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The future viability of algae-derived biodiesel under economic and technical uncertainties

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HIGHLIGHTS

- We assessed the economic viability of algal biodiesel under current uncertainties.
- A global sensitivity analysis was performed using a HDMR technique.
- Biodiesel production cost for large plants is likely to be £0.8–1.6 per kg.
- The algae oil content has the greatest effect on the biodiesel production cost.
- Annual productivity, and future oil and carbon prices are relatively important.

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ABSTRACT

This study presents a techno-economic assessment of algae-derived biodiesel under economic and technical uncertainties associated with the development of algal biorefineries. A global sensitivity analysis was performed using a High Dimensional Model Representation (HDMR) method. It was found that, considering reasonable ranges over which each parameter can vary, the sensitivity of the biodiesel production cost to the key input parameters decreases in the following order: algae oil content > algae annual productivity per unit area > plant production capacity > carbon price increase rate. It was also found that the Return on Investment (ROI) is highly sensitive to the algae oil content, and to a lesser extent to the algae annual productivity, crude oil price and price increase rate, plant production capacity, and carbon price increase rate. For a large scale plant (100,000 tonnes of biodiesel per year) the production cost of biodiesel is likely to be £0.8–1.6 per kg.

1. Introduction

Beside lignocellulosic biomass, microalgae have been identified as a versatile biomass feedstock upon which future biorefineries can be established (Williams and Laurens, 2010). Although microalgae fulfil all the major prerequisites of a sustainable biofuel feedstock there are still several technical challenges holding back the large scale production of liquid algal biofuels in an economic and environmentally-benign manner. The majority of these are related to the high energy requirements and costs of the cultivation and conversion processes.

The technical process of algal biodiesel production includes several different technology components: algal growth, algae dewatering, oil extraction, oil esterification, and a process for the conversion of the oil-extracted algae. The algae growth systems are primarily limited to two types: open pond raceways and photobioreactors (PBRs). Generally, the biomass yields from PBRs are higher than from open pond raceways; albeit, only at the price of higher capital and operating costs (Richardson et al., 2012). The annual yield of algal crops ranges from 50 to 150 tonnes of dry biomass per hectare. The algae lipid content usually increases if cultivated under nitrogen-deficient conditions (Yen et al., 2013). However, the inverse relationship between the lipid content and the annual productivity somewhat offsets the total amount of oil produced annually (Williams and Laurens, 2010). The required carbon for algae growth can be provided by bubbling flue gas from external sources into the growth medium, or alternatively via utilisation of wastewater. In the latter case, the treated water should be also considered as a product beside the produced biodiesel, as in this case the algae production essentially eliminates the need for the treatment of the wastewater. A major challenge concerning the production of algal biofuels in an economical and environmentally-benign manner is the low concentration of the feedstock

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which is typically between 0.05 wt% and 2 wt%. The initial feedstock can be effectively concentrated up to nearly 10 wt% using physical precipitation methods with low energy demands (e.g. clarifiers). However, due to small particle sizes and water-like density, further dewatering and drying of the microalgae slurries is significantly energy and carbon intensive. Therefore, it is likely that the technologies that directly fractionate and/or convert dilute microalgae slurry can offer inherent advantages over the conventional processes such as oil extraction from dried feedstock (Lardon et al., 2009). After extraction, the algae oil can be converted into biodiesel at high yields via transesterification process.

In a biofuel-only algae conversion strategy, three scenarios are plausible with respect to the conversion of the oil-extracted algae, each of which can prove more viable depending on the upstream harvesting and oil extraction processes and several other factors: (a) they can be combusted in boilers to generate process heat and electricity, (b) they can be converted to biogas using anaerobic digestion, and (c) they can be gasified to produce syngas, which can subsequently under go the Fischer–Tropsch (FT) process to produce more diesel fuel, or burnt in gas turbines to generate electricity.

The total production capacity of the plant is expected to have a considerable effect on the biofuel production cost due to the non-linear changes in the plant's *capital expenditure* (CAPEX) and *operating expenditure* (OPEX) with size. In addition to the above factors, the profitability of a biorefinery is heavily dependent on the commodity prices (e.g. crude oil, carbon, and fertiliser), plant life time, electricity price, and the carbon footprint of the produced biofuel. These issues, along with the other economic assumptions made in this study, are discussed in more detail in the methodology, Section 2.

