Preprint Cambridge Centre for Computational Chemical Engineering ISSN 1473 – 4273

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

Benjamin Taylor[1], Ning Xiao[1], Janusz Sikorski[1], Minloon Yong[1], Tom Harris[2,3], Tim Helme[2,3], Andrew Smallbone[2], Amit Bhave[2], Markus Kraft[1]

released: 15 November 2012

[1] Department of Chemical Engineering
and Biotechnology
University of Cambridge
New Museums Site
Pembroke Street
Cambridge, CB2 3RA
United Kingdom
E-mail: mk306@cam.ac.uk

[2] cmcl innovations
Sheraton House
Castle Park
Cambridge, CB3 0AX
United Kingdom
E-mail: anbhave@cmclinnovations.com

[3] Cambridge Judge Business School
University of Cambridge
Trumpington Street
Cambridge, CB2 1AG
United Kingdom

Preprint No. 119

UNIVERSITY OF CAMBRIDGE

Keywords: Algal biomass, Low carbon technologies, Scale-out, Biofuels

Edited by
Computational Modelling Group
Department of Chemical Engineering and Biotechnology
University of Cambridge
New Museums Site
Pembroke Street
Cambridge CB2 3RA
United Kingdom

Fax: + 44 (0)1223 334796
E-Mail: c4e@cam.ac.uk
World Wide Web: `http://como.cheng.cam.ac.uk/`

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 trans-esterification 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 with a discounted break-even time of 6 years.

Contents

List of Figures

List of Tables

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 at 1.3 trillion barrels in 2009 [65] - a volume that can only support the present rate of global liquid fuel consumption (31 billion barrels annually in 2008 [17]) for another four decades. The transport fuel sector accounted for 54% of the total liquid fuel consumption [17], and it is predicted to increase by 50% by 2030 [8]. Additionally global energy consumption resulted in 30 billion tonnes of GHG emissions, with transport fuel contributing to 20% of the total [17].

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 [21]). Hydrocarbons of the type used in liquid transport fuels such as diesel can be produced either from 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 [13, 14].

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) [54]. 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% [75]), 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% [81]). 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) [4], and one of the most promising sources for biodiesel production is algae, which could reportedly meet the global liquid fuel demand [14]. Chisti [14] demonstrated that microalgae typically have an oil yield 10 to 800 times higher but land requirements of 10 to 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 [14, 68]. 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 [7, 10].

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 [14].

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 [15]. 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 [44]. 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 [67].

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 [1, 6, 20, 45, 70, 74, 85]). 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.

2.1 CSP and Desalination

As many strains of fast-growing algae grow well in areas with abundant sunlight, solar power was selected over other renewable energy sources to generate electricity in scenario presented here for simplicity. For different locations, other renewable energy sources may be favoured (e.g. hydroelectric, wind, geothermal, etc.) based on environmental and geographical conditions.

The most common commercially available solar power systems are photovoltaic (PV) cells and concentrated solar power (CSP) [33]. CSP was chosen for this process rather than photovoltaic (PV) cells for its ability to store energy and provide continuous power. CSP is a method wherein solar energy is collected and used to heat water, which creates steam to spin a turbine that turns a generator, which creates electricity. As the heat can be stored in oil, water, or sand until needed for electricity generation, CSP offers the ability to produce electricity continuously despite time of day or periodic adverse weather conditions. PV is less appropriate for this situation as it suffers from intermittency and an inability to store energy without significant modifications (e.g. large arrays of high-capacity batteries). CSP technology comes in three basic forms: parabolic trough - a long u-shaped mirror, which focuses solar light on fluid passing through a tube that runs along the length of the trough; dish - a bowl-shaped mirror, which focuses solar light onto a central collection point; and power tower - a series of mirrors that focus solar light onto a receiver located atop a tower [3]. In all three designs, solar energy is captured and converted into heat. Parabolic trough CSP was selected, as it has relatively high annual solar-to-electric efficiency of 25-30% [47], and it is the most mature and commercially available CSP technology with proven investment and operating costs [3]. A typical capacity cost of CSP is approximately £0.15m p.a. to generate 1.0 MW/hr of electricity [29, 57].

The issue of cooling water required to maintain an appropriate temperature level within the algae cultivation stage was addressed by locating the process near to the coastline. By connecting with water desalination plants, the source of water to cultivate algae can also be self-supplied [47]. Additionally, as algae differ by strain in terms of water salinity requirement [14], the desalination plant would offer the flexibility of algal strain selection. Much of the water in the whole process can be recycled, and the excess water generated by the desalination plant can, in principle, be sold to local residential authorities [47]. On this basis, the cost of the desalination plant is assumed to be balanced with its water revenue.

2.2 Photobioreactor

High algal lipid content is dependent upon the strain and the growth conditions (e.g. carbon source and nutrient content of the medium, average light intensity and temperature, mixing method and intensity, etc.) [88]. The biological limitations of any particular algal strain have the greatest control on the natural productivity of lipid and biomass; however, optimisation of the growth conditions is also necessary in order to attain maximum productivity [34]. The strain and growth conditions also impact the fatty acid profile, which must fall within biodiesel quality regulations as set out in EN 14214 [27]. Moreover, lower lipid content strains generally grow faster than high lipid content strains [73]. For the purpose of this paper, no specific strain is identified as "the choice of strain", as it is also influenced by site locations and targeted product streams. Site location-specific analysis was not within the scope of this study. A typical lipid content of 20% at industrial level of productivity was used. By using a conservative yet realistic 20% lipid content, the vast majority of reported algal strains [14] could be represented within the model, thus the production model is not limited with respect to strain selection and is not restricted to inclusion of stressing techniques (which require a much larger residence time and a subsequent increase in land area and production facility design). Although not presented here, refined iterations of the model could account for the properties of specific strains.

Two of the most common cultivation methods for large-scale production of microalgae are open ponds and tubular photobioreactors (PBRs) [14]. Both system classes allow algal growth and pollution remediation through the uptake of industrial waste nutrients and CO_2 [69]. A photobioreactor is normally a system that provides an environment devoid of many of the limitations experienced in open systems in order to promote the growth of photosynthetic algae [50]. Closed tubular PBRs generally have an advantage over open ponds in terms of lower contamination risk, less water loss, almost no CO_2 loss, less complicated process control, reduced susceptibility to weather, nearly 30 times higher biomass concentrations and requiring about 30% less land area [14, 35]. Hence PBRs were selected to cultivate and harvest algae in this process. However, PBRs entail much higher construction costs along with increased risk of overheating problems and higher dissolved oxygen levels, which need to be accounted for during the design stage. Furthermore, Davis et al. [19] calculated the near-term selling price (10% ROI) of biodiesel as £1.56/litre when cultivated in open ponds and £3.25/litre when cultivated in PBRs (converted from their report using 0.6 GBP/USD). When compared with the current end-use price of diesel in the EU (weighted average, including taxes) at approximately £1/litre [48], it is clear that further design and optimisation of growth technology and production methodologies is of paramount importance. For example the techno-economic issue of cooling water required to maintain an appropriate temperature level within the photobioreactors can be addressed by connecting PBRs to a water recycle stream.

As PBRs are a relatively new technology and vary widely in terms of materials, geometric parameters and mechanical operation, it is very difficult to predict an accurate capacity cost. Generally the capacity cost of PBRs are in the order of magnitude varying from £1,000 [64] to £10,000 to produce one tonne of dry algae per year [38].

2.3 Extraction

Microalgae are unicellular organisms suspended in water, with certain biological aspects that must be addressed in the separation and extraction steps. For example, lipids are commonly located in the interior of the algae and are surrounded by a cell wall or membrane [72]. This presence of three phases (i.e. lipid, solids, and aqueous media) requires separation of each phase or at least a subset of the phases prior to further downstream processing. If whole algae (i.e. lipid and solid phases intact) are to be converted to biodiesel through gasification followed by Fischer-Tropsch, the process only requires separation of biomass from water, i.e. algal dewatering. On the other hand, if algal lipids are to be converted to biodiesel through transesterification, the process will also require an extraction step, whereby the lipid is extracted from the solid biomass [12, 62].

A solar dryer is one type of technology to separate biomass from the suspending aqueous medium. This technology works on the principle of converting sunlight to heat in order to dry the microalgae [49]. In its most simplistic form, a solar dryer can be merely a region within the production facility where algal sludge (wet algal biomass that has been filtered from the growth media) is exposed to the sun for a set time until most of the water has evaporated, such as on a moving conveyor belt between process steps or in confined storage vessels. In this study, it is assumed that energy inputs can be neglected for this step and no biomass is lost from this process. Using a simple ventilated storage vessel, the capacity cost of a solar dryer is assumed to be negligible compared to that of the other technologies included in the overall process.

Generally lipid extraction can be classified into two methods, mechanical and chemical [58], and these techniques are often performed in conjunction to varying degrees (see for example [9]). Mechanical methods could be expression or ultrasonic-assisted extraction, and chemical methods could include hexane solvent, Soxhlet extraction, or supercritical fluid extraction. With consideration of possible downstream processing to include co-production of valuable commodity products, such as nutraceuticals, pharmaceuticals, cosmetics, and animal feed, mechanical extraction can be advantageous over the chemical extraction route. Mechanical extraction ensures a solvent-free product stream that may be used to target niche “chemicals-free” markets. It also allows for isolation of high-value products from the lipid stream prior to any optional chemical extraction or reactions such as transesterification of the lower-value lipids. Separation of all three phases in a single step is also possible, and this may reduce costs and technical challenges associated with each individual step. For example, an existing, proven extraction technology applies an electromagnetic field to crack an alga’s cell wall and release lipid from biomass (including carbohydrates and proteins), and subsequently the lipid, water, and solid biomass are gravity separated [59]. In addition, water could be recycled at the extraction stage: a partial volume of the water after the extraction stage could be pumped back to photobioreactors, and the balance volume of the water could be pumped back to the CSP and desalination for recycling and cooling purposes.

As extraction technology varies widely in design and operation, so do the associated costs. For the single step extraction, generally it has capacity costs in the orders of magnitude from £1,000 to £10,000 to separate one tonne of algal suspension per annum [59].

2.4 Biomass-to-Biodiesel Conversion

The most common biomass-to-biodiesel conversion methods are 1) gasification followed by Fischer-Tropsch (FT) and 2) transesterification.

Gasification and Fischer-Tropsch technology has been in use in established industries for decades to convert coal, natural gas, and low-value refinery products into a range of high-value, clean-burning fuels and chemicals, including biodiesel [16, 31, 52, 55]. The biodiesel produced can be blended with conventional diesel at any ratio with little to no engine modification [84]; thus biodiesel can be used in the current transport infrastructure [37]. The main purpose of gasification is to produce syngas comprised mainly of CO and H_2 from dry biomass. FT synthesis then converts the syngas into a mixture of liquid hydrocarbon fuels, which can be cracked, separated, and purified using existing petroleum industry technology. The combined annual capacity cost of gasification and FT technology varies from £100 to £1,000 per tonne of diesel produced, depending upon the scale [30, 51, 86].

