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Key Points:
- EU28 blue water footprint could increase fourfold
- Water footprints and land use among microalgae systems differ
- Microalgal biofuels have smaller WFs and land use than biofuels from food crops

Supporting Information:
- Blue water footprint and land use of biofuels from algae

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The blue water footprint and land use of biofuels from algae

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Abstract Biofuels from microalgae are potentially important sources of liquid renewable energy. Algae are not yet produced on a large scale, but research shows promising results. This study assesses the blue water footprint (WF) and land use of algae-based biofuels. It combines the WF concept with an energy balance approach to determine the blue WF of net energy. The study considers open ponds and closed photobioreactors (PBRs). All systems have a positive energy balance, with output-input ratios ranging between 1.13 and 1.98. This study shows that the WF of algae-based biofuels lies between 8 and 193 m^3/GJ net energy provided. The land use of microalgal biofuels ranges from 20 to 200 m^2/GJ net energy. For a scenario in which algae-based biofuels provide 3.5% of the transportation fuels in the European Union in 2030, the system with the highest land productivity needs 17,000 km^2 to produce the 850 PJ/yr. Producing all algae-based biofuels through the system with the highest water productivity would lead to a blue WF of 7 Gm^3/yr, which is equivalent to 15% of the present blue WF in the EU28. A transition to algae-based transportation fuels will substantially increase competition over water and land resources.

1. Introduction

In the last decade, global biofuel production has increased more than fivefold [*Stromberg and Gasparatos*, 2012]. Energy security, climate change mitigation, foreign exchange savings, and rural development are the main drivers of this biofuel expansion [*Yan and Lin*, 2009]. Especially, energy security is an important driver of biofuel expansion. At the same time, biofuel production has been associated with several environmental impacts, such as greenhouse gas emissions, air quality, water consumption, deforestation, land use change, and biodiversity loss [*Stromberg and Gasparatos*, 2012]. The most important drawback of biofuel production is its competition with food production with impacts on food prices and food security [*Stromberg and Gasparatos*, 2012; *Erb et al.*, 2012; *Fischer et al.*, 2009; *Food and Agriculture Organization of the United Nations*, 2008].

Globally, liquid fuels for transportation provide a large part of the total energy used. In the European Union, for example, around 30% of total energy use is for transport [*International Energy Agency*, 2012; *European Commission*, 2010]. Worldwide, governments aim to introduce renewable transport biofuels. The European Union aims to replace 10% of transport fuels by renewables in 2020 [*European Commission*, 2011]. India aims to replace 20% of petrodiesel by biodiesel [*Government of India, Ministry of New & Renewable Energy*, 2008]; in China, the National Development and Reform Commission promotes the production of biofuels and aims for a share of 15% of biofuel for transport in 2020 [*Yang et al.*, 2009]. Based on energy use in 2006, U.S. aims to replace 15% of gasoline by biofuels in 2022 [*Dominguez-Faus et al.*, 2009]. These aims indicate a trend in which biofuels will partly replace fossil liquid fuels.

Biofuels are fuels produced from biomass, defined as all material of biological origin, excluding material embedded in geological formations and transformed to fossil energy sources [*FAO*, 2006]. Growing plants for biomass requires water and land. Freshwater is scarce in many parts of the world. In the coming decades, the strain put on this natural resource is expected to increase globally [*Gleick*, 1998; *Hoekstra et al.*, 2011]. This is driven by economic development, population growth, changing consumption patterns, and climate change, causing increasing competition over water between economic sectors. Land is needed to grow plants as well, and like freshwater, fertile land is a limited natural resource. Land resources can only be extended by converting natural areas, such as forests, causing a decrease and degradation of ecosystems [*Foley et al.*, 2005]. With the increasing production of biofuels, there is a need to assess their water and land requirements and to analyze whether the availability of these natural resources is sufficient to promote the expansion of biofuel production.

Biofuels are classified in three categories based on the feedstock: first, second, and third-generation biofuels. First-generation biofuels use food crops for production, while second-generation biofuels' feedstock include woody or fibrous biomass, such as nonedible remains of food crops, or dedicated biofuel crops [*Fischer et al*., 2009]. We define third-generation biofuels as future biofuels that are derived from microscopic organisms, such as microalgae. At present, most biofuels are first generation [*Stromberg and Gasparatos*, 2012; *Fischer et al*., 2009]. These biofuels have drawbacks, such as small net energy yields, large land and water use, and direct competition with food production [*Singh et al*., 2011].

Algae-based fuels are third-generation biofuels and might be a promising biofuel option. Their high growth rate and lipid content make microalgae an interesting biofuel feedstock. Algae do not need high-quality land to be cultivated and achieve high productivities [*Singh et al*., 2011; *Menetrez*, 2012]. This gives algae important advantages over other biofuel feedstocks. Information about the water footprint (WF) of most first-generation biofuels is available [*Gerbens-Leenes et al*., 2009], but the WF and land use of algae-based biofuels has received less attention.

First, previous evaluations of the water consumption of microalgae biofuels have not developed a lifecycle methodology comparable to other biofuel studies in literature. *Clarens et al*. [2010] analyzed microalgal biofuel WF including direct water consumption and water consumption associated with upstream processes, but notably missing from the LCA study of *Clarens et al*. [2010] was that their cradle-to-gate boundary did not take into account the downstream conversion processes. In a later research, *Clarens et al*. [2011] expanded their system boundary and included conversion of algae into consideration in evaluating the environmental impacts of algae as a transportation energy source. Specific conversion processes, including direct combustion, anaerobic digestion, and biodiesel production, were chosen as representative technologies. Results from *Clarens et al*. [2011] offered a complete picture of algae's performance relative to other bioenergy feedstocks. They suggested that both cultivation and conversion processes must be carefully considered to ensure the environmental viability of algae-to-energy processes. *Clarens et al*. [2011] made comprehensive comparisons of energy use, greenhouse gas (GHG) emissions, and water use among different crops. The comparisons were based on final results of their calculations, while there is lack of descriptions on the contribution of each step from algae to energy, such as cultivation, harvesting, dewatering, extraction, conversion, as well as fuel combustion. The authors of the present paper think that investigations and discussions on the energy and water distributions within the entire algae-to-energy process is essential to reveal the critical barriers in reducing energy and water use from algae to an energy source. *Yang et al*. [2011] studied the WF from microalgal biodiesel derived from an open pond cultivation system; however, the water requirements associated with energy and consumable materials are excluded in their study. *Wigmosta et al*. [2011] performed a geographically resolved water consumption analysis of microalgae production with the consideration of the downstream conversion; however, the distribution, transportation, and coproduct allocations were not included. The LCA study of *Vasudevan et al*. [2012] focused on freshwater consumption for dry and wet extraction technologies, but the water consumptions for the upstream process are not included. More recently, *Guieysse et al*. [2013] constructed a variability and uncertainty study in water demand and WF assessments of fresh algae cultivation based on case studies from five climatic regions. Specific focus of that study is on the accuracy and variability of the WF of microalgae cultivation in open ponds. The WF during the conversion of microalgae into biofuels is not discussed in that study. In general, the water consumption that accompanies the production and conversion of biomass into an energy form depends significantly on the type of biomass, the production method, and the applied conversion technology. The evaluation of the WF of microalgal biofuels should integrate the cultivation, lipid extraction, fuel conversion, transportation, as well as the coproduct allocations.

Second, because of the limitation of industrial testified data, most existing WF studies on microalgal biofuel are based on data from lab observation or experiments instead of field data. However, lab data can deviate significantly from field data, which will have consequential impacts on the WF results. *Harto et al*. [2010] performed a comparison of the lifecycle WF of open pond and tubular photobioreactor cultivation systems, but incorporated higher productivities than have been reported in studies of near-term, industrially realizable cultivation systems [*Quinn et al*., 2012]. *Batan et al*. [2013] carried out a thorough green and blue WF study of microalgae produced from a photobioreactor system from a lifecycle perspective. In that study, substantial focus is on the influence of process and climate variation on the WF of microalgal fuels. The climate variation data are simulated by lab experiments. In general, the synthesis of the results of WF analyses among studies is complicated by the many different system boundary conditions and different data inputs. We believe that a cradle-to-cradle boundary should be considered in order to carry out a comprehensive WF study, and microalgae fuels produced with different cultivation system and conversion routes at varied climate situations should be investigated and evaluated. Also, field data from industrial-scale operation systems should be used in order to achieve reliable results. *Menetrez* [2012] performed a literature study and identified several human exposure and environmental impact issues, concluding that the knowledge is still incomplete and fragmented. The objective of this study is to determine the WF and land use of algae-based biofuels, per unit of net energy obtained, with a cradle-to-cradle boundary using the data on productivities from seven microalgae production cases at different locations and the WF concept as proposed by *Hoekstra et al*. [2011]. The main research question of the current study is: what is the variation of WF (m^3/GJ) and land use (m^2/GJ) of microalgal biofuels for different production systems at different geography and climate situations? Specific questions are: (i) how much biofuels (mass and energy content) do microalgal cultivation systems produce? (ii) How much water and land is needed for the production of these biofuels? (iii) How much energy is needed for the production and is contained in the final products? (iv) What is the total WF and land use for a scenario in which 8% of the energy required for road transport in the European Union in 2030 is obtained from renewables and in which biodiesel from microalgae supply about half of this demand?

