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Techno-economic assessment of carbon-negative algal biodiesel for transport solutions

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HIGHLIGHTS

- A systems-level techno-economic analysis is presented for biodiesel from algae.
- Four production routes are explained, using currently available technology.
- A promising route converts algal solids and lipids separately.
- Economic scaling indicates profitable production of algal biodiesel.

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ABSTRACT

This paper presents a techno-economic analysis of carbon-negative algal biodiesel production routes that use currently available technologies. The production process includes the following stages: carbon–neutral renewable electricity generation for powering the plant, algal growth in photobioreactors, algae dewatering and lipid extraction, and biofuel conversion and refining. As carbon dioxide is consumed in the algal growth process, side products are not burned (with CO_2 release), and the energy supplied to the entire production process is obtained from concentrated solar power, the whole system is assumed carbon footprint negative. Under assumptions related to economics of scale, the techno-economic model is extended to account for varying industrial scales of production. Verified data from a selection of commercially available technologies are used as inputs for the model, and the economic viability of the various production routes is assessed. From the various routes investigated, one scheme involving combined gasification and Fischer–Tropsch of algal solids to produce biodiesel along with conversion of algal lipids into biodiesel through transesterification was found to be promising. Assuming a typical economic scaling factor of 0.8, an algal biodiesel process with an annual production rate of 100 Mt/year is identified to achieve a biodiesel price comparable to the current conventional diesel price (approximately £1.39/litre at the pump, or $114/barrel of crude) with a discounted break-even time of 6 years.

1. Introduction

The depletion of liquid fossil fuels, growing concerns related to greenhouse gas (GHG) emissions, and increasing demand for transport fuels require rapid development and implementation of large-scale sustainable alternatives.

Proven global oil reserves were estimated as high as 1.3 trillion barrels in 2009 [1] – a volume that can only support the present rate of global liquid fuel consumption (31 billion barrels annually in 2008 [2]) for another four decades. However, other sources have argued that these estimates are overly optimistic and that reserves could run out much sooner [3–5]. The transport fuel sector accounted for 54% of the total liquid fuel consumption [2], and it is predicted to increase by 50% by 2030 [6]. Additionally global energy consumption resulted in 30 billion tonnes of GHG emissions, with transport fuel contributing to 20% of the total [2].

Advantages such as high energy densities and stability of storage and transport lend liquid hydrocarbons a significant role in the transport fuel sector (over 90% of transport fuel was composed of hydrocarbons in 2010 [7]). Hydrocarbons of the type used in liquid transport fuels such as diesel can be produced either from

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Nomenclature

FT	Fischer–Tropsch
ROI	return on investment
GHG	greenhouse gas
PV	photovoltaic
CSP	concentrated solar power
PBR	photobioreactor
UNFCCC	United Nations Framework Convention on Climate Change
CAPEX	capital expenditure (£)
OPEX	operating expenditure (£/year)
C	cost (£)
Q	capacity
ϕ	Economics of Scale Exponent
RTFO	Renewable Transport Fuels Obligation
EU ETS	Europe Emissions Trading System
TRL	Technology Readiness Level

crude oil or from renewable sources (producing biodiesel). The similarity in composition suggests that biodiesel is an appropriate supplement or a direct alternative to diesel [8,9].

Generally biodiesel is defined as diesel derived from organic matter over a relatively short period of time (compared with lengthy time scales required for formation of fossil-derived crude oil) [10]. As organic matter consumes CO_2 to grow, the cultivation of feedstock for biodiesel production offers a more environmentally sustainable solution to globally increasing transportation energy requirements. Biodiesel functions as an energy carrier, storing energy in the form of combustible hydrocarbons, much as batteries store chemical energy for conversion into electricity. Even though energy-to-work conversion efficiency of combustion engines (about up to 40% [11]) is much lower than that of electric motors (up to 93% [12]), energy-to-electricity conversion efficiency is quite low (e.g. the average energy-to-electrical efficiency for a US coal plant in 2008 was 32.5% [13]). Thus biodiesel has an overall greater efficiency than electricity within the transport sector. Compared to batteries in electric vehicles, biodiesel has a much higher energy density. Furthermore biodiesel could share the existing diesel distribution channels and infrastructure, whereas it would take a long time and significant amount of investment to build up similar levels of infrastructure for electric vehicles.