Transesterification is another method to convert vegetable oil, animal fat, or other biological components, such as algal lipids, into biodiesel. It is a well established, simple chemical process with high yield of product as well as the co-production of glycerol [66]. In this reaction, a short chain alcohol, such as methanol, is added to react with triglycerides in the presence of a catalyst to produce mono-esters and glycerol. Typically transesterification is classified into three groups based on the catalyst used, chemical catalytic transesterification, non-catalytic transesterification and enzymatic transesterification [73]. In a recent published review [18], available algal conversion technologies were compared in terms of efficacy, and in situ transesterification for biodiesel production was presented as the most promising. Moreover, the capacity cost of transesterification relies on different catalytic methods applied but in general tends to be very low compared to gasification-FT. The relative costs are discussed later in this paper.

2.5 Technical Combination

The plant requirements of electricity and fresh water are obtained using a combined step of CSP and seawater desalination. In the next stage, exhaust gases from combustion processes within local industry and sterilised fertiliser bought from local waste water treatment facilities are provided to supply carbon dioxide and nutrients for algae to grow in photobioreactors. The process then may include different combination possibilities of extraction and conversion stages to produce biodiesel. The choice of the most feasible combination is highly constrained by economics. A logic diagram using various "off-the-shelf" technology components is presented in **Figure 1** in order to show some of the possible combinations (marked as different Routes in the figure).

Following an adequate growth period in photobioreactors, the mature algal suspension is harvested and can follow either Route 1, where it is dried by solar power and converted into biodiesel and naphtha by gasification and Fischer-Tropsch, or it can enter the extraction stage where lipid, solid biomass, and aqueous medium are separated. In the primary step of this stage, biomass is dewatered. A fraction of the water is recycled to cool the PBRs and the balance is sent back to the desalination plant to be sterilised and reused in the growth process. In the next stage, the lipids are extracted from the solid biomass and can be converted separately.

In Route 2, both the lipid fraction and the solid fraction are converted separately. Alter-

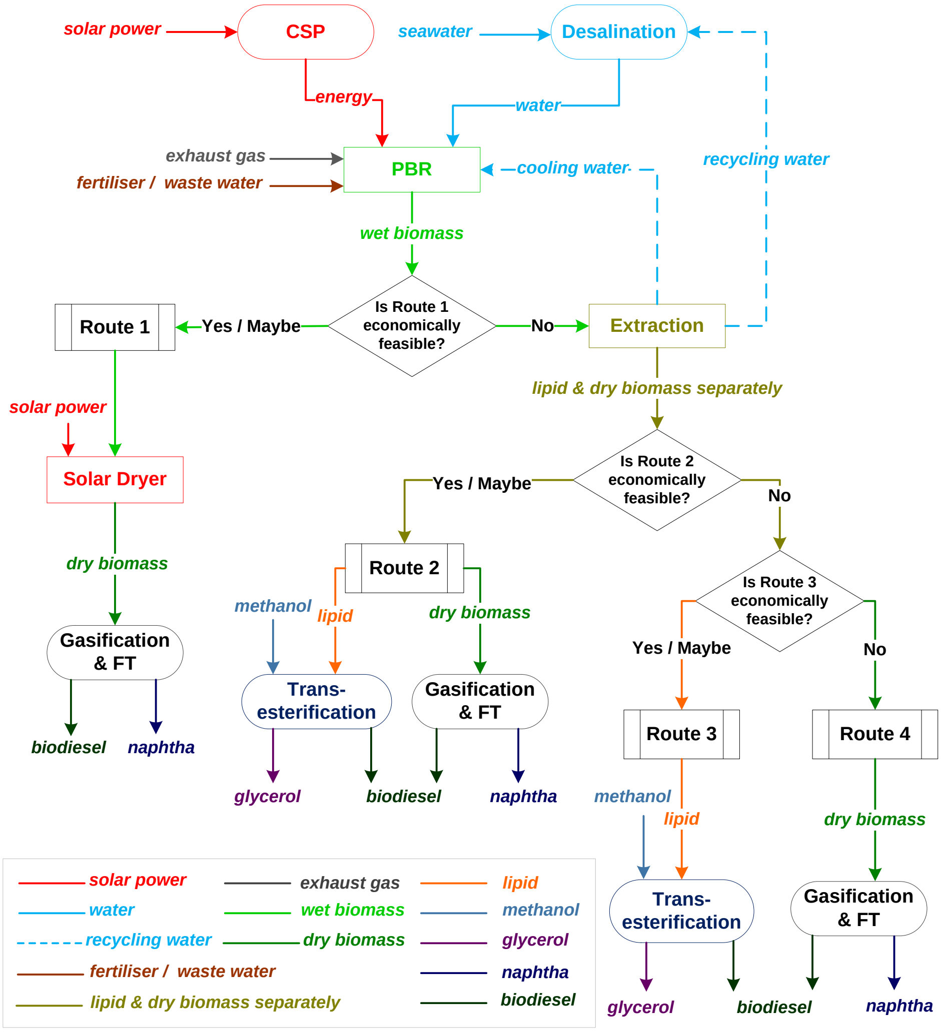

Figure 1: *Logic presentation to select the most economical combination of technologies.*

natively, Route 2 can be replaced by Route 3 if only lipids will be converted or Route 4 if only solids will be converted. Routes 3 and 4 would result in either unused biomass or unused lipids, respectively. These routes (3 and 4) are considered as they could offer the most carbon-negative solutions since the captured carbon would be buried and not released through later combustion.

As all the utilities (water and electricity) used in this process are supplied from renewable carbon-neutral solar energy [53] and the algal growth process is assumed to be carbon-negative, the overall process is considered carbon-negative. Algal growth is carbon-negative as CO_2 is captured from the atmosphere during photosynthesis and converted into biomass. Some of the biomass will be converted into biodiesel that will be burned by the consumer and some may be converted into other products (e.g. glycerol co-produced during transesterification) that will not be burned. Moreover, it is inevitable that some fraction of the algae grown will become waste, either in the form of char, captured by filtration systems, or otherwise through loss to biofouling within the PBRs and downstream processes [10, 25, 77]. As that waste will not be converted into fuels (and eventually burned by the consumer), the captured carbon will remain in solid form, rendering the growth process carbon-negative even without co-products [56].

3 Economic Evaluation

Before analysing the algal biodiesel market, its direct competitor, the diesel market, as well as a side revenue from the carbon market were studied. The capacity cost data of different technology components were collected from current technology suppliers and carefully reviewed (and wherever possible, compared with the equivalent data from literature). A techno-economic model was constructed based on that data, and the process is outlined in **Figure 1**. Under assumptions related to economics of scale, the techno-economic model was modified further at various industrial scales.

3.1 Preliminaries

Conventional oil price was analysed in order to compare with the algal biodiesel market price. It has been reported that the numerous existing biofuel conversion technologies result in products that are not cost-competitive with those from the petroleum industry [70]. However, algal biology and algal biorefineries can be optimised to improve the economics. In addition, as the algae growth process consumes CO_2, the algal biodiesel production process could generate a side revenue in terms of carbon credits by lowering CO_2 levels for other industries. Therefore it is also helpful to understand the carbon market price.

3.1.1 Oil Price

The price of oil has a significant impact on the diesel price, primarily because it accounts for 70% of the total diesel price excluding tax [82]. Crude oil price is affected generally by the fundamental demand and supply. As oil is a conventional energy resource, the supply of oil is strictly limited by its global reserve and geographical distribution. Meanwhile the demand for oil is dependent on a wide range of factors, such as global macro-economic performance, geo-politics and speculation in the futures market [80]. For instance, the oil price fall in 2008 and 2009 was a consequence of the drop in demand caused by the 2008 financial crisis. Moreover, the market for oil is global and so all sectors of the world economy may not be affected in the same way at once. For example, demand for oil caused by rapid economic growth in the Far East was a factor contributing towards the oil price rise in 2010 and 2011.

As the global oil demand is dependent on a wide range of factors, it is difficult to accurately predict future oil prices. However as oil prices have continually increased in recent years, quadrupling from 2000 to 2010 [87], it is assumed that crude oil prices will continue to increase, with direct impact on diesel prices.

Since algal biodiesel is a direct alternative to conventional diesel, its price will always compete with that of crude-derived diesel. Therefore if the target algal biodiesel price is lower than diesel price, it will be competitive in market. Furthermore, as crude oil reserves decrease, algal biodiesel is set to gain even greater market share.

3.1.2 Carbon Price

The Kyoto Protocol was set by the United Nations Framework Convention on Climate Change (UNFCCC) to unite 37 industrialised countries and the European community to reduce GHG emissions by five per cent against 1990 levels over the period 2008-2012 through carbon pricing in three ways: subsidies, carbon tax and carbon trading [79]. Subsidies are aimed at driving industry through the crossover from the refining of traditional fossil fuels toward the generation of more sustainable and ecologically-friendly energy sources, which can be politically favourable for this process. Carbon trading works similarly as carbon tax, since it requires the polluters to purchase carbon allowances in order to be allowed to emit carbon, which might generate another side revenue stream for this process as the algae growth may consume CO_2 from local industries.

Suitable governmental policies could promote algal biodiesel through laws, tax breaks, or other policy-driven incentives. However, Takeshita [74] used a sophisticated global energy model to determine that specific CO_2 abatement policies could actually limit rather than increase the competitiveness of algal biodiesel due to high CO_2 emissions from the production process and from the post-production burning of the fuel. The CO_2 emissions associated with the production process are high in Takeshita's work as the electrical power source is coal gasification and natural gas power plants. In the work presented in this paper, CO_2 emissions are significantly reduced due to the integration of alternative power generation.

3.2 Commercially Proven Data Sources

The main data sources were obtained through consulting the current technology suppliers for each process stage. It has been shown that a robust supply chain is very important for biofuel production [5]. To this end, eighteen different firms providing services in different stages of the production process were contacted in order to get a breakdown of the cost and performance offered, in addition to technical information. This was important as one of the key assessment criteria was that the technology had to be proven and ready for use today.

Holtermann and Madlener [43] recognised the large variation in available PBR technology and attempted to reconcile different reactor types by making assumptions about the materials employed in their construction. This approach provided information for costing estimations of similar reactor technology that could be built rather than relying on PBR suppliers to price their equipment and then make comparisons on the consumer end. The drawback is that the costing is more theoretical rather than representative of what is immediately available for construction by a vendor.

