanol or oil for biodiesel. Figure 2 shows that bioenergy can also be generated from residues or energy crops. The conversion is often more difficult and demands sophisticated technology (Cuellar and Straathof, 2015). When second generation bioenergy is produced, such as the biofuels bioethanol or pyrolysis oil, lignocellulosic feedstocks like straws, wood and stalks are converted to
fuel in processes like pyrolysis or fermentation. Pyrolysis is a thermochemical conversion process decomposing lignocellulosic biomass between 300 and 400°C, generating heat, volatile gases, pyrolysis oil and solid carbon (Basu, 2013). Pyrolysis oil has a relatively large oxygen content, larger than oil extracted from an oilseed crop, and therefore the energy content of pyrolysis oil is smaller than the energy content of first generation oils (Lehto et al., 2013). Biochemical conversion is a process in which bacteria or enzymes break down biomass molecules into smaller molecules (Basu, 2013). Another way of generating bioenergy is to convert the biomass directly into heat, or indirectly into electricity.

To estimate the WF related to future biomass use, the study calculated the global water consumption related to bioenergy use in 2040 based on the IEA scenarios (IEA, 2016). The IEA developed three different scenarios, the current policies scenario (annual bioenergy use 77 EJ), the new policies scenario (annual bioenergy use 79 EJ) and the 450 scenario (annual bioenergy use 97 EJ). For the estimation, the study combined bioenergy use according to the 450 scenario with average data on the WFs of first, second and third generation bioenergy. The total WF \( W_{F_{\text{total, m}^{3}/y}} \) is estimated as:
where $E$ is the bioenergy demand (GJ/y) of the 450 scenario, and $WF[s]$ the average WF per unit of bioenergy produced from bioenergy source $s$ (m$^3$/GJ). Next, the results were compared with the global average WF between 1996 and 2005. Data on the global average WF were derived from Hoekstra and Mekonnen (2012).

3. RESULTS

Figure 3 shows the global average water footprint (WF) of first generation biofuels in m$^3$ per GJ bioethanol or biodiesel. All WFs are dominated by the green WF, i.e. water from precipitation. The blue WF, i.e. water from irrigation, is relatively large for sugar cane, paddy rice and wheat. The grey WF is relatively large for potato and rapeseed. Figure 3 also shows that, in general, the WF of bioethanol is smaller than the WF of biodiesel. For bioethanol, total WFs range between 50 and 180 m$^3$ per GJ, for biodiesel total WFs are between 150 and 350 m$^3$ per GJ.

![Figure 3. Global average water footprint of first generation biofuel in m$^3$ per GJ ethanol or per GJ biodiesel](image)

Figure 4 shows the WF of second generation biofuels from residues in m$^3$ per GJ (average bioethanol and biodiesel). As could be expected, the WFs are also dominated by the green WF. Sugar beet shows the smallest WF, 7 m$^3$ in total, rapeseed has the largest total WF, 37 m$^3$. When Figure 4 is compared to Figure 3, we find that WFs for second generation biofuel from residues are much smaller than WFs of first generation biofuels. For sugar beet, for example, the difference is a factor of 7, for rapeseed a factor of 6.

Figure 5 shows the WF of second generation biofuel from energy crops in m$^3$ per GJ (average bioethanol, biodiesel and heat). The WF is only green. Especially the WF of bioethanol or biodiesel derived from pine is large, 350 m$^3$ per GJ, the WF of heat from firewood is relatively small and ranges between 19 and 100 m$^3$ per GJ with an average value of 60 m$^3$ per GJ.

