Environmental assessment of bioethanol from onshore grown *Ulva*

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ABSTRACT
Besides biofuels from microalgae, an emerging interest in using macroalgae as feedstock for biofuel production is observable. Macroalgae have the advantage that they are much easier to harvest than microalgae so that the problem of low feedstock concentration does not arise. The environmental performance of bioethanol from onshore grown green algae is assessed using literature data and initial laboratory scale data. The optimized system model allows for producing an environmentally efficient biofuel in comparison to fossil fuel and bioethanol from sugar cane. Handling the co-product by substitution instead of energy allocation significantly reduced the environmental impacts of the system and resulted in environmental bonuses in several impact categories. Thus, the management of the co-product in the LCA model (energy allocation vs. substitution) is a key step in the LCA, as it highly influences the impact assessment results.

Keywords: Bioethanol, macroalgae, *Ulva*, eco-design, allocation, substitution

1. Introduction

Algae (microalgae and macroalgae) have recently been identified as an attractive, alternative renewable source for biofuel production compared to biomass from food or cellulosic materials (John et al. 2011; Wei et al. 2013). Marine algae production does not compete with food production, as algae do not need fresh water or arable land, but may use land depending on the culture system selected. Algae can use CO_2 from industrial emissions as carbon source. In addition, the biomass yield per unit area is higher than that for terrestrial biomass (Gao and McKinley 1994). While the production of biofuels from microalgae is intensively studied since a couple of years, the interest of using macroalgae as feedstock for biofuel production just emerges. Macroalgae have the advantage that they are much easier to harvest than microalgae so that the problem of low feedstock concentration does not arise.

To our knowledge, only a few Life Cycle Assessment (LCA) studies have been carried out so far with respect to biofuel production from macroalgae. Pilicka et al. (2011) evaluated the environmental impact of biogas production from onshore cultivated macroalgae. Langlois et al. (2012) studied environmental effects of biogas production from offshore grown seaweed. Alvarado-Morales et al. (2013) conducted an LCA study of biofuels from offshore grown brown algae in Nordic conditions, focusing on biogas production, and both bioethanol and biogas production. Aitken et al. (2014) assessed environmental burdens of biofuel production from offshore grown macroalgae, focusing on different offshore cultivation methods and the production of biogas and biogas + bioethanol.

This study assesses the environmental performance of bioethanol from onshore cultivated green macroalgae (sea lettuce). The evaluation was based on literature data and initial laboratory scale data, as industrial scale facilities for bioethanol production from macroalgae do not exist. Limits of this approach were discussed with a focus on the co-product management in the LCA model.

2. Methods

2.1. Goal and scope, and functional unit

The goal of the study is to evaluate the environmental performance of bioethanol production from onshore grown macroalgae (*Ulva* sp.) using the Life Cycle Assessment (LCA) methodology. A reference scenario (Figure 1) is assessed to determine the main contributors to the environmental impact of the system. Based on this contribution analysis, an optimized system is proposed with eco-design improvements. The functional unit of the system is the production of 1 MJ by combustion in a passenger car in order to compare the environmental impact of the combustion of bioethanol from *Ulva* with that of other fuels. Environmental impacts are assessed at midpoint level using the ILCD 2011 impact assessment method (European Commission - Joint Research Centre - Institute for Environment and Sustainability 2011).

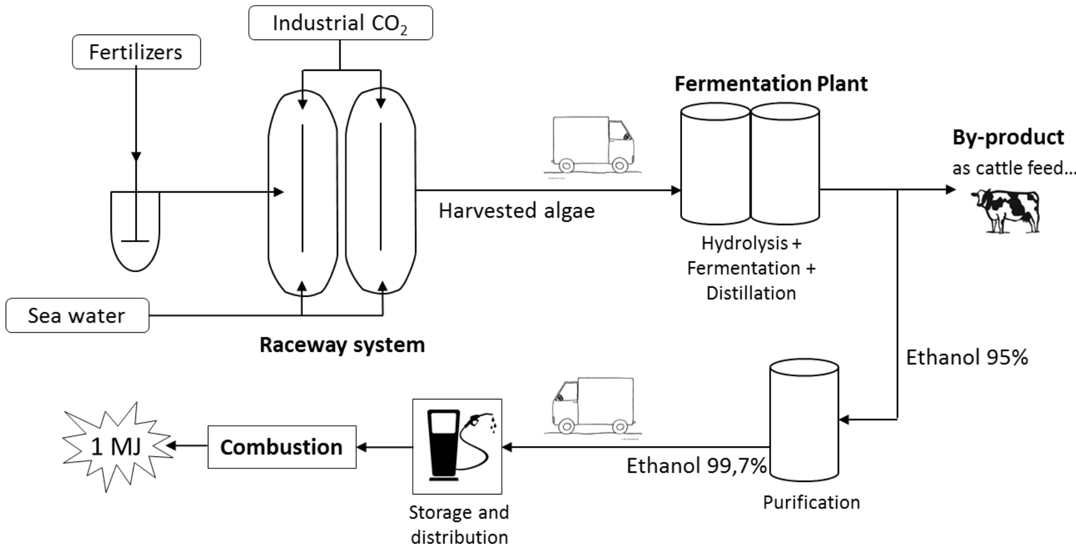

Figure 1. Schematic representation of the process chain for bioethanol production from onshore grown macroalgae.