When dealing with data from companies, careful consideration was given to determining whether the data provided were realistic or over-optimistic. Therefore other sources including peer-reviewed journal articles, and government reports were used to examine the reliability of the suppliers' data. Online databases of government statistics provided very accurate data on key technical parameters required for analysis. Company websites occasionally yielded useful data; however, due to commercial sensitivity, they tended to provide only qualitative descriptions of their processes rather than data directly suitable for the model. The data available from vendors and that from other studies on algal biorefineries were normalised to a set of input assumptions such that cross-comparisons could be made objectively [71].

3.3 Techno-economic Model Development

With the latest technology data collected from current suppliers, a techno-economic model was constructed to modularise the process for four combinations of technology components, as illustrated in **Figure 1** in the previous section, through an analysis of the associated capital expenditure (CAPEX), operating expenditure (OPEX), and revenues. Although other technologies are also included in the model, for simplicity, only the main technologies chosen for CSP, photobioreactor, extraction, gasification and Fischer-Tropsch, and transesterification are analysed for this model. The main model outputs are the production rate, CAPEX, OPEX, and energy requirement. The input and output parameters for the selected technologies in this project are shown in **Table 1** in the Appendix with an explanation of the choices.

As most of the technology suppliers only provided services for small industrial scales at the time of this study, a pilot plant scale with a biodiesel production of 330 tonnes/year [23] was initially chosen in order to evaluate techno-economic feasibility of "off-the-shelf" technology components without the need for scaling assumptions. This reflects low technology readiness levels (TRL) for algal derived technologies where large-scale capacity plants do not exist currently.

Once the production capacity was determined, the inputs and outputs for each stage were determined by linear extrapolation of individual stage capabilities; hence the CAPEX, OPEX, and revenue generated from products for each stage could be determined. For example, for Route 2, if the final biodiesel production is fixed, the amount of lipid and solid biomass required can be determined, and the energy requirement for the whole process can also be calculated, therefore the CAPEX, OPEX and revenue generated from products of each stage can be calculated.

A standard method of discounted cash flow analysis was applied to calculate the economically promising algal biodiesel prices, and the associated parameters used in the calculation are included in **Table 2** in the Appendix along with assumptions and justifications.

3.4 Economics of Scale

In order to build the process systematically, several biodiesel production capacity scales were considered for scaling up from pilot plant to industrial scales. These scales have annual diesel production rates of 1.5M tonnes/year (an average annual UK refinery plant diesel production rate [23]), 22.5M tonnes/year (the annual UK diesel consumption + export rate [24]), and 104M tonnes/year (the annual Saudi Arabia refinery capacity [83]).

When scaling up the whole process, the economics of scale must be considered. A simple standard method is used to introduce the effect of economics of scale in CAPEX and OPEX. If the cost of a piece of plant with a capacity Q_1 is C_1, then the cost C_2 of a similar piece of plant with a capacity Q_2 can be calculated as

$$C_2 = C_1 \left(\frac{Q_2}{Q_1} \right)^{\phi} \tag{1}$$

where the value of the exponent ϕ depends on the type of plant [36]. For complete process plants, ϕ is usually taken as 0.6. However in cases of process plants where capacity is increased by duplicating a number of pieces of equipment (scale-out), ϕ will be higher and may even approach a value of 1 [42].

In the economic analysis of pilot plant scale, ϕ was set to be 0.9 for technologies requiring scale-out and 1 for those not requiring scale-out. In greater scales, smaller values of ϕ (from 0.7 to 0.9) were applied in the techno-economic model.

3.5 Key Assumptions in the Model

The model itself carries a number of assumptions, which are necessary in order to analyse the data in a manageable way. Making assumptions may limit the precision of the estimates; however the iterative approach adopted meant that the model was developed with progressive refinement of the weakest assumptions. Some of the key assumptions are outlined below.

The scaling methodology given in Equation 1 is restricted to scale-out only, and whenever scale-down was modelled (e.g. a large technology component scaled down to suit a pilot plant), a linear scaling technique was assumed (i.e. $\phi = 1$). Sustainability limitations associated with large-scale production, such as the supply of nutrients [61], were not considered in the anaylsis.

The costs of desalination plants and solar dryers are not included in this model. As water is recycled in the whole process, it was assumed that the extra fresh water generated from the desalination plant could be sold to local residential areas to cover that cost. Additionally as the solar dryer is designed to apply solar power directly, the cost was assumed negligible compared to other equipment applied in this process. Furthermore, in the transesterification process, the side-revenue generated from glycerol was assumed to balance the cost of methanol added in.

The operating expenditure of the process was assumed to be a proportion of the capital expenditure. A typical value of 6.45% [78] of the CAPEX was used to estimate overall OPEX i.e. maintenance, operating labour, laboratory cost, plant overheads, local taxes and insurance costs. Processing uptime of 330 days/year (90%) was assumed for each plant scale modelled.

The algal growth kinetics and lipid compositions were based upon our own experimental experience with lab-scale algal growth, using average oil contents of 20% and sustainable concentrations of 0.75 g/l. These values are in close agreement with those reported by Sun et al. [71] and Chisti [14].

One of the most significant assumptions was that ash and other waste products produced during the gasification stage can be removed at zero cost. The International Food Policy Research Institute states that gasification ash is an underutilised valuable product for use in the construction industry [32]; however it is unclear whether the construction industry provides sufficient demand for this ash to remove all of the waste. This assumption will need to be investigated further as it may provide additional revenue or additional costs that could significantly affect the profitability of the project. If not used in the construction industry, the carbon-containing ash and / or biomass could be buried in landfills in order to make the plant even more carbon-negative.

There are a range of governmental schemes across the world which aim to promote the growth of low carbon technology; a carbon price is one of them. For example, in the UK the Renewable Transport Fuels Obligation (RTFO) has been introduced to increase the renewable content of the road fuel mix [22]. However, in this model, it was assumed that each of the technologies would receive carbon credits within the Europe Emissions Trading System (EU ETS) for the following reasons. The EU ETS is the largest carbon trading scheme in the world and is one of the more established, having been launched in 2005 [26]. The scheme covers approximately 50% of the EU's carbon emissions and is increasing its scope in the 3rd Phase (2013–2020). Moreover, the EU ETS is linked to the mechanism established by the Kyoto protocol for global carbon trading, so this scheme holds the most relevance when taking a global perspective on decarbonisation.

It was also assumed that the side product of gasification-FT, naphtha, could be sold at the current market price on the commodities market.

For clarity when comparing technologies, it was assumed that all of the capital spending was made in Year 0. It was assumed that yields would remain constant year on year. Tax is considered at UK rates, with capital allowances according to the reducing balance method. Whilst a project such as this might expect to receive special tax treatment, the impact of special tax arrangements has not been considered in this paper, though the model allows tax parameters to be easily adjusted [42].

The Appendix shows the input values used for the model and, where applicable, the justification for the values used.

3.6 Results of Techno-economic Analysis

The pilot plant scale with a biodiesel production of 330 tonnes/year [23] was chosen in the first instance in the techno-economic model. A standard discounted break-even point of 15 years was selected for the analysis of biodiesel prices with respect to different combinations of technology components (marked as different routes in **Figure 1**). For simplicity reasons, the exponent of economics of scale was set as 0.9 for pilot plant scale as it was quite close to the suppliers' service capabilities.

The resulting fuel prices for different combinations of technology components in the process is shown in **Figure 2**, where the discounted break-even point (time after which the project has produced the same financial return as an equivalent amount of capital invested at a set compound interest rate) was set as 15 years (production uptime of 330 days/year) and ϕ was set as 0.9.

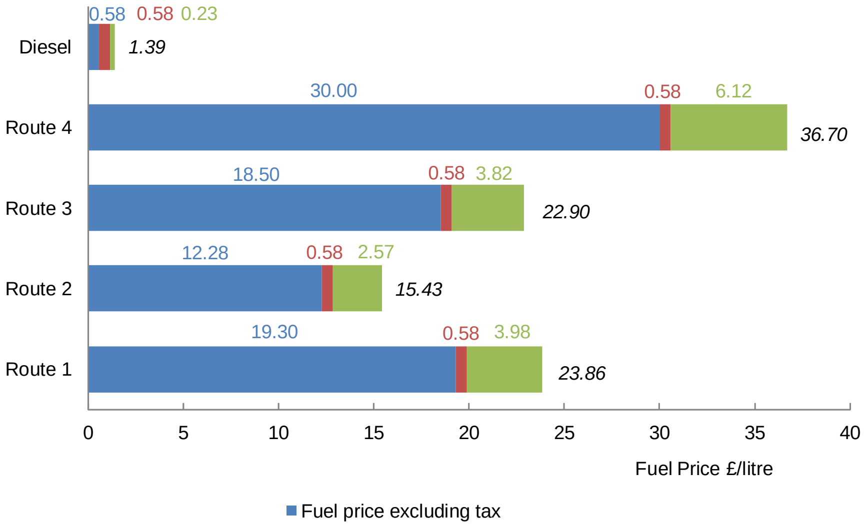

Figure 2: *The fuel prices with respect to different routes at pilot plant scale.*

From **Figure 2**, it can be seen that among the routes presented here, Route 2 (conversion of algal biomass and lipids into biodiesel through gasification-FT and transesterification) is the most economically feasible route. The targeted algal biodiesel selling price in Route 2 is approximately 40% of that in Route 4 (conversion of the extracted algal biomass into biodiesel through gasification-FT only, which would result in a waste of algal lipids), and it is nearly 65% of that in Route 1 (conversion of algal biomass into biodiesel through gasification-FT without extraction of lipids) and Route 3 (conversion of algal lipids into biodiesel through transesterification only, which would result in a waste of algal biomass).

The results of discounted cash flow analysis with respect to different routes in the process are shown in **Figure 3**, where the biodiesel price was set as £19.30/litre excluding tax, and the exponent of economics of scale was set as 0.9. This was the determined selling price for the three most financially attractive routes presented here to return on investment within 15 years. As the pilot plant's capability is similar to the capacity offered by the current technology suppliers, the pilot plant process was constructed by duplicating the supplied technology, hence a high economic exponent of 0.9 was chosen.