This study uses data from case studies from literature to model microalgal biofuel production systems. Using reported data on actual biomass production and conversion to biofuels, it calculates the mass and energy content of the biofuels. Next, using a theoretical approach, we assume that not only the biodiesel fraction but all biofuel fractions that result from the processing of algae are applied for transportation. We use the WF concept to calculate the WF of biofuels per unit mass (m^3/ton). Using an energy balance, we calculate the energy inputs and outputs, assessing the WF of the net energy produced (m^3/GJ). The calculation model is built in Excel with transparent calculations. The energy flow and WF in each process step from algae cultivation to biofuels production have been clearly described and discussed. Sensitivity studies among different locations, cultivation systems, dewatering methods, and conversion technologies have been carried out to reveal the critical steps in reducing the burden of energy and water use. Finally, we use the results to estimate WFs and land use for the scenario in which microalgal biofuels provide 3.5% of the energy needed for road transport in the European Union in 2030 according to the 450Scenario of the World Energy Outlook [*International Energy Agency*, 2012]. For the assessment of land use, we follow the same approach. When WFs and land use of biofuels are assessed, the energy balance of the production process is an important indicator of the feasibility of the process for energy production. To the best of our knowledge, this study is the first that combines an energy balance, in this case, of microalgal biofuel production, with the assessment of WFs and land use of biofuels, giving WFs and land use of biofuels per unit of net energy from microalgae.

2. Methods

2.1. Microalgal Biofuel Production

Microalgae are unicellular photosynthetic microorganisms, living in aquatic environments. Microalgae grow fast, some microalgae strains have lipid contents over 70% dry weight (dw.) [*Menetrez*, 2012; *US Department of Energy (US-DOE)*, 2010]. The remaining biomass includes carbohydrates, proteins, and nucleic acid [*Becker*, 1994]. There is a wide variety of algal species that fall in two categories: freshwater algae and saline algae. Several biofuel types can be produced from microalgae, depending on the composition of the biomass (see Figure 1). There are two types of microalgae: autotrophic and heterotrophic microalgae. Autotrophic algae use CO_2 for growth in the photosynthesis process. Heterotrophic algae do not apply the photosynthesis process, but use a carbon source, e.g., glucose. Heterotrophic cultivation is unsuitable for energy production, because it requires an energy intensive feedstock. Microalgae cultivation takes place in two types of autotrophic cultivation systems: open pond systems and closed photobioreactors (PBRs).

The cultivation process generates water with suspended microalgae, the microalgal slurry. Before further processing, the microalgae are condensed and dried. This process requires one or more solid-liquid separation steps. The original microalgal slurry from the open ponds contains about 0.05% dw. of microalgae [*Xu et al*., 2011]. We assume that flocculation in a settling pond may increase the concentration to 2% dw. PBRs

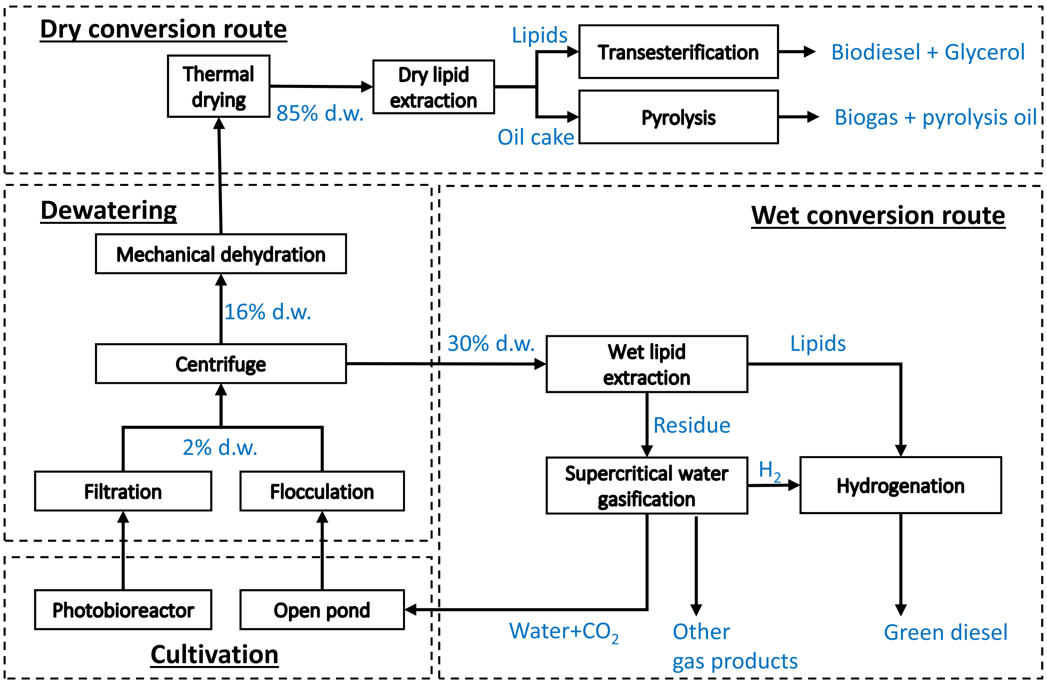

Figure 1. Biofuel from microalgae production using open pond or PBR cultivation and dry or wet conversion [*Wigmosta et al.*, 2011]. Arrows represent mass flows.

produce a slurry of 2% dw. after filtration. Following flocculation or filtration, centrifugation and mechanical dehydration is used to reach 30% dw. Depending on the conversion strategy, this 30% dw. slurry is converted directly (wet conversion) or is further dried to 85% dw. and then converted (dry conversion). In the case of dry conversion, this last drying step, thermal drying, is known to be energy intensive.

Xu et al. [2011] distinguished two routes to convert microalgae into biofuels: wet and dry conversion. In the wet conversion route, lipids are extracted from slurry of 30% dw. The extracted lipids are hydro treated to produce biodiesel. The extraction residues are converted using supercritical water gasification (SCWG) technology, producing hydrogen (H_2), methane (CH_4), ethane (C_2H_6), propane (C_3H_8), and carbon monoxide (CO). SCWG also produces water and carbon dioxide (CO_2) that are recycled. Dry conversion starts with the dry extraction of lipids, after which the lipids are converted to biodiesel and glycerol through a transesterification process. The residue (oil cake) is pyrolized to produce pyrolysis oil and biogas. Figure 1 shows the steps for microalgal biofuel production using PBRs and open ponds with dry and wet conversion routes.

2.2. Water Flows in Microalgal Biofuel Production

Figure 2 shows the water flows in a microalgal biofuel production system. There is one ingoing flow, water input, and four outgoing flows: (i) water flushed; (ii) water for evaporative cooling of PBRs (PBRs are sometimes cooled by spraying freshwater to avoid overheating); (iii) water evaporated from open ponds; and (iv) water evaporated in thermal drying and pyrolysis (dry conversion route). In outdoor-open pond systems, freshwater needs to be added on a regular basis to compensate for evaporation loss and to avoid salt buildup. Systems using saltwater microalgae also use freshwater to compensate evaporation losses to avoid this salt buildup [*Yang et al.*, 2011; *Committee on the Sustainable Development of Algal Biofuels, National Research Council of the National Academies*, 2012].