2.2. Life cycle inventory

The life cycle inventory is based on literature data and initial laboratory scale data, as industrial scale facilities for bioethanol production from macroalgae do not exist.

2.2.1. Seaweed production

Algae (*Ulva* sp.) are cultivated in open raceways, and are stressed by nitrogen starvation to obtain high starch contents (up to 40% of the dry matter). In total, 8 raceways, each with a surface area of 500 m^2 and a water volume of 250 m^3, are used for seaweed production. Four raceways are used for growing *Ulva* at high nitrogen concentrations (high biomass yields), while the other four raceways are used for nitrogen starvation of *Ulva*. The excavated raceways are lined with an EPDM liner of 1 mm thickness and are mixed by paddle wheels. The productivity of *Ulva* is estimated to be 20 g dry weight (DW)/m^2/day with an initial algae density of 3 kg fresh weight (FW)/m^2. Assuming that the *Ulva* production site is located in Brittany, France, the *Ulva* production season has a length of seven months, ranging from April to the end of October. A season of 28 weeks is assumed, resulting in an *Ulva* production of 3.92 kg DW/m^2/season (39.2 t DW/ha/season). The seawater in the raceways is exchanged once a week with fresh seawater, filtered by a drum filter. Nutrients are supplied once a week to the first raceway system by dosing a modified f/2 culture medium (without vitamin and silicium solutions) at recommended quantities (Andersen 2005). The nutrient solutions are stored in three stainless steel tanks with an effective volume of 1 m^3 each. The tanks are mixed during the night (12 hours) to ensure homogenization of the nutrient solutions. Compressed and liquefied CO_2 is injected into the raceways through PVC pipes. Seaweed is harvested using perforated conveyor belts.

2.2.2. Bioethanol production

The harvested seaweed is transported over 60 km from its production site to the bioethanol production plant. Ethanol is produced by hydrolyzing and fermenting starch, followed by a distillation. The ethanol production process is based on ethanol production processes inventoried in the EcoInvent v2.2 database and described in detail in Jungbluth et al. (2007). Data for input of chemicals and other materials, energy consumption (electricity and heat), needed equipment, and emissions to the environment are determined as dry weight-based averages from EcoInvent inventories for bioethanol production from other starch-rich biomasses (potatoes, rye, and corn). The bioethanol yield of *Ulva* is estimated to be 0.13 g bioethanol/g DW *Ulva*.

2.2.3. Bioethanol purification, storage, distribution, and combustion

Purification, storage, distribution to service stations, and combustion of bioethanol in a passenger car are based on processes inventoried in the EcoInvent v2.2 database for bioethanol from other feedstocks.

2.2.4. Valorization of by-products and allocation

The residue of the fermentation step (named Distiller's dried grains with solubles (DDGS) by analogy) is assumed to be valorized as animal feedstock, as it is done in EcoInvent v2.2 for fermentation residues issued from other starch-rich biomasses (potatoes, corn, rye) (Jungbluth et al. 2007). The production of 1 kg ethanol from *Ulva* generates 5.74 kg (dry weight) of a DDGS equivalent. The co-product is handled by energy allocation as recommended by the European Commission for biofuels (European Commission 2009). A lower heating value (LHV) of 28.1MJ/kg is assumed for ethanol (Jungbluth et al. 2007). For the by-product, a LHV of 13.5 MJ/kg is estimated based on the LHVs of its components. This results in an environmental burden of 26.6% for the produced bioethanol and 73.4% for the by-product.

3. Results

The contribution analysis for producing 1 kg bioethanol with the reference system showed that the main contributors to the environmental impact of the system were the electricity consumption (French electricity mix: 78.1% nuclear, 10.8% hydroelectric, 4.4% coal, 3.2% natural gas, 1.5% other fossil fuels, 2.0% other), the infrastructure of the macroalgae production system (scale-up effect), and the origin of the nutrients for macroalgae production. Based on these results, an optimized system was defined, which had a modified algae production infrastructure (raceway dimensions and choice of materials) resulting in reduced electricity consumption and used fish farm wastewater as nutrient source for macroalgae.

