Preprint Cambridge Centre for Computational Chemical Engineering ISSN 1473 – 4273

Algae under Uncertainty: The Future of the Algal Biodiesel Economy

George P.E. Brownbridge [1], Pooya Azadi [1], Andrew Smallbone [2], Amit Bhave [2], Benjamin J. Taylor [1], Markus Kraft [1]

released: 9 May 2013

[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

Preprint No. 126

UNIVERSITY OF CAMBRIDGE

Keywords: Algae, Biodiesel, Techno-Economic Assessment, Uncertainty, HDMR

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

We present a techno-economic assessment of algae-derived biodiesel under economic and technical uncertainties currently associated with the development of algal biorefineries. The proposed plant is comprised of photobioreactor (PBR), harvesting and oil extraction, oil esterification, and integrated gasification/Fischer-Tropsch units, and a concentrated solar power (CSP) system to provide the biorefinery with decarbonised electricity. The global sensitivity analysis was performed using a High Dimensional Model Representation (HDMR) method. It was found that, considering reasonable ranges over which each parameter can vary, the sensitivity of the biodiesel production cost to the key input parameters decreases in the following order: algae oil content > algae annual productivity per unit area > plant production capacity > carbon price increase rate. It was also found that the Return on Investment (ROI) is highly sensitive to the algae oil content, and to a lesser extent to the algae annual productivity, crude oil price and price increase rate, plant production capacity, and carbon price increase rate. For a large scale plant (100,000 tonnes of biodiesel per year) the production cost of biodiesel is likely to be between £0.8 to £1.6 per kg. The analysis herein presented should be of interests to researchers and decision makers in the energy, environment and agricultural sectors.

Contents

Nomenclature

CAPEX	Capital Expenditure (£)
CSP	Concentrated Solar Power
FT	Fischer-Tropsch
GHG	Greenhouse Gas
HDMR	High Dimensional Model Representation
ICE	Internal Combustion Engine
LCA	Life Cycle Assessment
MC	Monte Carlo
OPEX	Operating Expenditure (£/year)
PBR	Photobioreactor
QRS	Quasi-Random Sampling
ROI	Return on Investment
WTW	Well-to-Wheel
ϕ	Economies of Scale Exponent

1 Introduction

Global warming induced by anthropogenic greenhouse gas (GHG) emissions is currently one of the major concerns facing the world today. Furthermore, decline in the supply of conventional fossil fuels has increased exploitation of unconventional carbon-intensive resources such as tar sands which, in turn, will further increase the concentration of greenhouse gases in the atmosphere [11]. Production of biofuels with lower life cycle carbon footprints would help to simultaneously address both issues of GHG emission and the decline in fossil resources in a sustainable manner [6].

Beside the lignocellulosic biomass such as forest and agricultural residues, microalgae have been identified as a versatile biomass feedstock upon which future biorefineries can be established [8]. Microalgae fulfil all the prerequisites of a sustainable biofuel feedstock: they have enormous annual productivity, low demands for fresh water and nutrients as they can be fed with wastewater, and minimal indirect emissions due to land-use change as they can be grown on marginal lands [20]. Nevertheless, there are still several technical challenges holding back the large scale production of liquid algal biofuels in an economic and environmentally-benign manner, the majority of which are related to the high energy and carbon intensities of the cultivation and conversion processes.

The technical process of algal biodiesel production includes several different technology components: algal growth, algae dewatering, oil extraction, oil esterification, and a process for the conversion of the oil-extracted algae. Here, we briefly overview the primary issues associated with the economic viability of algal biorefineries.

Algae cultivation method: The algae growth systems are primarily limited to two types: open pond raceways and photobioreactors (PBRs). Generally, the biomass yields from PBRs are higher than from open pond raceways; albeit, only at the price of higher capital and operating costs [19]. The latter is due to the higher electricity consumption need to maintain turbulence in the narrow tubing. However, the PBR cultivation system is also less vulnerable to undesirable microorganisms that may attack the algae culture.

Annual biomass productivity and oil content: Generally, the annual yield of algal crops ranges from 50 to 150 tonnes of dry biomass per hectare. The annual algae productivity primarily depends on algae strain, solar irradiance, temperature, nutrients availability, and growth system. The algae lipid content usually increases if cultivated under nitrogen-deficient conditions. However, the inverse relationship between the lipid content and the annual productivity somewhat offsets the total amount of oil produced annually [8]. Furthermore, due to the presence of nitrogen, phosphorous, and sulphur heteroatoms in algal oil, only about 80 wt% of the oil can be used for biodiesel production [8].