2.3. Water Footprint

The water footprint (WF) of a product is the volume of freshwater used to produce the product, measured over the full supply chain. The WF of a product includes a green, a blue, and a gray component. The green WF refers to the consumption of green water resources (rainwater in so far as it does not become runoff). The blue WF refers to the consumption of blue water resources (surface and groundwater). The gray WF refers to pollution and is defined as the volume of freshwater that is required to assimilate the load of pollutants given natural background concentrations and existing ambient water quality standards [*Hoekstra*

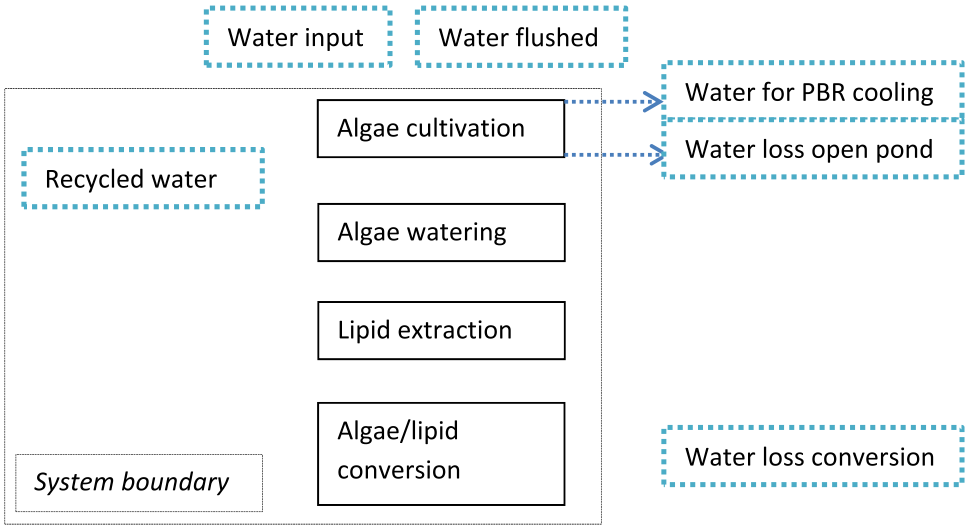

Figure 2. Water flows in microalgal biofuel production using open pond or PBR cultivation and dry or wet conversion. Systems using salt-water microalgae use freshwater to compensate evaporation losses to avoid salt buildup.

et al., 2011]. Biofuel production from microalgae does not generate a green WF. We assume that wastewater is treated in such a way that there is no water pollution. Our assumptions mean that the WF of microalgal biofuels only includes a blue component. WF specific calculations are given in the supporting information Appendices.

2.4. Energy Balance

We assess the WF and land requirement of microalgae-based biofuels per unit of net energy provided by the biofuel, which requires that the energy balance is included in the calculations. Figure 3 shows the defined boundary conditions in microalgal biofuel production.

We calculate the blue WF of the net energy of biofuels using the results from the energy balances by subtracting the energy inputs in microalgal biofuel production from the energy outputs. This gives the net energy content of the biofuels. The energy balance calculation includes: (i) cultivation; (ii) dewatering; (iii) dry conversion; and (iv) wet conversion. Each process contains several subprocesses, marked with an asterisk (*) in Figure 3. The energy inputs include heat and electricity. We apply the Energy Required for Energy (ERE) factor (MJ/MJ) to account for the fact that producing one unit of electricity costs a certain amount of energy [*International Energy Agency (IEA)*, 1999; *Reinders et al*., 2003; *Blok*, 2006]. The value of the ERE-factor for heat is assumed to be 1.0, for electricity it depends on the efficiency of the power plant, the energy carriers used (e.g., coal, natural gas, oil, or renewables) and on the specific energy mix of the country considered. In the Netherlands, for example, over time, ERE values for electricity decreased from 5.25 to 2.90 in 1998 [*Noorman and Schoot Uiterkamp*, 1998]. With increased efficiencies of power plants, the ERE values decrease further, like the ones for the Netherlands in 2003 of 2.65 [*Falkena et al*., 2003]. Globally, there is an opposite trend for ERE, because the fraction of coal increases for electricity generation [*OECD/IEA*, 2010]. Of the fossil fuels coal has the largest ERE factor, 2.89 [*IEA*, 1999]. Globally in 2007, the share of coal for electricity is 41.6%, for oil 5.6%, for gas 20.9%, for nuclear energy 13.8%, for renewables (mainly hydro) 15.6%, and for other energy sources 2.6% [*OECD*, 2010]. Based on these fractions, in 2007, the global ERE value for electricity was 2.46. In this study, we use the ERE factor for electricity in U.S. We assessed the ERE value of 2.61 based on data on ERE values for specific energy carriers from *IEA* [1999] and the energy mix for electricity in U.S. in 2008 from *U.S. Energy Information Administration* [2011]. We took the ERE value for the U.S., which is slightly higher than the global average, because there is an upward trend for ERE due to larger coal use. Besides the direct heat and electricity inputs, the indirect life cycle energy consumption in producing consumable materials, such as nutrients, solvents, catalyst, and methanol, has also been taken into account. More specifically, cultivation input includes energy for infrastructure, CO_2, urea, and superphosphate consumption, water pumping, paddlewheel stirring, and CO_2 bubbling for mixing. The first five processes apply to all production systems, the sixth and seventh only to a specific type (open pond or PBR). Dewatering

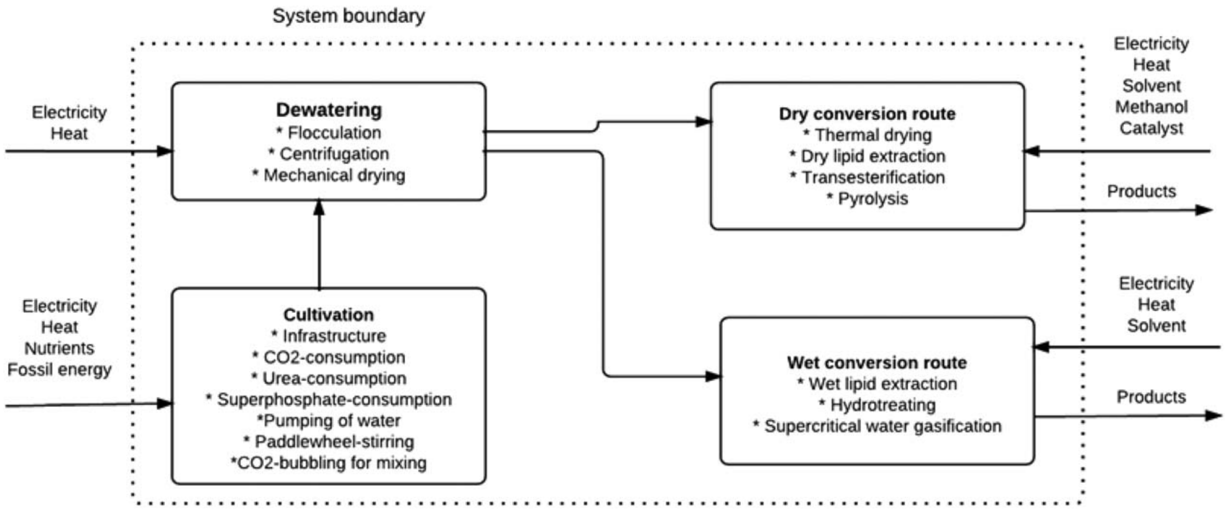

Figure 3. Energy flows in microalgal biofuel production using open pond or PBR cultivation and dry or wet conversion.

includes three subprocesses using electricity: (i) flocculation; (ii) centrifugation to dry the slurry after harvest; and (iii) mechanical drying to power a drying press. These processes apply to all production systems. The dry conversion route includes four subprocesses: (i) thermal drying, using heat to dry the slurry; (ii) dry lipid extraction, using energy for cell disruption, solvent loss, and evaporation; (iii) transesterification, using indirect energy for methanol, catalyst, heat, and electricity; and (iv) pyrolysis, using only electricity. The wet conversion route includes three processes: (i) wet lipid extraction, using energy for cell disruption as well as solvent loss and evaporation; (ii) hydro treating, using energy in the form of hydrogen, electricity and heat; and (iii) supercritical water gasification, using mainly heat and electricity. The higher heating value (HHV) of the fuel products are calculated as the outputs. The main assumptions used for the calculation of the energy balance are summarized in Table 1.

For the assessment of the energy balance of microalgal biofuels, we use case studies of microalgal biofuel production systems from literature. These studies include seven cultivation systems in different locations in seven countries: (i) Livorno, Italy; (ii) Perth, Australia; (iii) Roswell, New Mexico, USA; (iv) Tamaranset, Algeria; (v) Utrecht, Netherlands; (vi) Carpentras, France; and (vi) Hawaii, USA. The first two locations use an open pond for cultivation, the third uses a combination of an open pond and a photobioreactor (PBR) and the remaining four use PBRs. Table 2 gives the location characteristics. The daily water evaporation data, energy for cooling, the solar radiation, and the temperature range in different locations have been introduced in the supporting information Appendix.