Figure 3 also suggests that Route 2 in this process would be more economically feasible than the other presented routes. Discounted cash flow is commonly used as a tool for investors to comparatively analyse return on investment in a company versus return through a traditional savings or investment account. Here we use the discounted cash flow analysis to compare the profitability of different routes in a set time (with a discounted break-even point of 15 years and 15% discount rate). For a fixed algal diesel price of £19.30/litre, the discounted break-even point of Route 2 process is around 30% that of Route 1. The

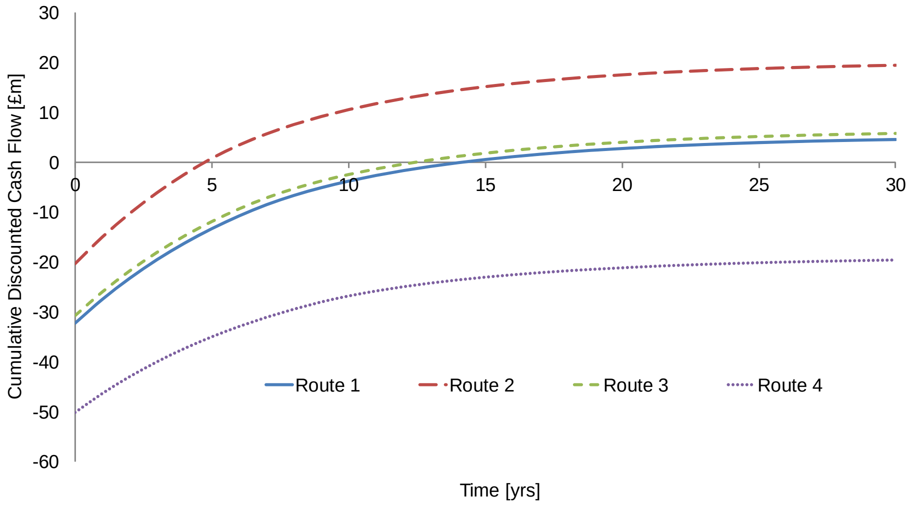

Figure 3: *The discounted cash flow analysis of the process with respect to different routes at pilot plant scale.*

discounted break-even point of Route 1 is slightly longer than that of Route 3, and the Route 4 process would not have a discounted break-even point at all.

The targeted algal fuel selling price for Route 2 shown in **Figure 2** is the most economically feasible (calculated to be £15.43/ litre) combination of technology components presented here but is still 11 times the current diesel price (£1.39/litre [28]). In order to understand the reasons behind the high targeted algal diesel price in Route 2, the CAPEX, OPEX and revenue streams were analysed in more detail as the targeted biodiesel price could be reduced by either decreasing the CAPEX and OPEX or increasing the revenue.

The results of CAPEX and OPEX for Route 2 in pilot plant scale are shown in **Figure 4**, where the discounted break-even point was set as 15 years and ϕ was 0.9.

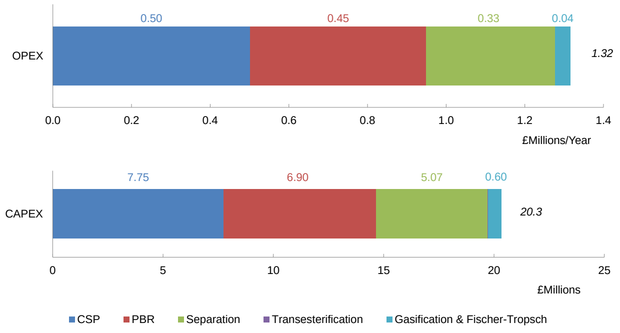

Figure 4: *The CAPEX and OPEX for route 2 at pilot plant scale.*

It has been reported that the overall biodiesel selling price is highly sensitive to many parameters, but the largest cost component is the feedstock, which accounts for 75%-80% of the total operating costs [20]. In this paper, the relative operating costs are presented differently for this estimation, primarily due to the assignment of all input energy operating costs to the centralised CSP technology component. For example, the total feedstock production operating cost (PBRs plus separation) for Route 2 totals 59%; however, these technology components constitute an additional fraction of the energy costs that are pinned to the overall CSP operating costs. From **Figure 4**, it can be seen that the most expensive stage in Route 2 is CSP to generate electricity, whose CAPEX and OPEX are nearly twice that of the second most expensive stage, PBRs. In this pilot plant scenario, the "off the shelf" CSP unit is the only oversized component, lending to disproportionate CAPEX and OPEX ratios for the individual components of the overall process. The CAPEX and OPEX for the extraction stage are quite close to that of PBRs, and the CAPEX and OPEX for conversion stages, transesterification and gasification and Fischer-Tropsh are negligible compared to that of other stages in the process. In order to cut the cost most efficiently and thereby lower the selling price of algal diesel, it is necessary to advance the technologies in CSP, PBR and separations in terms of performance improvement and cost control.

The first year's revenue for Route 2 at pilot plant scale is shown in **Figure 5**, where the discounted break-even point was set as 15 years, ϕ was set as 0.9, and the targeted algal biodiesel fuel price was £12.28/litre (same as shown in **Figure 2**).

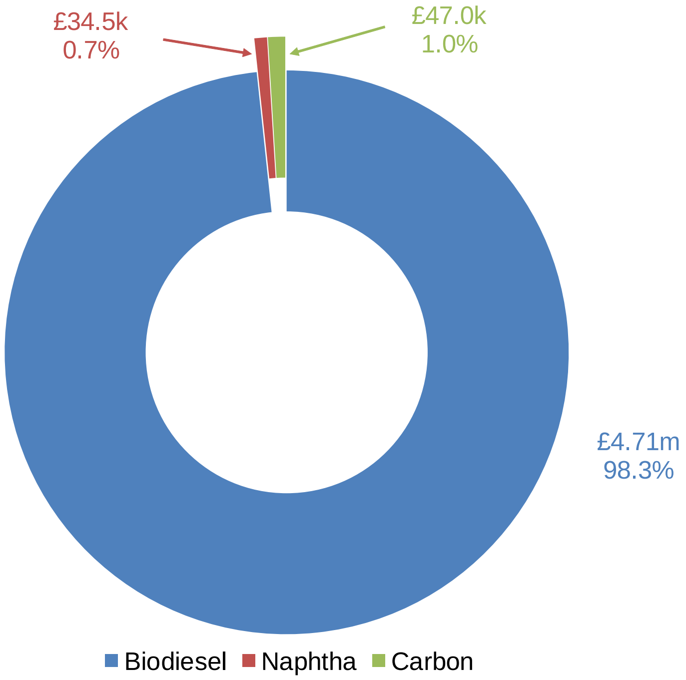

Figure 5: *The first year's revenue for Route 2 in pilot plant scale.*

From **Figure 5**, it can be seen that the revenue generated from carbon trading and side product revenue, naphtha sales, are negligible compared to the algal biodiesel sales. Therefore it would be extremely difficult to lower the biodiesel price through these particular revenue streams.

The high algal biodiesel fuel price could also be explained as the pilot plant scale technologies are not designed to be economically feasible. Scale-up of the original pilot plant might be another option to reduce the biodiesel production cost; however, here we consider only scale-out of existing technology. Three larger biodiesel production capacities are presented to illustrate the effect of scale-out on reducing the biodiesel price. The resulting prices with respect to different industrial scales in the process are shown in **Figure** 6, where the discounted break-even point is set as 15 years and ϕ is set to be 0.9.

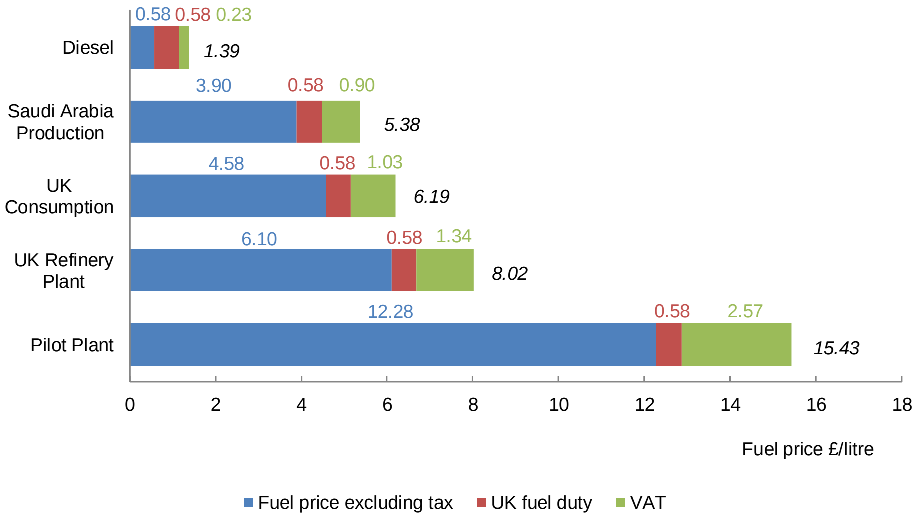

Figure 6: *The fuel prices in Route 2 with respect to different scales.*

From **Figure** 6, as the scale increases, and using the same value of economic exponent (0.9), the targeted algal biodiesel price in Route 2 is lowered effectively from £12.28/litre in the pilot plant scale to £3.90/litre in the Saudi Arabia diesel production scale. Additionally, as the scale increases, the value of the economic exponent in the economics of scales could be lowered accordingly [42]. Therefore it is important to study the impact of different values of economics exponent. The oil production of Saudi Arabia is selected in order to present such impact. The resulting fuel prices for Saudi Arabia with respect to different values of ϕ in the process are shown in **Figure** 7, where the discounted break-even point is set as 10 years and the exponent ϕ of economics of scale is set to vary from 0.7 to 0.9. However, a more detailed location-specific analysis is currently ongoing and will be published in due course.

From **Figure** 7, it can be seen that the target biodiesel price is very sensitive to the value of economic exponent. The targeted price was reduced by more than 65% by lowering the value of ϕ from 0.9 to 0.8. At $\phi = 0.8$, the targeted price (£1.96/litre) is comparable to the current diesel price (£1.39/litre). When $\phi = 0.7$, the price could be reduced to £0.96/litre, which is almost 70% of the current diesel price and makes the whole algal biodiesel process extremely economically promising. However at $\phi = 0.7$, the fuel price excluding tax is £0.22/litre, which is significantly lower than expected and might be due

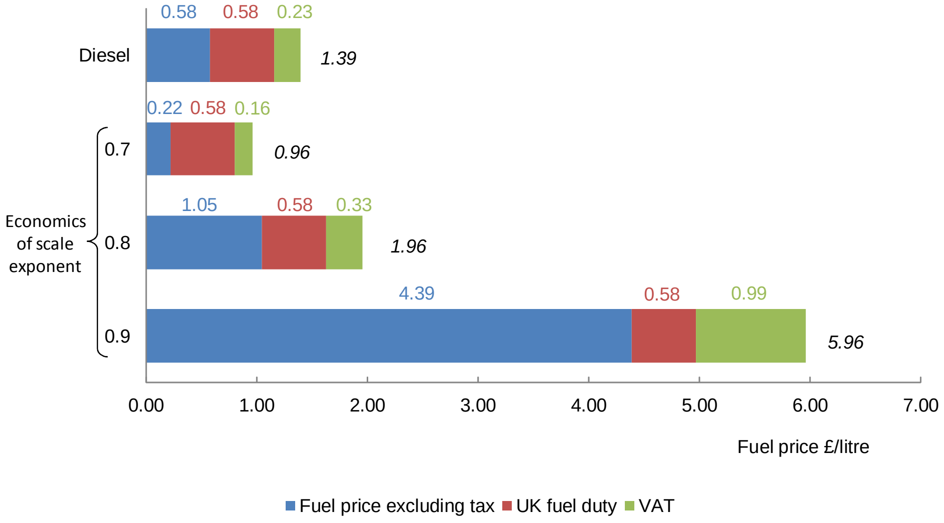

Figure 7: *The fuel prices for Route 2 at Saudi Arabia capacity scale with respect to different values of exponents of economics of scale.*

to the inherent limitations of the simplified scaling methodology and the discounted cash flow analysis. Therefore $\phi = 0.8$ was determined to be a more realistic lower limit for the exponent of economics of scale in this paper. For more accurate results, it is necessary to study the economics of scales in different processes to more depth.