Carbon and nutrients: The required carbon for algae growth can be provided by bubbling flue gas from external sources into the growth medium, or alternatively via utilisation of wastewater which not only provides the algae farm with a source of carbon and water but also partially or fully offsets the fertiliser demand. In the latter case, the treated water should be also considered as a product beside the produced biodiesel, as in this case the algae production essentially eliminates the need for the treatment of the wastewater. In this study, however, we assumed the carbon is provided by flue gas from an adjacent power plant and the revenue that can be generated from the treatment of wastewater was excluded from the analysis.

Harvesting and oil extraction: A major challenge concerning the production of algal biofuels in an economical and environmentally-benign manner is the low concentration of the feedstock which is typically between 0.05–2 wt%. The initial feedstock can be effectively concentrated up to nearly 10 wt% using physical precipitation methods with low energy demands (e.g. clarifiers). However, due to small particle sizes and water-like density, further dewatering and drying of the microalgae slurries is significantly energy and carbon intensive. Therefore, it is likely that the technologies that directly fractionate and/or convert dilute microalgae slurry can offer inherent advantages over the conventional processes such as oil extraction from dried feedstock [7]. Regardless of the utilisation of a dry or wet extraction method, the algae oil can be converted into biodiesel at high yields via transesterification process.

Conversion strategy for oil-extracted algae: In a biofuel-only algae conversion strategy, three scenarios are plausible with respect to the conversion of the oil-extracted algae, each of which can prove more viable depending on the upstream harvesting and oil extraction processes and several other factors: a) They can be combusted in boilers to generate process heat and electricity, b) They can be converted to biogas using anaerobic digestion, and c) They can be gasified to produce syngas, which can be subsequently fed to Fischer-Tropsch (FT) to produce more diesel fuel or burnt in gas turbines to generate electricity. Based on our previous analysis [23], we considered an integrated gasification-FT plant to convert the residues into synthetic diesel and naphtha.

Life cycle carbon footprint: The well-to-wheel (WTW) carbon footprint of a biofuel determines to what extend its widespread use can help countries to reach their GHG reduction targets. Therefore, the carbon credit given to any biofuel producer, amongst the other factors, should be proportional to the difference between the carbon footprints of the biofuel and fossil fuel to be displaced. A life cycle inventory for the WTW carbon footprint of algal biodiesel includes a credit for the sequestrated carbon dioxide, and GHG emissions from on-site activities and processes, embedded emissions in the raw materials and commodities (e.g. fertilisers, methanol, glycerol, and plant constructing materials), electricity generation, and the combustion of the biofuel in ICE. Only with a proper accounting of all these factors one can assess the potential of algae-derived biodiesel in mitigating the GHG emissions.

Electricity: The source of electricity and the process electricity demand considerably affect the economics and the carbon footprint of the produced algal biodiesel [21]. Consequently, beside implementation of less electricity-intensive processes, decarbonisation of the electricity can greatly suppress the adverse environmental impacts of algal biorefineries and would allow for the realisation of the full advantages of algae-derived biofuels. Given that the algae farms will be primarily located in the areas with high daily hours of sunshine, the use of solar power seems to be an inherently good choice. In our analysis presented herein, we assumed the process electricity is provided by an adjacent plant using concentrated solar power (CSP) via parabolic trough mirrors.

Other economic factors: The total production capacity of the plant is expected to have a considerable effect on the biofuel production cost due to the non-linear changes in the plant's *capital expenditure* (CAPEX) and *operating expenditure* (OPEX) with size. Furthermore, the profitability of a biorefinery is heavily dependent on the commodity prices (e.g. cruide oil, carbon, and fertilizer) over the lifetime of the plant. These issues along with the other economic assumptions made in this study are discussed in more detail in the methodology, Section 2.

Given the wide range of the suggested solutions for addressing the challenges of algal biofuel production, along with the likely enhancements in the annual algae productivity and lipid content in the future, the economics of algal biorefineries are currently associated with extensive uncertainties. Consequently, models that take into account the technical and economic uncertainties surrounding algal biorefineries are highly useful and can be employed to shed light on the viability of such plants in the future.