Supporting information Appendix G gives information on the characteristics of the production systems. To put our results in perspective, we compare total WFs of microalgae (green, blue, and gray) with total WFs of other crops providing first-generation biofuels, maize, sugarcane, soybean, and rapeseed for the same locations. To do the comparison, we first convert the microalgae yields (dm.) to fresh yields assuming a water content of 80% [*Pizarro et al*., 2006]. We derive data on WFs of crops from *Mekonnen and Hoekstra* [2011].

2.5. Projected Biofuel Use for Road Transport in the European Union in 2030

The World Energy Outlook [*International Energy Agency*, 2012] 450Policy scenario projects biofuel use in the European Union (EU). This scenario assumes that between 2030 and 2035, renewable energy required for transport will be between 46 and 54 Mtoe (million tonnes of oil equivalent). This comes down to 1926–1952 PJ/yr. Following *Gerbens-Leenes et al*. [2012], we assume that bioethanol will supply about 56% and biodiesel 44% of the total biofuel. In this paper, we consider a scenario in which all biodiesel between 2030 and 2035 is obtained from microalgae. Thus, microalgal biofuels will have to supply 853 PJ/yr (3.5% of the total energy use for transport in the European Union between 2030 and 2035). We assume that all biofuel fractions that result from the processing of microalgae are applied for transportation, not only the biodiesel

Table 1. Main Assumptions Related to the Energy Balance

	Item	Unit	Assumptions
Energy inputs	Infrastructures[a]	MJ/m^2	80.4
	Equipments	MJ	Neglected
	Paddle wheel[b]	kWh/ha^1	0.37
	Water pump	kWh/m^3	19.1
	CO_2 pump	kWh/m^3	2.77
	Flocculation	GJ/ton biomass	0.078
	Centrifuge	Water content after centrifugation	84%
		kWh/m^3	0.53
	Mechanical dryer	Water content after centrifugation	70%
		kWh/ton biomass	60
	Thermal dryer	Water content after centrifugation	15
		GJ/ton water	2.0
	Dry lipid extraction, heat	GJ/ton lipid	0.76
	Dry lipid extraction, electricity	GJ/ton lipid	0.24
	Wet lipid extraction, cell disruption	kWh/ton lipid	4.63
	Wet lipid extraction, solvent	GJ/ton biomass	1.61
	Pyrolysis	kWh/kg of feed	0.18
	Hydrogenation	GJ/ton lipid	2.59
	Supercritical water gasification	kWh/ton lipid	0.42
Materials	CO_2[c]	kWh/ton	22.2
	Nitrogen (urea)[d]	Kg/m^3	0.150
		MJ/kg	62.7
	Phosphorus (single superphosphate)[d]	Kg/m^3	0.052
		MJ/kg	13.0
	K, Mg, S	Kg/m^3	Neglected
	Methanol	GJ/ton lipid	4.92
	Catalyst	GJ/ton lipid	1.04

[a]It is estimated that the fossil energy requirement to construct the entire facility including maintenance is 80.4 MJ/m^2 and the life time is 20 years [*Chisti*, 2008].
[b]Operating at 10 rpm to keep the culture medium at 25 cm/s [*Clarens et al.*, 2010].
[c]Including the cost of a transportation from a power plant to the ponds via pipelines [*Kadam*, 2002]. For the wet route, the energy consumption for CO_2 recycling is neglected.
[d]Nutrient requirements are based on the elemental composition. The water in the raceway ponds is flushed every 6 months for bacteria and toxic control. As a consequence, nutrient loss caused by flushing is included in the model [*Geider and La Roche*, 2002].

fraction. For example, methane and hydrogen are also applied as fuels, e.g., for busses. The supporting information Appendices provide the calculations.

3. Results

3.1. Energy Balances

The energy inputs and outputs for all the seven cases are summarized in Table 3. The differences in energy inputs and outputs are caused by different project sizes. The ratio between end products is also influenced by the lipid content of the biomass.

Table 2. Location Characteristics and Cultivation Parameters

Location	System Type	Water Type	Growing Period (days)	Volume (m^3)	Production (ton/yr)	Area (m^2)
New Mexico[a]	Open pond	Salt[b]	365	483.30	7.300	2150.00
Perth[c]	Open pond	Salt[b]	300	0.17	0.006	1.05
Hawaii[d]	Open pond/PBR	Fresh	365	75.00	2.300	601.00
Italy[e]	PBR	Salt[b]	180	488.80	32.000	10,000.00
Netherlands[f]	PBR	Fresh	365	392.00	115.000	10,000.00
France[f]	PBR	Fresh	365	410.40	155.000	10,000.00
Algeria[f]	PBR	Fresh	365	458.70	185.000	10,000.00

[a]*Sheehan et al.* [1998].
[b]Systems using saltwater microalgae use freshwater to make up for losses.
[c]*Moheimani and Borowitzka* [2006].
[d]*Huntley and Redalje* [2006].
[e]*Rodolfi et al.* [2009].
[f]*Slegers et al.* [2011].

Table 3. Energy Balance Inputs per Stage for Seven Locations and Dry and Wet Conversion Routes

	Cultivation (GJ)	Dewatering (GJ)	Dry Route (GJ)	Wet Route (GJ)	Total Inputs (GJ)	Total Outputs (GJ)
New Mexico—dry conversion	32.8	6.5	74.0	0.0	113.3	166.90
New Mexico—wet conversion	32.2	6.5	0.0	77.5	116.2	149.70
Perth—dry conversion	0.020	0.005	0.059	0.000	0.085	0.13
Perth—wet conversion	0.020	0.005	0.000	0.063	0.088	0.12
Hawaii—dry conversion	13.5	2.0	21.0	0.0	36.6	43.40
Hawaii—wet conversion	13.2	2.0	0.0	22.9	38.2	39.40
Italy—dry conversion	69.7	28.5	345.3	0.0	443.5	813.60
Italy—wet conversion	65.7	28.5	0.0	353.4	447.6	730.40
Netherlands—dry conversion	550.3	102.4	1013.8	0.0	1666.5	2042.40
Netherlands—wet conversion	534.5	102.4	0.0	1122.2	1759.1	1871.20
France—dry conversion	725.4	138.0	1366.5	0.0	2229.9	2752.80
France—wet conversion	704.1	138.0	0.0	1512.5	2354.6	2522.10
Algeria—dry conversion	857.4	164.7	1631.0	0.0	2653.1	3285.50
Algeria—wet conversion	832.0	164.7	0.0	1805.2	2802.0	3006.40

The energy balance, expressed as the **Energy Output-Input ratio** (EOI-ratio), i.e., the ratio between energy output and input of the production systems, is an important factor for the WFs and land use of biofuels from microalgae, because we express WFs and land use per unit of net energy. Based on the energy input and output data from Table 3, the EOI ratio for dry and wet conversion are summerized in Table 4.

Table 4 shows that all systems have a net energy production with slight differences between wet and dry conversion routes. All EOI ratios are larger than 1.0, which means that the products contain more energy than was needed to produce them. However, for some systems, the net energy gain is almost negligible. In addition, we find a correlation between the EOI ratio and the algal biomass lipid content. The system with the largest EOI ratio (Italy) produces microalgae with a lipid content of 53%, whereas the systems with the smallest EOI ratios (Hawaii, Netherlands, France, and Algeria) give microalgae with lipid contents between 20 and 25%. Moreover, the energy inputs influence the lipid contents and outputs of the production systems. Increasing microalgae lipid contents go along with a larger biomass energy output and smaller inputs. Especially the decrease of nitrogen needed is the most significant reason that lower nutrients inputs are needed.

3.2. Biofuel Products

The dry conversion route generates the biofuel products, biodiesel, glycerol, pyrolysis oil, and combustible biogas, while wet conversion generates biodiesel, carbon monoxide, hydrogen, methane, ethane and propene. The fractions of the different biofuel products differ per production location and depend on the composition of the microalgae. Table 5 gives the fractions of biofuels for dry and wet conversion per location. In general, the biodiesel fraction is the largest and varies between 0.4 and 0.7, followed by the fraction of pyrolysis oil (dry conversion), which lies between 0.2 and 0.5 and methane (wet conversion) with fractions between 0.2 and 0.3. The type of production system, therefore, determines the size of the fraction of biofuels.