4 Conclusions

A techno-economic systems-level analysis was carried out for an algal biodiesel production process concept. By varying the individual technology components and combinations of technology components within the production process, considerable differences were found in the economic feasibility of the entire process. It was shown through a simple comparative study involving CAPEX, OPEX, discounted break-even point, etc., that a certain combination of technologies offered more economically favourable production of biodiesel than others. In this combination of technologies, or production route, a single step extraction (extract biomass from water and lipid from biomass simultaneously) followed by transesterification and Fischer-Tropsch to convert algae to biodiesel was demonstrated to be more economically favourable than the others. However even for this combination, it was shown that considerable cost and technology advances are required to make smaller scales economically viable. Larger plants are required in order to lower the biodiesel price. For instance, the targeted algal biodiesel price was lowered to £1.96/litre for the Saudi Arabia oil production scale with exponent of scale factor of 0.8, which is comparable to current conventional diesel price and makes the algal biodiesel production economically promising. Further development of the parameters surrounding specific costs and relevant economies of scale for the individual technology components will evolve over time as suppliers test their equipment at larger-scale capacities. Following these developments, or perhaps coinciding with them, commercial scale production of biodiesel and other related products from algae has the potential to become economically feasible.

Acknowledgements

Part of this work was funded by the Technology Strategy Board (TSB) grant programme, "Carbon Abatement Technologies - Phase 2 competition for collaborative R&D and feasibility", grant number TS/J004553. The Technology Strategy Board is an executive body established by the United Kingdom Government to drive innovation. It promotes and invests in research, development and the exploitation of science, technology and new ideas for the benefit of business - increasing sustainable economic growth in the UK and improving quality of life.

The authors are thankful to Dr. Jethro Akroyd, Dr. Sebastian Mosbach, George Brownbridge, and Peter Man for their generous help throughout this project.

A Appendix

A.1 Key Results

Table 1: *The input and output parameters per unit equipment obtained from some of today's most economically feasible technology suppliers.*

Process Stage	Input	Capability	Output	Capability	CAPEX £	OPEX £/year
CSP	sunlight		electricity	1.59×10^5 MWh/year	2.66×10^8	1.72×10^7
PBR	electricity	1.53×10^{-1} MWh/year	biomass	4.43×10^{-2} tonne/year	6.66×10^2	4.33×10^1
	CO_2	1.02×10^{-1} tonne/year				
Separation	electricity	3.50×10^{-2} MWh/year	lipid	2.37 tonne/year	9.15×10^4	5.90×10^3
	wet biomass	1.48×10 tonne/year	solid biomass	1.24×10 tonne/year		
Transesterification	electricity	5.34×10^3 MWh/year	biodiesel	5.34×10^3 tonne/year	2.50×10^5	1.61×10^4
	lipid	5.31×10^3 tonne/year	glycerol	5.53×10^2 tonne/year		
Gasification and Fischer-Tropsch	biomass	5.48×10^5 tonne/year	biodiesel	6.35×10^4 tonne/year	3.05×10^8	1.97×10^7
			naphtha	2.72×10^4 tonne/year		

Table 2: *General parameters in the techno-economic model.*

Parameter	Value	Comment
Technology Performance	100%	There is a level of uncertainty surrounding the performance of each technology depending upon the nature of the inputs (climate, quality of material inputs), whether estimates for the output of the technology are realistic and the effect of unpredictable circumstances.
OPEX	$CAPEX \times 0.0645$	[78]
Diesel price	£0.58/litre (exl. tax)	[28]
Naphtha price	£0.43/litre (exl. tax)	Europe naphtha prices soften on lower crude values [63]
Carbon price	£15 /tonne	[2]
Biodiesel / naphtha price increase rate	1% /year	It is assumed that the biodiesel and naphtha price increase rate is the same as that of diesel.[46]
Carbon price increase rate	5.6% /year	5.6% increase based on increase required to meet UK Treasury floor price of £30 / tonne by 2020 [39].
Economics of Scale Exponents	0.7–0.9	The value of the exponent depends on different types of plants [36]. For complete process plants, the exponent is usually taken as 0.7. However for duplicating equipments process, the exponent will be higher and may even approach to a value of 1 [42].
Discount rate	15%	Based on mid-range discount rate for high risk/low maturity technologies [60]
Corporate Tax Rate	25%	UK corporate tax rate for 2012 [40]
Capital Allowances	25%	Depreciated by reducing balance method. [41]

Table 3: *CAPEX and OPEX for different routes at pilot plant scale with economic exponent of 0.9 for scale-out and 1 for scale-down.*

	Different Route	CSP	PBR	Separation	Transesterification	Gasification&FT	Total
CAPEX (£)	Route 1	1.65×10^7	1.43×10^7	N/A	N/A	1.59×10^6	3.24×10^7
	Route 2	7.75×10^6	6.90×10^6	5.07×10^6	9.66×10^3	5.97×10^5	2.03×10^7
	Route 3	1.24×10^7	1.05×10^7	7.75×10^6	1.55×10^4	N/A	3.07×10^7
	Route 4	1.97×10^7	1.66×10^7	1.22×10^7	N/A	1.59×10^6	5.01×10^7
OPEX (£/year)	Route 1	1.06×10^6	9.22×10^5	N/A	N/A	1.02×10^5	2.08×10^6
	Route 2	5.01×10^5	4.48×10^5	3.27×10^5	6.22×10^2	3.86×10^4	1.32×10^6
	Route 3	8.04×10^5	6.85×10^5	5.00×10^5	9.97×10^2	N/A	1.99×10^6
	Route 4	1.27×10^6	1.08×10^6	7.88×10^5	N/A	1.02×10^5	3.25×10^6

Table 4: *CAPEX and OPEX for different industrial scales of Route 2 with economic exponent of 0.9 for scale-out and 1 for scale-down.*

	Different Scale	CSP	PBR	Separation	Transesterification	Gasification&FT	Total
CAPEX (£)	Pilot Plant	7.75×10^6	6.90×10^6	5.07×10^6	9.66×10^3	5.97×10^5	2.03×10^7
	U.K. Refinery	2.16×10^{10}	1.35×10^{10}	9.91×10^9	2.61×10^7	2.18×10^9	4.72×10^{10}
	U.K. Consumption	2.47×10^{11}	1.54×10^{11}	1.14×10^{11}	2.99×10^8	2.50×10^{10}	5.40×10^{11}
	K.S.A. Production	9.77×10^{11}	6.10×10^{11}	4.49×10^{11}	1.18×10^9	9.86×10^{10}	2.13×10^{12}
OPEX (£/year)	Pilot Plant	5.01×10^5	4.48×10^5	3.27×10^5	6.22×10^2	3.86×10^4	1.32×10^6
	U.K. Refinery	1.40×10^9	8.76×10^8	6.39×10^8	1.68×10^6	1.41×10^8	3.05×10^9
	U.K. Consumption	1.60×10^{10}	1.00×10^{10}	7.32×10^9	1.93×10^7	1.61×10^9	3.50×10^{10}
	K.S.A. Production	6.32×10^{10}	3.97×10^{10}	2.89×10^{10}	7.62×10^7	6.37×10^9	1.38×10^{11}

Table 5: *CAPEX and OPEX at Saudi Arabia scale of Route 2 with different economic exponents.*

	Different Exponent	CSP	PBR	Separation	Transesterification	Gasification&FT	Total
CAPEX (£)	0.9	9.77×10^{11}	6.10×10^{11}	4.49×10^{11}	1.18×10^{9}	9.86×10^{10}	2.13×10^{12}
	0.8	3.92×10^{11}	6.16×10^{10}	8.10×10^{10}	4.62×10^{8}	5.19×10^{10}	5.87×10^{11}
	0.7	1.58×10^{11}	6.22×10^{9}	1.46×10^{10}	1.80×10^{8}	2.73×10^{10}	2.06×10^{11}
OPEX (£/year)	0.9	6.32×10^{10}	3.97×10^{10}	2.89×10^{10}	7.62×10^{7}	6.37×10^{9}	1.38×10^{11}
	0.8	2.54×10^{10}	4.00×10^{9}	5.22×10^{9}	2.98×10^{7}	3.35×10^{9}	3.80×10^{10}
	0.7	1.02×10^{10}	4.04×10^{8}	9.43×10^{8}	1.16×10^{7}	1.76×10^{9}	1.33×10^{10}

A.2 Sample Calculation for Route 1 at Pilot Plant Scale

Here is the sample calculation for CAPEX, OPEX, revenue and fuel price for the algal biodiesel process in Route 1 to meet the annual pilot plant diesel production of 3.30×10^2 tonne/year. The calculation of CAPEX and OPEX is based on the method of economics of scale ($\phi = 0.9$) discussed in the paper, and the analysis of net present value is based on the assumption of discounted break-even point of 15 years.

A.2.1 Sample Calculation for CAPEX and OPEX

In the algal biodiesel process through Route 1 discussed in the paper, CSP and desalination plants are applied to generate electricity and water required in the whole process. Algae are grown and harvested in PBRs, and then the algae suspension is dried by solar dryer. The dry algae are converted into biodiesel with side product of naphtha through gasification and Fischer-Tropsch. As discussed in the paper, the costs of desalination plant and solar dryer are negligible compared to that of the others, and the cost of land and water is not included. Therefore, the CAPEX and OPEX of the process in Route 1 should only include the CAPEX and OPEX for CSP, PBR and gasification & Fischer-Tropsch plants.