The improved system model significantly reduced the environmental impacts of bioethanol production from onshore grown macroalgae (Figure 2). While the reference system had the highest environmental impacts on 12 of the 16 impact categories, the optimized system did not have the highest impact on any impact category. With the optimized system, bioethanol from macroalgae can be produced at lower environmental burdens than from sugar cane. The large impact of bioethanol from macroalgae on ionizing radiation resulted from the consumption of French electricity for macroalgae production. Using electricity from offshore wind power plants drastically reduced the impact on ionizing radiation to a level similar for petrol or bioethanol from sugar cane (data not shown). Macroalgae based biofuel combustion (optimized scenario) reduced greenhouse gas emissions by 57% and ozone depletion by 67% compared to fossil fuel combustion. In general, the optimized system model allows for producing an environmentally efficient biofuel in comparison to fossil fuel and bioethanol from sugar cane.

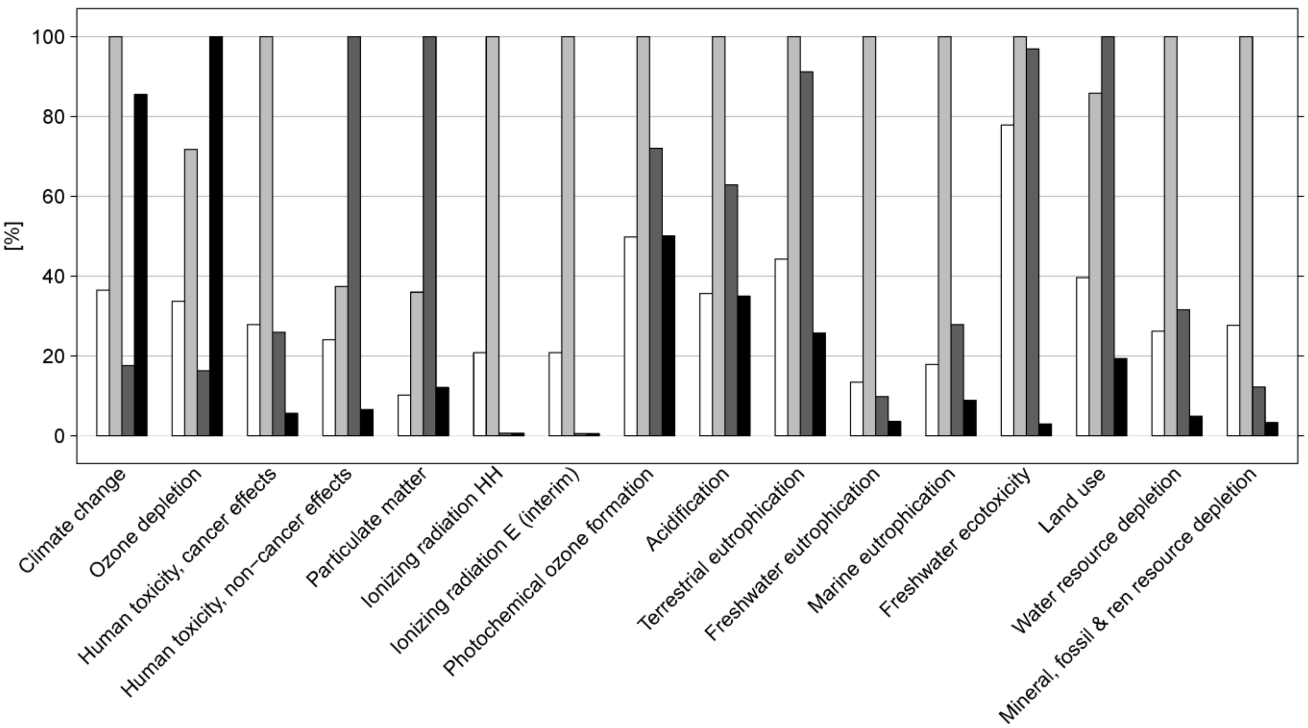

Figure 2. Life cycle impact assessment of 1 MJ obtained by combustion of petrol (black) and bioethanol from sugar cane (dark gray), from algae with the reference scenario (gray), and from algae with the optimized scenario (white).

4. Discussion

Co-product handling is a reiterated topic in LCA. We handled the obtained co-product, which was valorized as animal feedstock as for fermentation residues issued from other starch-rich biomasses (potatoes, corn, rye) (Jungbluth et al. 2007), by energy allocation as recommended by the European Commission for biofuels (European Commission 2009). As a consequence, only a quarter of the environmental burdens of the system were attributed to the produced bioethanol. Following ISO 14044 (2006), allocation should, however, be avoided wherever possible by dividing the unit process to be allocated or by expanding the product system. In order to avoid allocation, we extended the product system by substituting the produced co-product (DDGS equivalent, valorized as animal feedstock) for animal feedstocks, such as DDGS from rye, or grass silage (from intensive farming). Substitution of animal feeds is based on the dry weight of the feedstocks and their neutral detergent fiber (NDF) content, as NDF is the most common measure of fiber used for animal feed analysis. The composition of DDGS from rye was taken from the animal feed resources information system Feedipedia (www.feedipedia.com) and the one of grass silage from Yan and Agnew (2004). For the production of 1 kg ethanol from *Ulva*, 6.24 kg DDGS equivalent from *Ulva* (fresh weight) replace 5.85 kg of DDGS from rye or 10.11 kg grass silage. Whether a DDGS equivalent co-product from *Ulva* grown on intensive fish farming effluents is suitable as animal feed, due to (1) potential contamination with pharmaceuticals and other pollutants from the fish farm absorbed by the macroalgae and (2) possible aversion of animals to DDGS equivalent feed, remains, however, to be studied and discussed. The goal of comparing the different co-product handlings was to evaluate the impact of the choice of co-product handling on LCA results.