3.3. Water Footprint of Biofuels per Unit Net Energy

For the calculation of net energy, we found ERE values for the wet conversion process of 1.55 and for dry conversion of 1.26, smaller than the value for electricity of 2.61. Figure 4 shows the blue WF of biofuels from microalgae per unit of net energy provided by the system for the seven case studies and two conversion routes. The PBRs in the Netherlands and Italy have the smallest WFs; the open pond systems and PBRs in Australia, New Mexico and France show similar results, while the WF for biofuels from PBRs in Algeria is larger than the other WFs and the WF of biodiesel from microalgae in Hawaii is very high compared to the other locations. Cooling is the major part of water consumption for the PBRs. The water use for PBR cooling in Netherlands, however, is small. The figure also shows that for all systems, the WF for dry conversion is smaller than the WF of wet conversion.

Table 4. The Energy Output-Input Ratio (EOI Ratio) of Wet and Dry Conversion Routes of Microalgae Production Systems

Location	EOI Ratio[a] (Wet Conversion)	EOI Ratio[a] (Dry Conversion)
Livorno, Italy	1.83	1.98
Perth, Australia	1.55	1.54
New Mexico, USA	1.47	1.48
Tamaranset, Algeria	1.24	1.16
Utrecht, Netherlands	1.23	1.15
Carpentras, France	1.23	1.15
Hawaii, USA	1.19	1.13

[a]The EOI ratio is the energy output-input ratio.

Table 5. Fractions of Biofuels for Dry and Wet Conversion per Location of Microalgae Production Systems

	Dry Conversion				
Location	Biodiesel	Glycerol	Pyrolysis Oil	Biogas	
New Mexico, USA	0.597	0.060	0.282	0.061	
Perth, Australia	0.567	0.056	0.309	0.067	
Hawaii, USA	0.448	0.045	0.416	0.090	
Livorno, Italy	0.694	0.069	0.195	0.042	
Utrecht, Netherlands	0.385	0.038	0.474	0.103	
Carpentras, France	0.385	0.038	0.474	0.103	
Tamaranset, Algeria	0.385	0.038	0.474	0.103	
	Wet Conversion				
Location	Biodiesel	CO[a].	C_2H_6[b], C_3H_8[c]	CH_4[d]	H_2[e]
New Mexico, USA	0.636	0.021	0.064	0.244	0.035
Perth, Australia	0.602	0.022	0.068	0.258	0.051
Hawaii, USA	0.471	0.026	0.079	0.305	0.119
Livorno, Italy	0.730	0.017	0.053	0.200	0.000
Utrecht, Netherlands	0.401	0.028	0.086	0.329	0.156
Carpentras, France	0.401	0.028	0.086	0.329	0.156
Tamaranset, Algeria	0.400	0.028	0.086	0.329	0.156

[a]Carbonmonoxide.
[b]Ethane.
[c]Propene.
[d]Methane.
[e]Hydrogen.

The product WFs vary between locations. This is caused by two factors: (i) differences in total WFs and (ii) differences in product fractions caused by variations in lipid content. In general, higher lipid content gives more biodiesel. The smallest product WFs are for the system in the Netherlands, the largest for Hawaii. Hawaii's large WF is caused by a relatively large water use in combination with low production. The open pond evaporation is 3.98 mm/d, versus 2.80 in Perth and 2.27 in New Mexico. For open pond systems, the largest water losses are related to evaporation. For PBRs, the largest losses are related to cooling.

3.4. Land Use of Biofuel

Figure 5 gives the total land use (m^2/GJ) of microalgae biofuels for dry and wet conversion per unit of net energy. Land use varies between 20 and 200 m^2/GJ, a difference of a factor ten. Especially, the production system in Hawaii shows relatively large land use per unit of net energy.

3.5. Comparison With Other Crops

In order to put our results in perspective, we compare the WF of microalgae to the WFs for four crops that are used to produce first-generation biofuels [*Mekonnen and Hoekstra*, 2010]. We use m^3/GJ gross biofuel as indicator to compare the WF between different energy crops. We compare to the WFs of maize, sugarcane, soybean, and rapeseed grown at the same locations as the locations of the microalgae production systems. For algae, we also give the WF per unit of net energy. Table 6 gives the results.

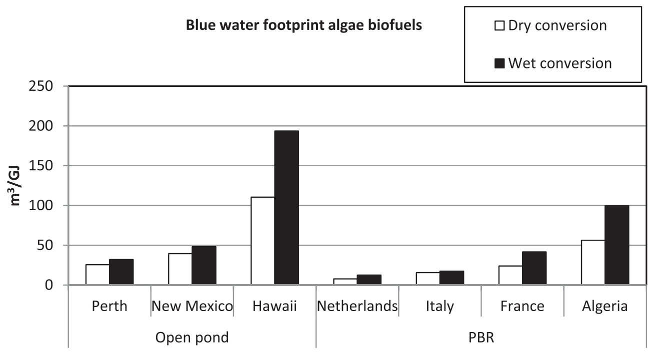

Figure 4. Blue water footprint of microalgae biofuels (m^3/GJ) for dry and wet conversion.

Compared to the WFs of ethanol from maize and sugar cane, and biodiesel from soybean and rapeseed, the WFs of the biofuels from microalgae are small. Microalgae do not have a green WF, and we assumed that wastewater is properly treated before disposal, so that also the gray WF is zero. However, microalgae do have a blue WF, which is in some cases larger than the blue WF of the crops, e.g., for soybean and rapeseed

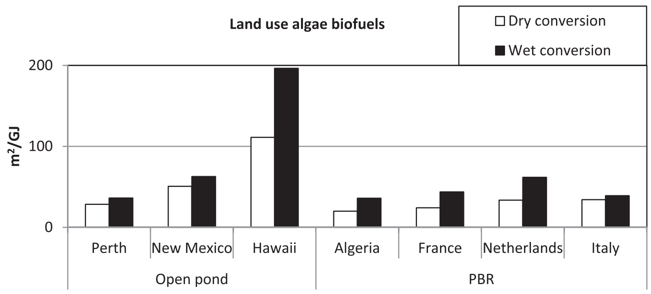

Figure 5. Land use of microalgae biofuels (m^2/GJ) for dry and wet conversion.

from New Mexico and Perth, for rapeseed from Italy and for maize from Algeria. The opportunity cost of green water consumption is smaller than for blue water consumption. Specific focus on the blue and gray WFs is warranted because in the case of blue water (groundwater, surface water), agricultural water demand competes with various other human demands for water, like water demands for households and industries, while gray WFs contribute to water pollution. Another issue is that the difference between WFs per unit of net or gross energy is large. We included the WFs of ethanol and biodiesel per unit of gross energy here, because data on net energy are not available for the specific locations.

3.6. Scenario Analysis

Figure 6 shows the blue WF (m^3) and land use (km^2) for a scenario in which biofuels from microalgae provide 3.5% of the renewable fuels needed in the European Union for road transport in 2030 according to the 450Scenario of the World Energy Outlook.

The WF of microalgae-based biofuels in the EU28 would be smallest, 7 Gm^3, if all fuel would be produced based on the parameters of the system in the Netherlands, using the dry conversion route. The WF would be largest, 165 Gm^3, if all fuel would be produced based on the parameters of the system in Hawaii, using wet conversion. To put these values in perspective: the current total blue WF in the EU28 (all water-using sectors together) is 47 Gm^3/yr [*Hoekstra and Mekonnen*, 2012]. The system using dry conversion in Algeria needs 17,000 km^2 to produce 3.5% of the liquid biofuels needed for transport in the EU28. This is 1% of the agricultural land area of the EU28 of 1,741,000 km^2 [*European Union*, 2013]. If all fuels for transport would be produced using algae, 28% of the EU agricultural area would be needed. Figure 6 also shows that there can be a trade-off between water and land use. The Netherlands, for example, shows the smallest WF, but not the smallest land use.