Data given by selected gasification & Fischer-Tropsch supplier are provided below, (also shown in **Table 1**). For each unit of gasification & Fischer-Tropsch supplied, it has

$$\begin{aligned}\text{Annual diesel production} &= 6.35 \times 10^4 \text{tonne/year}\\ \text{Annual naphtha production} &= 2.72 \times 10^4 \text{tonne/year}\\ \text{Annual biomass requirement} &= 5.48 \times 10^5 \text{tonne/year}\\ \text{CAPEX per unit} &= £3.05 \times 10^8\end{aligned}$$

Therefore to meet the design requirement, annual pilot plant diesel production of 3.30×10^2 tonne/year, it must have

$$\begin{aligned}\text{Annual naphtha production} &= \left(\frac{3.30 \times 10^2}{6.35 \times 10^4}\right) \times 2.72 \times 10^4 && = 1.41 \times 10^2 \text{tonne/year}\\ \text{Annual biomass requirement} &= \left(\frac{3.30 \times 10^2}{6.35 \times 10^4}\right) \times 5.48 \times 10^5 && = 2.85 \times 10^3 \text{tonne/year}\end{aligned}$$

A simple standard method was used to introduce the effect of economics of scale in CAPEX and OPEX [36]. If the cost of a piece of plant of capacity Q_1 is C_1, and the cost C_2 of a similar piece of plant of capacity Q_2 can be calculated as

$$C_2 = C_1 \left(\frac{Q_2}{Q_1}\right)^{\phi}$$

where the value of ϕ depends on different types of plants [36] and as long as $\frac{Q_2}{Q_1} \geq 1$, otherwise $\phi = 1$. In the calculation of CAPEX for the process at pilot plant scale, the exponent of 0.9 was chosen for any scale-out as the capacity is of the same order of magnitude as that offered by these technologies. OPEX of the equipment is estimated as $OPEX = CAPEX \times 0.0645$ [78].

CAPEX and OPEX for gasification & Fischer-Tropsch required to meet the design could be calculated through

$$\begin{aligned}
\text{CAPEX} &= \left(\frac{3.30 \times 10^2}{6.35 \times 10^4}\right)^1 \times 3.05 \times 10^8 &&= £1.59 \times 10^6 \\
\text{OPEX} &= 1.59 \times 10^6 \times 0.0645 &&= £1.02 \times 10^5/\text{year}
\end{aligned}$$

Similarly data given by selected PBR supplier are provided below, (also shown in **Table 1**). For each unit of PBR supplied, it has

$$\begin{aligned}
\text{Annual biomass production} &= 4.43 \times 10^{-2}\text{tonne/year} \\
\text{Annual CO}_2\text{ consumption} &= 1.02 \times 10^{-1}\text{tonne/year} \\
\text{Annual electricity requirement} &= 1.53 \times 10^{-1}\text{MWh/year} \\
\text{CAPEX per unit} &= £6.66 \times 10^2
\end{aligned}$$

Therefore to meet the design requirement, annual biomass requirement of 2.85×10^3 tonne/year, it must have

$$\begin{aligned}
\text{Annual CO}_2\text{ consumption} &= \left(\frac{2.85 \times 10^3}{4.43 \times 10^{-2}}\right) \times 1.02 \times 10^{-1} &&= 6.56 \times 10^3\text{tonne/year} \\
\text{Annual electricity requirement} &= \left(\frac{2.85 \times 10^3}{4.43 \times 10^{-2}}\right) \times 1.53 \times 10^{-1} &&= 9.84 \times 10^3\text{MWh/year}
\end{aligned}$$

Then CAPEX and OPEX for PBR required to meet the design could be calculated through

$$\text{CAPEX} = \left(\frac{2.85 \times 10^3}{4.43 \times 10^{-2}}\right)^{0.9} \times 6.66 \times 10^2 \qquad = £1.43 \times 10^7$$
$$\text{OPEX} = 1.42 \times 10^7 \times 0.0645 \qquad = £9.22 \times 10^5/\text{year}$$

In addition, data given by CSP supplier are provided below, (also shown in **Table 1**). For each unit of CSP supplied, it has

$$\text{Annual electricity production} = 1.59 \times 10^5 \text{MWh/year}$$
$$\text{CAPEX per unit} = £2.66 \times 10^8$$

Therefore to meet the design requirement, CAPEX and OPEX could be calculated through

$$\text{CAPEX} = \left(\frac{9.84 \times 10^3}{1.59 \times 10^5}\right)^{1} \times 2.66 \times 10^8 \qquad = £1.65 \times 10^7$$
$$\text{OPEX} = 1.65 \times 10^7 \times 0.0645 \qquad = £1.06 \times 10^6/\text{year}$$

Table 6: *CAPEX and OPEX for route 1 at pilot plant scale with economic exponent of 0.9 for scale-out and 1 for scale-down.*

Different Cost	CSP	PBR	Gasification&FT	Total
CAPEX	1.65×10^7	1.43×10^7	1.59×10^6	3.24×10^7
OPEX	1.06×10^6	9.22×10^5	1.02×10^5	2.08×10^6

A.2.2 Sample Calculation for Revenue

The algal biodiesel process through Route 1 at pilot plant scale diesel production of 3.30×10^2 tonne/year will generate

$$\text{Annual naphtha production} = 1.41 \times 10^2\text{tonne/year}$$
$$\text{Annual biodiesel production} = 3.30 \times 10^2\text{tonne/year}$$
$$\text{Annual CO}_2\text{ consumption} = 6.56 \times 10^3\text{tonne/year}$$

The data of densities and prices of these three product are given below

$$\text{naphtha density} = 6.65 \times 10^2\text{kg/m}^3 \qquad = 6.65 \times 10^{-4}\text{tonne/litre[76]}$$
$$\text{biodiesel density} = 8.70 \times 10^2\text{kg/m}^3 \qquad = 8.70 \times 10^{-4}\text{tonne/litre[76]}$$
$$\text{naphtha price} = \text{£}0.426\text{/litre[63]}$$
$$\text{set biodiesel price} = \text{£}19.30\text{/litre, as shown in } \textbf{Figure 3}$$
$$\text{carbon price} = \text{£}15.10\text{/tonne[2]}$$

Therefore the revenue at year 0 should be calculated as below

$$\text{naphtha revenue} = \left(\frac{1.41 \times 10^2}{6.65 \times 10^{-4}}\right) \times 0.426 \qquad = \text{£}9.03 \times 10^4\text{/year}$$
$$\text{biodiesel revenue} = \left(\frac{3.30 \times 10^2}{8.32 \times 10^{-4}}\right) \times 19.3 \qquad = \text{£}7.66 \times 10^6\text{/year}$$
$$\text{carbon revenue} = \text{£}15.10 \times 6.56 \times 10^3 \qquad = \text{£}9.90 \times 10^4\text{/year}$$

A.2.3 Net Present Value Analysis

It is assumed that the biodiesel and naphtha price increase rate is the same as that of diesel. Therefore the increase rates of each revenue streams are given as below

$$\text{naphtha price increase rate} = 1\%\text{/year [46]}$$
$$\text{biodiesel price increase rate} = 1\%\text{/year [46]}$$
$$\text{carbon price increase rate} = 5.6\%\text{/year [39]}$$

Other parameters used in the calculation are given as below

$$\begin{aligned} \text{discount rate} &= 15\%[60] \\ \text{corporate tax rate} &= 25\%[40] \\ \text{capital allowances} &= 25\%[41] \end{aligned}$$

A standard discounted cash flow analysis [42] is carried out to calculate the target biodiesel price in algal biodiesel process in Route 1 at pilot plant scale. The results are shown in **Tables 7 and 8**, and the method is demonstrated as below, where

$$\begin{aligned}
\text{Total Expenditure in year } i &= \text{CAPEX in year } i + \text{OPEX in year } i \\
\text{Revenue in year } i &= \text{Revenue in year } 0 \times (1 + \text{price increase rate})^i \\
\text{Total Revenue in year } i &= \text{Biodiesel Revenue in year } i + \text{Naphtha Revenue in year } i + \text{Carbon Revenue in year } i \\
\text{Cash Flow in year } i &= \text{Total Expenditure in year } i + \text{Total Revenue in year } i \\
\text{Depreciation Value in year } 0 &= \text{CAPEX in year } 0 \\
\text{Depreciation Value in year } i &= \text{Depreciation Value in year } 0 \times (1 - \text{capital allowances})^i \\
\text{Taxable Cash Flow in year } 0 &= 0 \\
\text{Taxable Cash Flow in year } i &= \text{Cash Flow in year } i + \text{Depreciation Value in year } i \\
\text{Tax in year } i &= -\text{Taxable Cash Flow in year } (i\text{-}1) \times \text{corporate tax rate} \\
\text{Cash Flow after Tax in year } i &= \text{Cash Flow in year } i + \text{Tax in year } i \\
\text{Discounted Cash Flow in year } i &= \left(\frac{\text{Cash Flow after Tax in year } i}{(1 + \text{discount rate})^i} \right) \\
\text{Cumulative Discounted Cash Flow in year } i &= \text{Cumulative Discounted Cash Flow in year } (i\text{-}1) + \text{Discounted Cash Flow in year } i
\end{aligned}$$

Note i is the year, and $i \geq 1$, $i = 1, 2, 3, 4, etc.$, and the exact values of CAPEX and OPEX are negative in **Tables 7 and 8**.

As the cumulative discounted cash flow is greater than zero at year 15 and the biodiesel price is set as £19.3 /litre in year 0, the discounted break-even point for the algal biodiesel process in Route 1 at pilot plan scale is demonstrated as 15 years. Therefore in order to have a discounted break-even point of 15 years in this process, the biodiesel price should be targeted as £19.3 /litre.

Table 7: *The results of discounted cash flow analysis of Route 1 with discounted break-even point of 15 years (Part A).*

Year	0	1	2	3	4	5	6	7
Total Expenditure (£m)	-32.3	-2.09	-2.09	-2.09	-2.09	-2.09	-2.09	-2.09
Biodiesel Revenue (£m)	0	7.41	7.48	7.56	7.63	7.71	7.79	7.87
Naphtha Revenue (£k)	0	91.2	92.1	93.1	94.0	94.9	95.9	96.8
Carbon Revenue (£m)	0	0.105	0.110	0.117	0.123	0.130	0.137	0.145
Total Revenue (£m)	0	7.61	7.69	7.77	7.85	7.94	8.02	8.11
Cash Flow (£m)	-32.3	-5.51	5.60	5.68	5.76	5.84	5.93	6.02
Depreciation Value (£m)	-32.3	-24.2	-18.1	-13.6	-10.2	-7.65	-5.74	-4.31
Taxable Cash Flow (£m)	0	-18.7	-12.5	-7.93	-4.45	-1.81	-0.190	-1.71
Tax (£m)	0	0	0	0	0	0	0	0.047
Cash Flow after Tax (£m)	-32.3	5.51	5.60	5.68	5.76	5.84	5.93	5.97
Discounted Cash Flow (£m)	-32.3	4.80	4.23	3.73	3.29	2.91	2.56	2.24
Cumulative Discounted Cash Flow (£m)	-32.3	-27.5	-23.2	-19.5	-16.2	-13.3	-10.7	-8.49

Table 8: *The results of discounted cash flow analysis of Route 1 with discounted break-even point of 15 years (Part B).*