Given the wide range of suggested solutions for addressing the challenges of algal biofuel production, as well as likely future improvements in annual algae productivity and lipid content, the economics of algal biorefineries are currently associated with extensive uncertainties. As an example, a summary of selected techno-economic studies for the production of algal biodiesel are given in Table 1. From the values listed in this table, one can see that the differences in the technical and economic assumptions behind the algae production and conversion processes can result in almost one order of magnitude difference in the final price of the product. Consequently, models that take into account the technical and economic uncertainties surrounding algal biorefineries are highly useful and can be employed to shed light on the viability of such plants in the future. Furthermore, although the economy of algal bioproducts has been studied in the literature, very little is known about the relative importance of the key technical and economic factors with respect to the economy of algal biorefineries. This issue has been addressed in this study using a global sensitivity analysis.

In this study, different aspects of low carbon algal biofuel production, given the current technical and economic uncertainties, are assessed. In the proposed strategy, the algae oil and the oil-extracted algae are converted into liquid biofuels, suitable for diesel engines, using transesterification and an integrated gasification/Fischer–Tropsch process, respectively. In the following section the process is described in more detail, and the assumptions and ranges over which the variables were varied are set out. Subsequently, using the High Dimensional Model Representation (HDMR) method, the extent to which each parameter can affect the economics of such plants is shown. Finally, the results obtained from an extensive Monte Carlo (MC) uncertainty analysis are presented and the economic viability under various scenarios is discussed.

2. Methods

2.1. Algae conversion process

A schematic process flow diagram of the algal biodiesel plant considered in the model is depicted in Fig. 1. The main consumption and production rates of the feedstocks and products of the key process units, for the production of 1 kg algal diesel, are given in Table 2. The algae is grown in the PBRs using carbon dioxide from an adjacent power plant. In the described process, 2.6 kg dry algae is needed to produce 1 kg algal diesel, of which 0.8 kg is produced via lipid transesterification and 0.2 kg via gasification of the oil-extracted algae followed by the Fischer–Tropsch process. This would approximately require 5.3 kg of CO_2 from the flue gas. Considering typical CO_2 concentrations in the flue gases of a gas-fired power plants (i.e. ~15 wt%), nearly 35 kg of flue gas is required to obtain 1 kg biodiesel. In the process considered in this study, the dilute algae culture is fed to a wet harvesting system in which up to 95% of its water is removed (OriginOil, 2012). The lipids are then separated using conventional solvent extraction process to allow for direct conversion into biodiesel via transesterification, in which 1 kg lipids and 0.1 kg methanol are reacted to yield 1 kg biodiesel and 0.1 kg crude glycerol. Furthermore, it was assumed that 100% of the algae lipid is converted to methyl esters suitable for internal combustion engines. Based on a previous analysis by Taylor et al., 2013, an integrated gasification–FT plant was considered for the conversion of the residues into synthetic diesel and naphtha. Here, the term *algal diesel* is used to collectively refer to the combined biodiesel and synthetic diesel

Table 1
Selected values from the previous techno-economic assessment reports for the production of algae and algae-derived biodiesel. The oil density, dollar to pound ratio, and euro to pound ratio were assumed to be 930 kg/m^3, 0.63, and 0.78, respectively.

Product	Cultivation system	Oil content (wt%)	Capacity (tonnes/year)	Price (£/kg)	Ref.
Algae	PBR		4.1×10^3	3.23	Norsker et al. (2011)
Algae	Pond		2.1×10^3	3.86	Norsker et al. (2011)
Algae	Combined	35		0.26	Williams and Laurens (2010)
Algae oil	PBR	30	1.0×10^2	0.95	Chisti (2007)
Algae oil	Pond	30	1.0×10^2	1.22	Chisti (2007)
Biodiesel	PBR		3.5×10^4	5.59	Richardson et al. (2012)
Biodiesel	Pond		3.5×10^4	2.28	Richardson et al. (2012)
Biodiesel	PBR	20	1.5×10^6	6.56	Taylor et al. (2013)
Biodiesel	PBR	20	1.0×10^8	4.19	Taylor et al. (2013)
Biodiesel	Combined	35		1.06	Williams and Laurens (2010)
Biodiesel	Combined	35		2.42	Delrue et al. (2013)
Green diesel	PBR	25	3.5×10^4	11.40	Davis et al. (2011)
Green diesel	Pond	25	3.5×10^4	5.37	Davis et al. (2011)