Figure 6 gives an overview of WFs of first, second and third generation biofuels. First and second generation biofuels from residues are dominated by their green WF, but also have a blue and grey one, while second generation biofuels from energy crops only have a green WF and third generation biofuels from algae only have a blue WF. The WFs of biofuels from residues are smallest. The green WF of biofuel from energy crops is much larger than green WFs of the other biofuels. For biofuels from algae, the blue WF is largest.
Figure 4. Water footprint of second generation biofuel from residues in m$^3$ per GJ (average ethanol and biodiesel)

Figure 5. Water footprint of second generation biofuel from energy crops in m$^3$ per GJ (average ethanol, biodiesel and heat)

Figure 6. Overview of water footprints of first, second and third generation biofuel
Figure 7 shows the global WF of bioenergy in the IEA New Policies Scenario for 2040 together with the global average WF for the period 1996-2005. Between 1996 and 2005, the global average WF was 9,087 Gm$^3$ per year, of which 74% was green, 11% blue and 15% grey. This WF is completely dominated by agriculture, 92%. Crops require 7,400 Gm$^3$ per year and pasture 900 Gm$^3$ per year. Part of the crops is applied for energy purposes, for example sugar cane in Brazil is partly used as a feedstock for ethanol.

In many regions of the world, water was already a scarce resource between 1996 and 2005. With the introduction of bioenergy in the IEA 450 scenario, the WF of bioenergy will exceed the global average WF from the end of the 20th and the beginning of the 21st century. When energy crops are applied, the green WF will exceed the average global green WF. For the third generation bioenergy, especially the blue WF might be problematic. The only option would be to use residues for bioenergy.

4. DISCUSSION

- The WFs of bioenergy were derived from existing literature. It is possible that when more detailed data become available, the WFs also change. However, large differences exist between the energy feedstocks, i.e. WFs of first generation feedstocks are much larger than WFs of second generation feedstocks from residues. Also, this WF contains not only a green component, but also a blue WF component related to irrigation and a grey one related to pollution. The WFs of second generation energy crops, like wood or miscanthus are relatively large. However, they only contain the green component. The data for the third generation feedstocks, algae, have been based on a limited amount of studies. Although other research might show more sustainable options to produce algae, the WF of algae feedstock is based on the application of blue water that has a larger impact on water scarcity than green water.

- Another issue is that the IEA scenario’s with a large bioenergy contribution might not be realistic. Large contribution of bioenergy, as shown in this paper, requires a lot of fresh water that for some scenarios even exceeds present global water consumption. This might cause feedback mechanisms that cause a decrease of the use of bioenergy. Also, the energy mixes or total energy production might be different due to factors like shale gas development,
population characteristics or other growth scenarios than assumed by the developers of the IEA scenarios.

- The scenario using algae as a feedstock has a WF that is smaller than the WFs of scenarios using first generation feedstocks or second generation energy crops; however the WF is completely blue. Blue water use is even larger than present blue water use. This might also not be realistic. Another issue is the enormous land use related to algae production (Gerbens-Leenes et al., 2014) making this scenario problematic.

- The scenario applying crop residues is favorable in terms of WFs. The WFs of the residues were based on a WF recalculation in which the total WF of a specific crop was reallocated over the crop yield and the crop residue. This means that the total WF for agriculture does not increase. From this point of view, this scenario using residues is possible. However, this scenario depends on the availability of residues and the possibility to convert them into bioenergy. Globally the availability is huge (Montforti et al., 2013), but there are still technical challenges for the conversion into bioenergy and it is uncertain whether all these residues are really available for energy purposes.

5. CONCLUSIONS

When WFs of first, second and third generation bioenergy are compared, residues are the most favourable bioenergy feedstocks in terms of water use. The total WF does not increase when residues are applied for energy purposes. When crops are grown specifically for energy, food crops or energy crops, the WFs are large. Food crops have a green, blue and grey WF, while energy crops, such as miscanthus, are dominated by a green WF. The 450 IEA scenario for 2040 shows that when bioenergy from food crops is applied, the WF of the bioenergy exceeds the present global WF. Today, there is already water scarcity in many river basins. Therefore, the use of food crops for bioenergy is probably impossible. The use of bioenergy crops has a large demand for green water, also exceeding the present global green WF. For the third generation feedstock, algae, the blue WF exceeds the present blue WF. Using energy crops or algae for large scale energy supply might not be realistic from a water perspective. Only the use of residues for energy does not increase the WF, because all water was already allocated to the crops and the assessment has been based on a WF reallocation. The question remains whether the residues are really available for energy purposes.

ABBREVIATIONS

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<tr>
<td>EJ</td>
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