Handling the co-product by substitution instead of energy allocation significantly reduced the environmental impacts of the system and resulted in environmental bonuses in several impact categories for both replaced animal feedstocks (Figure 3). Thus, the management of the co-product in the LCA model (energy allocation vs. substitution) highly influenced the impact assessment results.

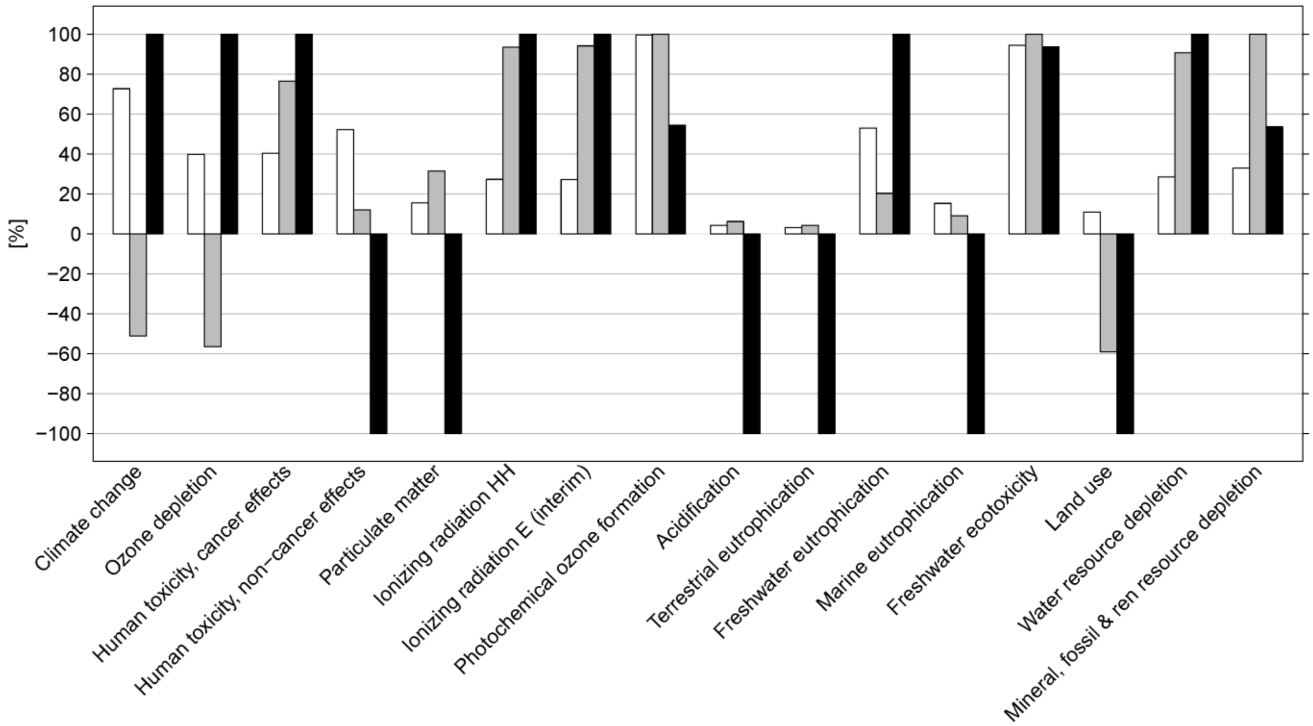

Figure 3. Life cycle impact assessment of one mega joule (MJ) obtained by combustion of bioethanol from algae with the optimized scenario applying energetic allocation (white), substitution for DDGS from rye (gray), and substitution for grass silage (black).

5. Conclusion

Based on literature data and preliminary studies, this work assesses environmental burdens of bioethanol from onshore grown macroalgae. The study revealed that an optimized system model allows for producing an environmentally efficient biofuel in comparison to fossil fuel and bioethanol from sugar cane. LCA results were highly dependent on the type of co-product management selected, as changing the co-product management from energy allocation to substitution significantly reduced the environmental burdens of the studied system.

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