Year	8	9	10	11	12	13	14	**15**
Total Expenditure (£m)	-2.09	-2.09	-2.09	-2.09	-2.09	-2.09	-2.09	-2.09
Biodiesel Revenue (£m)	7.94	8.02	8.10	8.18	8.27	8.35	8.43	8.52
Naphtha Revenue (£k)	97.8	98.8	99.8	101	102	103	104	105
Carbon Revenue (£m)	0.153	0.162	0.171	0.180	0.190	0.201	0.212	0.224
Total Revenue (£m)	8.20	8.28	8.37	8.47	8.56	8.65	8.75	8.85
Cash Flow (£m)	6.10	6.19	6.28	6.38	6.47	6.56	6.66	6.76
Depreciation Value (£m)	-3.23	-2.42	-1.82	-1.36	-1.02	-0.766	-0.575	-0.431
Taxable Cash Flow (£m)	2.88	3.77	4.47	5.01	5.45	5.80	6.08	6.32
Tax (£m)	0.428	-0.719	-0.943	-1.12	-1.25	-1.36	-1.45	-1.52
Cash Flow after Tax (£m)	5.68	5.47	5.34	5.26	5.22	5.20	5.21	5.23
Discounted Cash Flow (£m)	1.86	1.56	1.32	1.13	0.975	0.845	0.736	0.643
Cumulative Discounted Cash Flow (£m)	-6.63	-5.08	-3.76	-2.63	-1.65	-0.805	-0.069	**0.574**

References

[1] A. Aden, M. Ruth, K. Ibsen, J. Jechura, K. Neeves, J. Sheehan, B. Wallace, L. Montague, A. Slayton, and J. Lukas. Lignocellulosic biomass to ethanol process design and economics utilizing co-current dilute acid prehydrolysis and enzymatic hydrolysis for corn stover. Technical Report June, National Renewable Energy Laboratory, Golden, Colorado, 2002.

[2] E. Ares. Carbon price support. Technical Report SN/SC/5927, House of Commons, 2012. URL `http://www.parliament.uk/briefing-papers/SN05927`.

[3] R. Aringhoff, G. Brakmann, M. Geyer, and S. Teske. Concentrated Solar Power-Now, September 2005. URL `http://www.solarpaces.org/Library/CSP_Documents/Concentrated-Solar-Thermal-Power-Plants-2005.pdf`.

[4] A. Avami. A model for biodiesel supply chain: A case study in Iran. *Renew Sustain Energy Rev*, 16:4196–4203, Aug. 2012. ISSN 13640321. doi:10.1016/j.rser.2012.03.023.

[5] I. Awudu and J. Zhang. Uncertainties and sustainability concepts in biofuel supply chain management: A review. *Renew Sustain Energy Rev*, 16:1359–1368, Feb. 2012. ISSN 13640321. doi:10.1016/j.rser.2011.10.016.

[6] L. Borowitzka and M. A. Borowitzka. Industrial production: methods and economics. In R. Cresswell, T. Rees, and N. Shah, editors, *Algal and Cyanobacterial Biotechnology*, pages 294–316. Longman Scientific, London, 1989.

[7] M. A. Borowitzka. Commercial production of microalgae: ponds, tanks, tubes and fermenters. *J Biotechnol*, 70:313–321, 1999. doi:10.1016/S0168-1656(99)00083-8.

[8] BP. BP Energy Outlook 2030. Technical report, BP, January 2011. URL `http://www.bp.com/liveassets/bp_internet/globalbp/globalbp_uk_english/reports_and_publications/statistical_energy_review_2011/STAGING/local_assets/pdf/2030_energy_outlook_booklet.pdf`.

[9] L. Brennan and P. Owende. Biofuels from microalgae - A review of technologies for production, processing, and extractions of biofuels and co-products. *Renew Sustain Energy Rev*, 14:557–577, Feb. 2010. ISSN 13640321. doi:10.1016/j.rser.2009.10.009.

[10] A. P. Carvalho, L. A. Meireles, and F. X. Malcata. Microalgal reactors: a review of enclosed system designs and performances. *Biotechnol Prog*, 22:1490–506, 2006. ISSN 8756-7938. doi:10.1021/bp060065r.

[11] J. A. Caton. The thermodynamic characteristics of high efficiency, internal-combustion engines. *Energy Convers Manage*, 58:84–93, 2012. ISSN 0196-8904. doi:10.1016/j.enconman.2012.01.005.

[12] L. Chen, T. Liu, W. Zhang, X. Chen, and J. Wang. Biodiesel production from algae oil high in free fatty acids by two-step catalytic conversion. *Bioresour Technol*, 111 (0):208–214, 2012. ISSN 0960-8524. doi:10.1016/j.biortech.2012.02.033.

[13] F. Cherubini. The biorefinery concept: Using biomass instead of oil for producing energy and chemicals. *Energy Convers Manage*, 51:1412–1421, July 2010. ISSN 01968904. doi:10.1016/j.enconman.2010.01.015.

[14] Y. Chisti. Biodiesel from microalgae. *Biotechnol Adv*, 25(3):294–306, 2007. ISSN 0734-9750. doi:10.1016/j.biotechadv.2007.02.001.

[15] Y. Chisti and J. Yan. Energy from algae: current status and future trends algal biofuels – a status report. *Appl Energy*, 88(10):3277–3279, 2011. ISSN 0306-2619. doi:10.1016/j.apenergy.2011.04.038.

[16] G. N. Choi, A. Helgeson, A. Lee, S. Tam, V. Venkataraman, and S. Rogers. Design/economics of an associated (or sub-quality) gas Fischer-Tropsch plant. In *Natural Gas Conversion VI*, volume 136 of *Studies in Surface Science and Catalysis*, pages 453–458. Elsevier, 2001. doi:10.1016/S0167-2991(01)80345-1.

[17] J. Conti and P. Holtberg. International energy outlook 2011. Technical Report DOE/EIA-0484(2011), U.S. Energy Information Administration, September 2011. URL `http://www.eia.gov/forecasts/ieo/pdf/0484(2011).pdf`.

[18] M. Daroch, S. Geng, and G. Wang. Recent advances in liquid biofuel production from algal feedstocks. *Appl Energy*, In Press, Aug. 2012. ISSN 03062619. doi:10.1016/j.apenergy.2012.07.031.

[19] R. Davis, A. Aden, and P. T. Pienkos. Techno-economic analysis of autotrophic microalgae for fuel production. *Appl Energy*, 88:3524–3531, Oct. 2011. ISSN 03062619. doi:10.1016/j.apenergy.2011.04.018.

[20] A. Demirbas. Competitive liquid biofuels from biomass. *Appl Energy*, 88(1):17–28, Jan. 2011. ISSN 03062619. doi:10.1016/j.apenergy.2010.07.016.

[21] Department for Transport. Transport energy and environment statistics, 2011. URL `http://assets.dft.gov.uk/statistics/releases/transport-energy-and-environment-statistics-2011/energy-2011.pdf`.

[22] Department for Transport. Renewable transport fuels obligation. Technical report, 2012. URL `http://www.dft.gov.uk/topics/sustainable/biofuels/rtfo`.

[23] Department of Energy and Climate Change. The UKŠs refinery output and demand in an international context, September 2010. URL `http://www.decc.gov.uk/assets/decc/statistics/publications/trends/articles_issue/565-trendssep10-uk-refinery-output-article.pdf`.

[24] Department of Energy and Climate Change. Background information on UK downstream oil industry. Technical report, 2012. URL `https://www.decc.gov.uk/assets/decc/11/meeting-energy-demand/oil-gas/5748-background-information-on-uk-downstream-oil-indust.pdf`.

[25] S. Durr and J. Thomason. *Biofouling*. Blackwell Publishing Ltd., Chichester, UK, 2010.

[26] D. Ellerman and B. Buchner. The European Union emissions trading scheme: Origins, allocation, and early results. *Rev Environ Econ Policy*, 1(1):66–87, 2007. doi:10.1093/reep/rem003.

[27] European Standard EN 14214. Automotive fuels – fatty acid methyl esters (FAME) for diesel engines – requirements and test methods, 2004. URL `http://www.aascarburants.com/assets/files/pdf/Biodiesel-EN14214.pdf`.

[28] Europe's Energy Portal, March 2012. URL `http://www.energy.eu`.

[29] L. Fan, C. S. Norman, and A. G. Patt. Electricity capacity investment under risk aversion: A case study of coal, gas, and concentrated solar power. *Energy Econ*, 34 (1):54–61, 2012. ISSN 0140-9883. doi:10.1016/j.eneco.2011.10.010.

[30] FuturePundit. Fischer-Tropsch Coal Gas Cost Effective With Current Oil Prices?, December 2005. URL `http://www.futurepundit.com/archives/003199.html`.

[31] H. R. Ghatak. Biorefineries from the perspective of sustainability: Feedstocks, products, and processes. *Renew Sustain Energy Rev*, 15(8):4042–4052, Oct. 2011. ISSN 13640321. doi:10.1016/j.rser.2011.07.034.

[32] M. Ginster and R. Matjie. Beneficial utilisation of sasol coal gasification ash, April 2005. URL `http://www.flyash.info/2005/94gin.pdf`.

[33] R. Glennon and A. Reeves. Solar energy's cloudy future. *Ariz J Environ Law Policy*, 1:91–137, 2010.

[34] L. Gouveia and A. C. Oliveira. Microalgae as a raw material for biofuels production. *J Ind Microbiol Biotechnol*, 36:269–74, 2009. doi:10.1007/s10295-008-0495-6.

[35] J. Grobbelaar. Factors governing algal growth in photobioreactors: the open versus closed debate. *J Appl Phycol*, 21:489–492, 2008. ISSN 09218971. doi:10.1007/s10811-008-9365-x.

[36] J. Hackney. Capial cost estimate for process industries. *Chemical Engineering*, 67 (5), 1960.

[37] C. N. Hamelinck, A. P. Faaij, H. Den-Uil, and H. Boerrigter. Production of FT transportation fuels from biomass; technical options, process analysis and optimisation, and development potential. *Energy*, 29(11):1743–1771, 2004. ISSN 0360-5442. doi:10.1016/j.energy.2004.01.002.

[38] L. Haspeslagh. Aquatic phototrophs for the production of fuels and green chemicals. Technical report, Total, March 2012. URL `http://www.biofuelstp.eu/spm3/pdf/TOTAL_Microalgae.pdf`.

[39] HM Treasury. Budget 2011, March 2011. URL `http://cdn.hm-treasury.gov.uk/2011budget_complete.pdf`.

[40] HMRC. Corporation tax rates, May 2011. URL `http://www.hmrc.gov.uk/rates/corp.htm`.

[41] HMRC. Capital allowances investment schemes, May 2011. URL `http://www.hmrc.gov.uk/capital_allowances/investmentschemes.htm`.

[42] F. Holland, F. Watson, and J. Wilkinson. *Introduction to Process Economics*, chapter Costs and Traditional Methods of Estimating Profitability, pages 35–35. John Wiley and Sons, 1974.