Table 6. WFs Gross Energy of Microalgae and Four Crops That Are Used to Produce First-Generation Biofuels for Seven Different Locations [*Mekonnen and Hoekstra*, 2010][a]

		WF (m^3 per GJ)				
Location	WF Component	Maize (Ethanol)	Sugarcane (Ethanol)	Soybean (Biodiesel)	Rapeseed (Biodiesel)	Algae (Mixture of Fuels)
New Mexico, USA	Green	39		293	469	0
	Blue	40		0	0	10 (46)
	Gray	16		2	96	
Hawaii, USA	Green					0
	Blue					14 (52)
	Gray					
Perth, Australia	Green	117	23	303	162	0
	Blue		11	0	0	7 (32)
	Gray	16	5	0	38	
Tamanranset, Algeria	Green	90			89	0
	Blue	0			145	9 (31)
	Gray	0			3	
Livorno, Italy	Green	37		178	286	0
	Blue	23		29	0	6 (29)
	Gray	18		0	1	
Carpentras, France	Green	48		266	115	0
	Blue	8		49	0	4 (13)
	Gray	15		38	16	
Utrecht, Netherlands	Green	34			75	0
	Blue	2			0	1 (4)
	Gray	3			5	

[a]For algae, also the WF per unit of net energy is given within brackets.

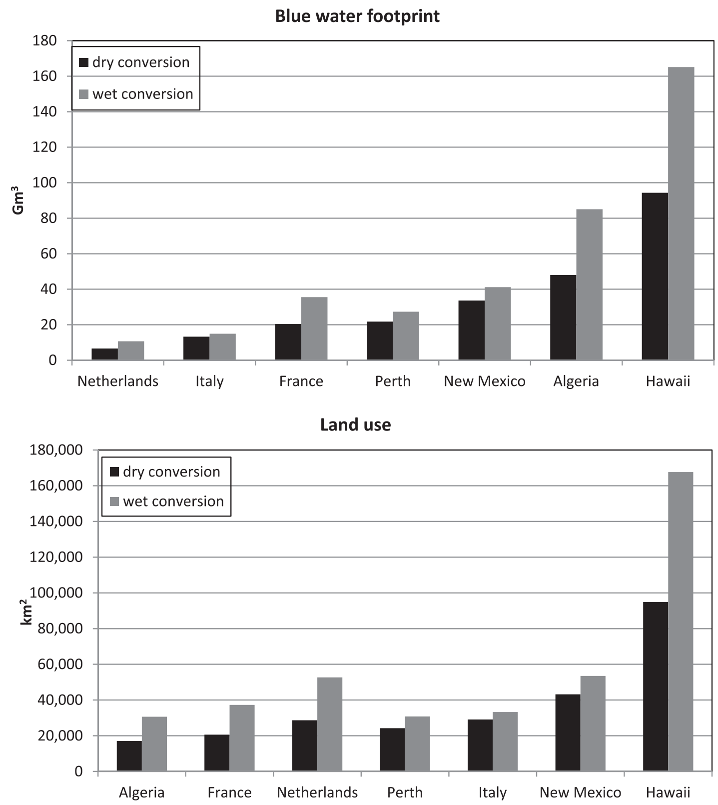

Figure 6. Blue WF (m^3) (upper graphic) and land use (km^2) (lower graphic) for a scenario in which biofuels from microalgae provide 3.5% of the fuels needed in the European Union for transport in 2030 according to the 450Scenario of the World Energy Outlook. The results depend on which of the seven production systems as considered in this paper is used for making assumptions on land and water productivity of microalgae and biofuel production.

4. Discussion

4.1. Uncertainties in the Results

We emphasize that assessing the sustainability of an algal biofuel requires insight into the separate components of the production system. The production of biofuels from algae is not an established industry and processing options propose over sixty different pathways for the production [*Committee on the Sustainable Development of Algal Biofuels, National Research Council of the National Academies*, 2012]. Our results indicate that scaling up algal biofuel production places a demand on freshwater and land that will strongly depend on the selected technology and local circumstances. We use several assumptions to calculate the WF and land requirement of biofuels from microalgae that lead to uncertainties in the results. Our results, however, are supported by earlier research [*Committee on the Sustainable Development of Algal Biofuels, National Research Council of the National Academies*, 2012] emphasizing the need to improve biological and engineering variables of algal production. Important assumptions are

1. We may over or underestimate open pond evaporation, because we use 10 year average climate data. Using longer data series might produce more reliable results.
2. Considering the PBRs, there are several uncertainties. We assume that PBRs are cooled by the evaporation of water. We calculate water for cooling PBRs with a thermodynamic model, which has not been verified. If PBRs are cooled with a closed system, we overestimate the water footprint. On the other hand, cooling using a closed system requires more energy causing a trade-off between energy and water.
3. We assume that for PBRs, the filtration of the first harvest step has no water consumption. It is possible that large-scale harvesting using filtration is not practical and another method is needed, which may involve water losses.
4. This study assumes that flushing does not generate a gray WF since the water is cleaned before discharge. However, if the water is not cleaned before discharge, a gray WF is generated.
5. We excluded cooling water for electricity. For a coal fired power plant values are about 170 m^3/TJe [*BP International Ltd*., 2013], which is small compared to the WF of algae.
6. Regarding the energy balance, there are several uncertainties that can have significant influence. The amounts of urea and superphosphate needed are estimated based on the lipid content. Nutrient use can have a significant impact on the energy balance, so more information on the amounts needed could reveal both under and overestimation of energy inputs. Our output-input ratios based on specific case studies range from 1.13 to 1.98, which is a small range compared to results from existing literature. The EOI overview given by the *Committee on the Sustainable Development of Algal Biofuels, National Research*

Council of the National Academies [2012], for example, gives values for open ponds ranging between 0.13 and 7.01, while most PBRs have a net negative energy balance. Also *Murphy and Allen* [2011] indicate that for current technologies more energy is needed to produce the algae than the energy output. We assumed the use of the most recent technology in which apart from the biodiesel also the other coproducts, such as glycerol, pyrolysis oil, biogas, and hydrogen are used for energy purposes, causing a more favorable EROI value.

7. The PBRs modeled by *Slegers et al*. [2011] for the Netherlands, France, and Algeria, use both heating and cooling to keep the temperature constant at 23°C. The energy required for heating is not taken into account, but it is likely that these systems are unfit for biofuel production in this form.
8. The ERE factor used is an average value for the United States, but this value varies among countries. Since the ERE value has a large influence on the energy balance, this can imply an over- or underestimation of the energy requirements.
9. We assume that all biofuels, including the gases, are applied for transportation. However, the production of a wide range of biofuels from microalgae has only been performed on a laboratory scale yet, and does not apply for the case studies. When a fraction is wasted, we underestimate the total blue WF and total land use.
10. We excluded the energy needed for the treatment of wastewater. Also, we excluded the energy to supply the water, e.g., groundwater pumping, or surface water intake. When there is sufficient water available, these energy requirements are a minor part of algae cultivation. For example, *Plappally and Lienhard* [2012] report energy requirements for wastewater treatment between 0.04 and 5.40 MJ/m^3. However, when water needs to be transported over long distances or when desalinated water is used, energy requirements could form a substantial part of total requirements.
11. Considering the upscaling of the systems, there are several uncertainties. The CO_2 supply could be a logistical challenge when microalgal biofuel production systems operate on a large scale. Moreover, the area required for the systems may have been underestimated in this study because in some of the smaller systems only the pond area is counted as system area, but larger facilities also need infrastructure (roads, pipes, etc.) to operate.
12. The focus of this study was on freshwater for microalgae. Using saltwater algae grown in a saline environment instead could reduce the blue WF substantially [*Committee on the Sustainable Development of Algal Biofuels, National Research Council of the National Academies*, 2012]. Another option could be to use wastewaters from municipal, agricultural, and industrial activities [*Pittman et al*., 2011], and in this way reduce the nutrient requirements and thus energy inputs of algae cultivation. A drawback could be that the availability of wastewater is limited.

4.2. Putting the Results in Perspective

The WF of the net energy provided by microalgal biofuels varies from 8 to 193 m3/GJ, a difference of a factor of 25. Other studies show that the global average green+blue WF of the gross energy for biodiesel crops ranges from 150 m^3/GJ for oil palm to 4723 m3/GJ for coconuts [*Mekonnen and Hoekstra*, 2011]. This means that microalgal biofuels have a significantly smaller WF per unit of energy when the production system is chosen carefully. We also show, however, that when microalgae-based biofuels provide 3.5% of the EU transportation fuels in 2030, this would require between 7 and 165 Gm^3 of water and an area between 17,000 and 168,000 km^2. The present blue WF within the EU28 is 47 Gm^3/yr [*Hoekstra and Mekonnen*, 2012]. The most efficient microalgae biofuel system would thus require about 15% of the current blue water consumption in the EU to produce 3.5% of the transportation fuels. If *all* transportation fuels would be produced through the most efficient microalgae production systems, the blue WF in the EU28 would increase fourfold. In this way, water for biofuels would severely compete with water for food and other purposes. With respect to land use, if *all* transportation fuels in the EU28 would be produced by the most efficient microalgae production system, an area would be needed equivalent to one fourth the agricultural area of the EU28.