Biodiesel can be produced from many different feedstocks (e.g. corn, rape, soy, animal fat) [14], and one of the most promising sources for biodiesel production is algae, which could reportedly meet the global liquid fuel demand [8]. Chisti [8] demonstrated that microalgae typically have an oil yield 10–800 times higher but land requirements of 10–800 times less than any other biofuel feedstock. In addition microalgae do not compete with food supplies, whereas many other bio-derived feedstocks compete with food supplies either directly or indirectly [8,15]. Despite the higher productivity and reduced land requirements, large-scale algae production has not yet been realised. Technical and economic challenges to commercial development include, for example, sensitivity of many algal strains to adverse environmental conditions, limited knowledge of algal growth at practical scales, and high capital costs associated with photobioreactors [16,17].

There are a few basic requirements for the production of algal biodiesel: a cultivation system, a system to dewater the algal suspension, an optional system to extract lipids from the algal biomass, a system to convert the lipids/biomass to fuels, and electricity to power all the systems within the plant [8].

According to a 2011 editorial survey of many current top-level research endeavours into algal biofuels, producing biofuels from algae at smaller scales is already well established, but the current production methods require significant improvement [18]. Specifically, upstream advancements regarding genetic modification of algal species and downstream upgrades to separation and extraction technologies are necessary for commercial viability of biofuels produced from algae [19]. Algal biodiesel production is currently 2.5 times as energy intensive as conventional diesel, but co-production and decarbonisation of the electricity utilised in the production process will make algal biodiesel a financially and environmentally viable option for future transport energy infrastructure [20].

The details of currently available technologies necessary for the production of algal biodiesel are outlined in this paper.

Techno-economic modelling of biorefineries has been carried out in literature to varying degrees of rigorousness and at various production capacity scales (see for example [21–27]). These models also vary in product portfolios, routes to production, and motivation (e.g. CO_2 mitigation, competition with fossil-derived fuels, maximisation of return on investment, or minimisation of discounted break even time). Depending upon the assumptions employed and the design of the production plant, the economics of producing biodiesel from algae also varies, making comparisons difficult. The precise assumptions and model used in this work are described later in this paper.

The purpose of this paper is to address these critical techno-economic issues by presenting a process for the production of algal biodiesel with a negative carbon footprint. One of the major obstacles of producing algal biodiesel is the high energy requirement and the associated high cost to cultivate and process the algae into a usable liquid hydrocarbon fuel. Self-supplying utilities (water and electricity) from carbon neutral renewable energy resources, such as solar power, and maintaining an algal production process in a carbon-negative manner are key to designing an overall carbon-negative production process. Carbon-negative biodiesel is presented here on the basis that the mass of CO_2 released during the production and combustion of the biodiesel is smaller than the mass of CO_2 absorbed from the atmosphere (or a CO_2 point source) to produce it. This is in part due to the co-production of other carbonaceous products (e.g. glycerol), which are not necessarily intended for later combustion. A techno-economic model was constructed from currently available technology to determine the future of technology in this area and to identify sensitive points in the production process in economic terms.

2. Technical Process

The technical process of algal biodiesel production includes different technology components: algal growth in photobioreactors, algae dewatering and lipid extraction, and biodiesel conversion. An appropriate combination of these technology components can provide an effective production process. In order to lower the carbon footprint, concentrated solar power and desalination plants are also applied to generate carbon neutral electricity and water in this process. This section presents a broad view of each technology component included in this project and identifies some of the potential technical combinations.