[43] T. Holtermann and R. Madlener. Assessment of the technological development and economic potential of photobioreactors. *Appl Energy*, 88:1906–1919, May 2011. ISSN 03062619. doi:10.1016/j.apenergy.2010.11.018.

[44] G. Huang, F. Chen, D. Wei, X. Zhang, and G. Chen. Biodiesel production by microalgal biotechnology. *Appl Energy*, 87:38–46, Jan. 2010. ISSN 03062619. doi:10.1016/j.apenergy.2009.06.016.

[45] D. Humbird, R. Davis, L. Tao, C. Kinchin, D. Hsu, and A. Aden. Process design and economics for biochemical conversion of lignocellulosic biomass to ethanol. Technical Report NREL/TP-5100-47764, National Renewable Energy Laboratory, Golden, Colorado, 2011. URL `http://www.nrel.gov/biomass/pdfs/47764.pdf`.

[46] InflationData. Historical crude oil prices, October 2011. URL `http://www.inflationdata.com/inflation/inflation_rate/historical_oil_prices_table.asp`.

[47] International Energy Agency. Technology roadmap: concentrating solar power. Technical report, 2010. URL `http://www.iea.org/publications/freepublications/publication/csp_roadmap.pdf`.

[48] International Energy Agency. End-use petroleum product prices and average crude oil import costs August 2012. Technical Report August, Paris, 2012. URL `http://www.iea.org/stats/surveys/mps.pdf`.

[49] K. L. Kadam. Microalgae production from power plant flue gas: Environmental implications on a life cycle basis. Technical Report 29417, June 2001. URL `http://www.fao.org/uploads/media/0106_NREL_-_Microalgae_production_from_power_plant_flue_gas.pdf`.

[50] A. Kommareddy and G. Anderson. *Design and construction of light guides for efficient transfer of light in to a dense algal culture in a photo-bio reactor (PBR)*. American Society of Agricultural and Biological Engineers Annual Meeting, 2003.

[51] T. G. Kreutz, E. D. Larson, G. Liu, and R. H. Williams. Fischer–Tropsch fuels from coal and biomass. In 25^{th} *Annual International Pittsburgh Coal Conference*, October 2008.

[52] D. Leckel. Diesel production in coal-based high-temperature Fischer-Tropsch plants using fixed bed dry bottom gasification technology. *Fuel Process Technol*, 92(5): 959–969, 2011. ISSN 0378-3820. doi:10.1016/j.fuproc.2010.12.017.

[53] Y. Liang, Z. Xu, J. Xia, S.-T. Tsai, Y. Wu, G. Li, C. Ray, and L. Yu. For the bright future-bulk heterojunction polymer solar cells with power conversion efficiency of 7.4. *Adv Mater*, 22:E135–8, May 2010. ISSN 1521-4095. doi:10.1002/adma.200903528.

[54] R. Luque, L. Herrero-Davila, J. M. Campelo, J. H. Clark, J. M. Hidalgo, D. Luna, J. M. Marinas, and A. A. Romero. Biofuels: a technological perspective. *Energy Environ Sci*, 1:542–564, 2008. doi:10.1039/B807094F.

[55] J. J. Marano, S. Rogers, G. N. Choi, and S. J. Kramer. Product valuation of Fischer-Tropsch derived fuels. *Fuel Energy Abstr*, 36(2):90–90, 1995. ISSN 0140-6701. doi:10.1016/0140-6701(95)92934-7.

[56] J. A. Mathews. Carbon-negative biofuels. *Energy Policy*, 36:940–945, Mar. 2008. ISSN 03014215. doi:10.1016/j.enpol.2007.11.029.

[57] National Renewable Energy Laboratory. Concentrating solar power projects, June 2011. URL `http://www.nrel.gov/csp/solarpaces/project_detail.cfm/projectID=3`.

[58] oilgae. Algae oil extraction, March 2012. URL `http://www.oilgae.com/algae/oil/extract/extract.html`.

[59] OriginOil. Strategies for utilizing whole algae biomass. In *Pacific West Biomass Conference & Trade Show*, January 2012. URL `http://www.originoil.com/pdf/OriginOil_Pacific_West_Biomass_Conference`.

[60] Oxera. Discount rates for low-carbon and renewable generation technologies: Prepared for the Committee on Climate Change, April 2011. URL `http://www.oxera.com/Oxera/media/Oxera/downloads/reports/Oxera-report-on-low-carbon-discount-rates.pdf?ext=.pdf`.

[61] R. Pate, G. Klise, and B. Wu. Resource demand implications for US algae biofuels production scale-up. *Appl Energy*, 88:3377–3388, Oct. 2011. ISSN 03062619. doi:10.1016/j.apenergy.2011.04.023.

[62] P. D. Patil, V. G. Gude, A. Mannarswamy, S. Deng, P. Cooke, S. Munson-McGee, I. Rhodes, P. Lammers, and N. Nirmalakhandan. Optimization of direct conversion of wet algae to biodiesel under supercritical methanol conditions. *Bioresour Technol*, 102(1):118–122, 2011. ISSN 0960-8524. doi:10.1016/j.biortech.2010.06.031.

[63] J. Pitches. Europe naphtha price soften on lower crude values. ICIS, May 2011. URL `http://www.icis.com/Articles/2011/05/04/9456909/europe-naphtha-prices-soften-on-lower-crude-values.html`.

[64] Power Plant CCS. Costs of PBR, 2011. URL `http://www.powerplantccs.com/ccs/cap/fut/alg/costs_of_pbr.html`.

[65] M. Radler. Special report: oil, gas reserves rise as oil output declines. *Oil Gas J*, 107, 2009.

[66] Y. Sharma and B. Singh. Development of biodiesel: Current scenario. *Renew Sustain Energy Rev*, 13(6Ű-7):1646–1651, 2009. ISSN 1364-0321. doi:10.1016/j.rser.2008.08.009.

[67] T. Shirvani, X. Yan, O. R. Inderwildi, P. P. Edwards, and D. A. King. Life cycle energy and greenhouse gas analysis for algae-derived biodiesel. *Energy Environ Sci*, 4(10):3773–3773, 2011. ISSN 1754-5692. doi:10.1039/C1EE01791H.

[68] T. Shirvani, X. Yan, O. R. Inderwildi, P. P. Edwards, and D. A. King. Life cycle energy and greenhouse gas analysis for algae-derived biodiesel. *Energy Environment Sci.*, 4(3773–3778), August 2011. doi:10.1039/C1EE01791H.

[69] A. Singh and S. I. Olsen. A critical review of biochemical conversion, sustainability and life cycle assessment of algal biofuels. *Appl Energy*, 88(10):3548–3555, Oct. 2011. ISSN 03062619. doi:10.1016/j.apenergy.2010.12.012.

[70] K. Srirangan, L. Akawi, M. Moo-Young, and C. P. Chou. Towards sustainable production of clean energy carriers from biomass resources. *Appl Energy*, In Press, June 2012. ISSN 03062619. doi:10.1016/j.apenergy.2012.05.012.

[71] A. Sun, R. Davis, M. Starbuck, A. Ben-Amotz, R. Pate, and P. T. Pienkos. Comparative cost analysis of algal oil production for biofuels. *Energy*, 36:5169–5179, Aug. 2011. ISSN 03605442. doi:10.1016/j.energy.2011.06.020.

[72] P. Sze. *A Biology of the Algae*. McGraw-Hill Science / Engineering / Math, 3^{rd} edition edition, 1997. ISBN 978-0697219107.

[73] H. Taher, S. Al-Zuhair, A. H. Al-Marzouqi, Y. Haik, and M. M. Farid. A review of enzymatic transesterification of microalgal oil-based biodiesel using supercritical technology. *Enzyme Res*, 2011:25–25, July 2011. doi:10.4061/2011/468292.

[74] T. Takeshita. Competitiveness, role, and impact of microalgal biodiesel in the global energy future. *Appl Energy*, 88:3481–3491, Oct. 2011. ISSN 03062619. doi:10.1016/j.apenergy.2011.02.009.

[75] The Engineering ToolBox. Electrical motor efficiency, March 2012. URL `http://www.engineeringtoolbox.com/electrical-motor-efficiency-d_655.html`.

[76] The Engineering ToolBox. Densities of some common liquids - acetone, beer, oil, water and more, March 2012. URL `http://www.engineeringtoolbox.com/liquids-densities-d_743.html`.

[77] S. E. M. Thompson. *Cell Biology of Settlement and Adhesion Processes of Biofouling Algae*. PhD thesis, University of Birmingham, 2007.

[78] G. Towler and R. Sinnott. *Chemical Engineering Design*. A Butterworth-Heinemann Title, 5^{th} edition, 2008. ISBN 978-0750685511.

[79] United National Framework Convention on Climate Change. Kyoto Protocol, 2011. URL `http://unfccc.int/kyoto_protocol/items/2830.php`.

[80] US Commodity Future Trading Commission. CFTC announces multiple energy market initiatives. Technical report, May 2008. URL `http://web.archive.org/web/20080601035005/http://www.cftc.gov/newsroom/generalpressreleases/2008/pr5503-08.html`.

[81] U.S. Energy Information Administration. EIA Annual Energy Outlook 2009. Technical Report DOE/EIA-0383, 2009. URL `http://www.eia.gov/oiaf/archive/aeo09/`.

[82] US Energy Information Administration. Gasoline and Diesel Fuel Update, March 2012. URL `http://www.eia.gov/petroleum/gasdiesel/`.

[83] U.S. Energy Information Administration. Saudi Arabia. Technical report, 2012. URL `http://www.eia.gov/countries/country-data.cfm?fips=SA#pet`.

[84] U.S. Environmental Protection Agency. Clean Alternative Fuels: Fischer–Tropsch, March 2002. URL `http://www.afdc.energy.gov/afdc/pdfs/epa_fischer.pdf`.

[85] A. Vlysidis, M. Binns, C. Webb, and C. Theodoropoulos. A techno-economic analysis of biodiesel biorefineries: Assessment of integrated designs for the co-production of fuels and chemicals. *Energy*, 36:4671–4683, Aug. 2011. ISSN 03605442. doi:10.1016/j.energy.2011.04.046.

[86] A. C. Vosloo. Fischer-Tropsch: a futuristic view. *Fuel Process Technol*, 71(1-Ű3): 149–155, 2001. ISSN 0378-3820. doi:10.1016/S0378-3820(01)00143-6.

[87] J. L. Williams. Oil price history and analysis, 2011. URL `http://www.wtrg.com/prices.htm`.

[88] H. Xu, X. Miao, and Q. Wu. High quality biodiesel production from a microalga chlorella protothecoides by heterotrophic growth in fermenters. *J Biotechnol*, 126 (4):499–507, 2006. ISSN 0168-1656. doi:10.1016/j.jbiotec.2006.05.002.

Citation index