While land and water availability are often considered issues of global concern, there is wide variation in the availability of these resources. Upscaling algae production systems to provide substantial amounts of biofuels produced in a sustainable way requires careful selection of areas without water scarcity. Figure 7, adopted from *Hoekstra et al*. [2012], shows that in August, a period with sufficient global radiation available for algae growth in the northern hemisphere, large areas suffer from blue water scarcity, limiting

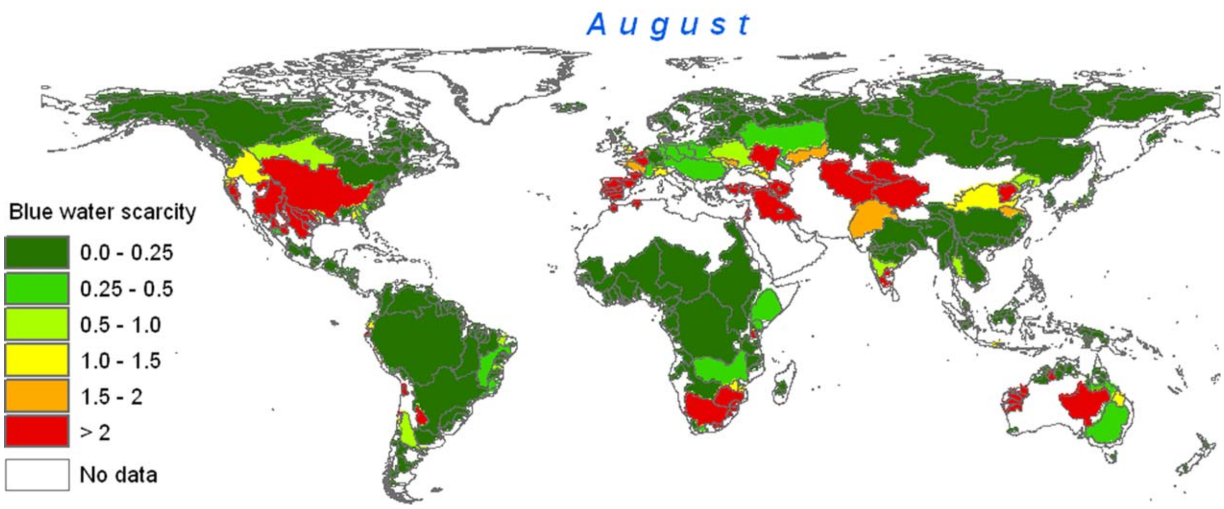

Figure 7. Global blue water scarcity map for August [*Hoekstra et al*., 2012].

production. Moreover, the focus should not only be on efficient use of water resources in water-scarce areas alone, because using water more efficient in the water abundant parts of the world contributes to an increase of production [*Hoekstra*, 2014].

5. Conclusions

The WF of microalgal biofuels produced in seven microalgae production cases are evaluated. The blue WF of the net energy provided by microalgal biofuels are concluded to be significantly smaller compared with fuels from other energy crops. The values of WF from different microalgae production locations vary between 8 and 193 m^3/GJ. The difference of WF is caused by both the climate feature of a location and the concept of a microalgae production system. Differences between conversion routes for the same system are small, where WFs of dry conversion are slightly smaller due to more favorable ERE values related to dry conversion. The major factors contributing to the WF are open pond evaporation and, in the case of PBRs, water used for PBR cooling. The WF of PBRs can be reduced by cultivating microalgae that grow at higher temperatures or to apply closed cooling systems. Although algae have a high requirement of fertilizer, we assumed that wastewater is properly treated. If this is not the case, water pollution might occur making the production unsustainable. The systems considered have an energy balance that is in equilibrium, providing almost no net energy, to positive, with EOI ratios varying between 1.13 and 1.98. Systems with relatively large lipid content have a more positive energy balance than systems with relatively small lipid content, meaning they are more interesting for biofuel production. The land use for the production of microalgal biofuels varies from 20 to 200 m^2/GJ. To produce 3.5% of the energy required for road transport in the EU in 2030, 7–165 Gm^3 of blue water and an area of 17,000–168,000 km^2 is needed. Our results show large differences in WFs and land use among microalgae. Some microalgal biofuels have much lower blue WFs and lower land use for production than other biofuel feedstocks, making them an interesting subject for further development. Our scenario analysis for Europe based on real-world facility data shows that if *all* transportation fuels would be produced through the most efficient microalgae production systems, the blue WF in the EU28 would increase fourfold and an area would be needed equivalent to one fourth the agricultural area of the EU28. In this way, water and land for biofuels would severely compete with water and land for food and other purposes. Especially in summer, when algae grow fast, algae production would increase water scarcity and put additional pressure on freshwater and land resources. The large water and land needs, with increasing water scarcity in summer does not make biofuels from algae a sustainable scenario for Europe.

Notation

β	conversion factor from kWh to GJ (0.0036).
CH_4	methane.
C_2H_6	ethane.

C_3H_8	propane.
CO	carbon monoxide.
CO_2	carbon dioxide.
dw.	dry weight.
ERE	energy required for energy factor.
EOI-ratio	energy output-input ratio.
H_2	hydrogen.
HHV	higher heating value.
IEA	international energy agency.
lgp	length of growing period.
PBR	photobioreactor.
Ψ	ERE factor symbol.
SCWG	supercritical water gasification.
TAG	triacylglycerides.
WF	water footprint.

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References

Batan, L., J. C. Quinn, and T. H. Bradley (2013), Analysis of water footprint of a photobioreactor microalgae biofuel production system from blue, green and lifecycle perspectives, *Algal Res.*, *2*(3), 196–203.
Becker, E. W. (1994), *Microalgae: Biotechnology and Microbiology*, Cambridge Univ. Press, N. Y.
Blok, K. (2006), *Introduction to Energy Analysis*, Techne Press, Amsterdam.
BP International Ltd. (2013), *Water in the Energy Industry, An Introduction*, London, U. K.
Chisti, Y. (2008), Response to Reijnders: Do biofuels from microalgae beat biofuels from terrestrial plants?, *Trends Biotechnol.*, *26*, 351–352.
Clarens, A. F., E. P. Resurreccion, M. A. White, and L. M. Colosi (2010), Environmental life cycle comparison of algae to other bioenergy feedstocks, *Environ. Sci. Technol.*, *44*, 1813–1819.
Clarens, A. F., H. Nassau, E. P. Resurreccion, M. A. White, and L. M. Colosi (2011), Environmental impacts of algae-derived biodiesel and bioelectricity for transportation, *Environ. Sci. Technol.*, *45*, 7554–7560.
Committee on the Sustainable Development of Algal Biofuels, National Research Council of the National Academies, (2012), *Sustainable Development of Algal Biofuels*, The Natl. Acad. Press, Washington, D. C.
Dominguez-Faus, R., S. E. Powers, J. G. Burken, and P. J. Alvarez (2009), The water footprint of biofuels: A drink or drive issue, *Environ. Sci. Technol.*, *43*(9), 3005–3010.
Erb, K. H., A. Mayer, F. Krausmann, C. Lauk, and C. Plutzar (2012), The interrelations of future bioenergy potentials, food demand, and agricultural technology, in *Socioeconomic and Environmental Impacts of Biofuels*, edited by A. Gasparatos and P. Stromberg, pp. 27–52, Cambridge Univ. Press, N. Y.
European Commission (2010), *EU Energy Trends to 2030 Update*, Brussels.
European Commission (2011), *Energy: What Do We Want to Achieve?*, Brussels.
European Union (2013), Agriculture, forestry and fishery statistics, Publications Office of the European Union, Luxembourg.
Falkena, H. J., H. C. Moll, K. J. Noorman, R. Kok, and R. M. J. Benders (2003), Household metabolism in Groningen. Dutch National Report—Groningen, *IVEM—Res. Rep. 109*, Cent. for Energy and Environ. Stud., Univ. of Groningen, Groningen, Netherlands.
FAO (2006), *Introducing the International Bioenergy Platform (IBEP)*, Rome.
Fischer, G., E. Hizsnyik, S. Prieler, M. Shah, and H. Van Velthuizen (2009), *Biofuels and Food Security*, Int. Inst. for Appl. Syst. Anal., Laxenburg, Austria.
Foley, J. A., et al. (2005), Global consequences of land use, *Science*, *309*(5734), 570–574.
Food and Agriculture Organization of the United Nations (2008), *The State of Food and Agriculture 2008. Biofuels: Prospects, Risks and Opportunities*, Rome.
Geider, R. J., and J. La Roche (2002), Redfield revisited: Variability of C:N:P in marine microalgae and its biochemical basis, *Eur. J. Phycol.*, *37*, 1–17.
Gerbens-Leenes, W., A. Y. Hoekstra, and T. H. Van der Meer (2009), The water footprint of bioenergy, *Proc. Natl. Acad. Sci. U. S. A.*, *106*(25), 10,219–10,223.
Gerbens-Leenes, P. W., A. R. Van Lienden, A. Y. Hoekstra, and T. H. Van der Meer (2012), Biofuel scenarios in a water perspective: The global blue and green water footprint of road transport in 2030, *Global Environ. Change*, *22*, 764–775.
Gleick, P. H. (1998), Water in crisis: Paths to sustainable water use, *Ecol. Appl.*, *8*, 571–579.
Government of India, Ministry of New & Renewable Energy (2008), *National Policy on Biofuels*, Gov. of India, New Delhi. [Available at http://mnes.nic.in/policy.biofuel-policy.pdf., last accessed 5 Jan. 2010.]
Guieysse, B., Q. Bysseyers, and E. Willia (2013), Variability and uncertainty in water demand and water footprint assessments of fresh algae cultivation based on case studies from five climatic regions, *Bioresour. Technol.*, *128*, 317–323.
Harto, C., R. Meyers, and E. Williams (2010), Life cycle water use of low-carbon transport fuels, *Energy Policy*, *38*, 4933–4944.
Hoekstra, A. Y. (2014), Sustainable, efficient and equitable water use: The three pillars under wise freshwater allocation, *WIREs Water*, *1*(1), 31–40.
Hoekstra, A. Y., and M. M. Mekonnen (2012), The water footprint of humanity, *Proc. Natl. Acad. Sci. U. S. A.*, *109*(9), 3232–3237.
Hoekstra, A. Y., A. K. Chapagain, M. M. Aldaya, and M. M. Mekonnen (2011), *The Water Footprint Assessment Manual: Setting the Global Standard*, Earthscan, London, U. K.
Hoekstra, A. Y., M. M. Mekonnen, A. K. Chapagain, R. E. Mathews, and B. D. Richter (2012), Global monthly water scarcity: Blue water footprints versus blue water availability, *PLoS ONE*, *7*(2), e32688.
Huntley, M. E., and D. G. Redalje (2006), CO_2 mitigation and renewable oil from photosynthetic microbes: A new appraisal, *Mitigation Adaptation Strategies Global Change*, *12*(4), 573–608.

International Energy Agency (IEA) (1999), *Energy Balances of OECD Countries, 1995–1996*, Paris.

International Energy Agency (2012), *World Energy Outlook 2012*, Organ. for Econ. Coop. and Dev., Paris.

Kadam, K. L. (2002), Environmental implications of power generation via coal-microalgae cofiring, *Energy*, *27*, 905–922.

Mekonnen, M. M., and A. Y. Hoekstra (2010), The green, blue and grey water footprint of crops and derived crop products, in *Value of Water Research Report Series, Rep. 47*, UNESCO_IHE, Delft, Netherlands.

Mekonnen, M. M., and A. Y. Hoekstra (2011), The green, blue and grey water footprint of crops and derived crop products, *Hydrol. Earth Syst. Sci.*, *15*(5), 1577–1600.

Menetrez, M. Y. (2012), An overview of algae biofuel production potential and environmental impact, *Environ. Sci. Technol.*, *46*, 7073–7085.

Moheimani, N. R., and M. A. Borowitzka (2006), The long-term culture of the coccolithophore pleurochrysis carterae (haptophyta) in outdoor raceway ponds, *J. Appl. Phycol.*, *18*(6), 703–712.

Murphy, C. F., and D. T. Allen (2011), Energy-water nexus for mass cultivation of algae, *Environ. Sci. Technol.*, *45*(13), 5861–5868.

Noorman, K. J., and A. J. M. Schoot Uiterkamp (1998), *Green Households? Domestic Consumers, Environment and Sustainability*, Earthscan, London, U. K.

OECD (2010), *OECD Factbook 2010. Economic, Environmental and Social Statistics*, Paris.

OECD/IEA (2010), *Power Generation From Coal, Measuring and Reporting Efficiency Performance and CO_2*, Paris.

Pittman, J. K., A. P. Dean, and O. Osundeko (2011), The potential of sustainable algal biofuel production using wastewater resources, *Bioresour. Technol.*, *102*(1), 17–25.

Pizarro, C., W. Mulbry, D. Blersch, and P. Kangas (2006), An economic assessment of algal turf scrubber technology for treatment of dairy manure effluent, *Ecol. Eng.*, *26*(4), 321–327.

Plappally, A. K., and J. H. Lienhard (2012), Energy requirements for water production, treatment, end use, reclamation, and discharge, *Renewable Sustainable Energy Rev*., *16*(7) 4818–4848.

Quinn, J., T. Yates, N. Douglas, J. Butler, T. H. Bradley, and P. J. Lammers (2012), Nannochloropsis production metrics in a scalable outdoor photobioreactor for commercial applications, *Bioresour. Technol.*, *117*, 164–171.

Reinders, A. H. M. E., K. Vringer, and K. Blok (2003), The direct and indirect energy requirement of households in the European Union, *Energy Policy*, *31*(2), 139–153.

Rodolfi, L., G. Chini Zittelli, N. Bassi, G. Padovani, N. Biondi, G. Bonini, and M. R. Tredici (2009), Microalgae for oil: Strain selection, induction of lipid synthesis and outdoor mass cultivation in a low cost photobioreactor, *Biotechnol. Bioeng.*, *102*(1), 100–112.

Sheehan, J., T. Dunahay, J. Benemann, and P. A. Roessler (1998), *A Look Back at the US Department of Energy's Aquatic Species Program—Biodiesel From Algae*, Natl. Renewable Energy Lab., Denver, Colo.

Singh, A., P. S. Nigam, and J. D. Murphy (2011), Renewable fuels from algae: An answer to debatable land based fuels, *Bioresour. Technol.*, *102*(1), 10–16.

Slegers, P., R. Wijffels, G. Van Straten, and A. Van Boxtel (2011), Design scenarios for flat panel photobioreactors, *Appl. Energy*, *88*(10), 3342–3353.

Stromberg, P., and A. Gasparatos (2012), Biofuels at the confluence of energy security, rural development, and food security: A developing country perspective, in *Socioeconomic and Environmental Impacts of Biofuels*, edited by A. Gasparatos and P. Stromberg, pp. 3–26, Cambridge Univ. Press, N. Y.

US Department of Energy (US-DOE) (2010), *National Algal Biofuels Technology Roadmap*, U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Biomass Program, Washington, D. C.

U.S. Energy Information Administration (2011), *Electric Power Monthly. Table 1.1 Net Generation by Energy Source: Total (All Sectors) 1996 Through October 2010*, Washington, D. C. [Available at http://www.eia.doe.gov/cneaf/electricity/epm/table1_1.html, last accessed 17 Sep. 2011.]

Vasudevan, V., R. W. Stratton, M. N. Pearlson, G. R. Jersey, A. G. Beyene, and J. C. Weissman (2012), Environmental performance of algal biofuel technology options, *Environ. Sci. Technol.*, *46*, 2451–2459.

Wigmosta, M. S., A. M. Coleman, R. J. Skaggs, M. H. Huesemann, and L. J. Lane (2011), National microalgae biofuel production potential and resource demand, *Water Resour. Res.*, *47*, W00H04, doi:10.1029/2010WR009966.

Xu, L., D. W. Brilman, J. A. Withag, G. Brem, and S. Kersten (2011), Assessment of a dry and a wet route for the production of biofuels from microalgae: Energy balance analysis, *Bioresour. Technol.*, *102*(8), 5113–5122.

Yan, J., and T. Lin (2009), Biofuels in Asia, *Appl. Energy*, *86*, S1–S10.

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

Yang, J., M. Xu, X. Z. Zhang, Q. A. Hu, M. Sommerfeld, and Y. S. Chen (2011), Life-cycle analysis on biodiesel production from microalgae: Water footprint and nutrients balance, *Bioresour. Technol.*, *102*, 159–165.