A summary of selected techno-economic studies for the production of algal biodiesel are given in Table 1. From the values listed in this table, one can see that the differences in the technical and economic assumptions behind the algae production and conversion process can result in almost one order of magnitude difference in the final price of the product, which in turn highlights the need for a systematic study of the algae economy. Furthermore, although the economy of algal bioproducts has been extensively studied in the literature, very little is known about the relative importance of the key technical and economic factors with respect to the economy of algal biorefineries. Sensitivity analysis allows researchers and decision makers to qualitatively measure the importance of different factors with regard to the outputs they are concerned with. Local sensitivity analysis calculates effect of the input parameters only about a given point and usually just the linear component. Global sensitivity analysis however calculates the effect of the input parameters over the whole parameter space, which means that it not only takes into account the inherent uncertainties in the input parameters but also potential non-linearities and contributions due to interactions between input parameters. In this paper we use a Quasi-Random Sampling High Dimensional Model Representation (QRS-HDMR) method to simultaneously calculate global sensitivities and generate surrogate models [17].

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

Product	Cultivation system	Oil content (wt%)	Capacity (tonne/yr)	Price (£/kg)	Ref.
Algae	PBR		4.1×10^3	3.23	[15]
Algae	Pond		2.1×10^3	3.86	[15]
Algae	Combined	35		0.26	[8]
Algae oil	PBR	30	1.0×10^2	0.95	[2]
Algae oil	Pond	30	1.0×10^2	1.22	[2]
Biodiesel	PBR		3.5×10^4	5.59	[19]
Biodiesel	Pond		3.5×10^4	2.28	[19]
Biodiesel	PBR	20	1.5×10^6	6.56	[23]
Biodiesel	PBR	20	1.0×10^8	4.19	[23]
Biodiesel	Combined	35		1.06	[8]
Green diesel	PBR	25	3.5×10^4	11.40	[3]
Green diesel	Pond	25	3.5×10^4	5.37	[3]

Sensitivity analysis is an important tool for understanding the relationships between the inputs and outputs of a model. However, uncertainty propagation can be used to answer questions such as, “Given the current data, on prices and forecasts, etc. what are the probabilities of achieving target values of the model’s outputs?”. In the context of this paper, one such question could be, “Given the best estimates of parameters such as the algae annual productivity, the algae oil content, and the annual increase in the price of biodiesel what is the likelihood that the return on investment will be above a certain level?”. The standard method used for uncertainty propagation is Monte Carlo (MC) sampling. By sampling the input parameters from distributions that convey the uncertainty in their values probabilities can be assigned to the condition of achieving desired output values.

In this study, we assess different aspects of low carbon algal biofuel production given the current technical and economic uncertainties. In our proposed strategy, the algae oil and the oil-extracted algae are converted into liquid biofuels suitable for diesel engines using transesterification and an integrated gasification/Fischer-Tropsch process, respectively. In the following section, we describe the process in more detail and set out the assumptions and the ranges over which the variables were varied. Subsequently, using the HDMR method, we show to what extent each parameter can affect the economics of such plants. Finally, we present the results obtained from an extensive MC uncertainty analysis and discuss the economic viability under various scenarios.

2 Methodology

2.1 Algae Conversion Process

A schematic process flow diagram of the algal biodiesel plant considered in the model is depicted in Figure 1. The main feedstocks and products of the key process units, for the production of 1 kg algal diesel, are given in Table 2. The algae is grown in the PBRs using carbon dioxide from an adjacent power plant. In the described process, 2.6 kg dry algae is needed to produce 1 kg algal diesel, of which 0.8 kg is produced via lipid transesterification and 0.2 kg is produced via gasification of the oil-extracted algae followed by Fischer-Tropsch process. This would approximately require 5.3 kg of CO_2 from the flue gas. Considering typical CO_2 concentrations in the flue gases of a gas-fired power plants (i.e. ∼15 wt%), nearly 35 kg of flue gas is required to obtain 1 kg biodiesel. In the process considered in this study, the dilute algae culture is fed to a wet harvesting system in which 95% of its water is removed [16]. The lipids are then separated using conventional solvent extraction process to allow for direct conversion into biodiesel via transesterification, in which 1 kg lipids and 0.1 kg methanol are reacted to yield 1 kg biodiesel and 0.1 kg crude glycerol. Furthermore, it was assumed that 100% of the algae lipid is converted to methyl esters suitable for ICEs. The oil-extracted algae mass undergoes gasification followed by the Fischer-Tropsch reaction to generate synthetic diesel and naphtha, through the intermediate formation of syngas. Herein, we use the term *algal diesel* to collectively refer to the combined biodiesel and synthetic diesel produced via transesterification and Fischer-Tropsch, respectively. The mass ratio of synthetic diesel and naphtha obtained from FT process is approximately 2.3. Furthermore, it was assumed that the market value of diesel and naphtha over the lifetime of the plant is consistently equal to 75% and 67.5%, respectively, of the crude oil price at that time.

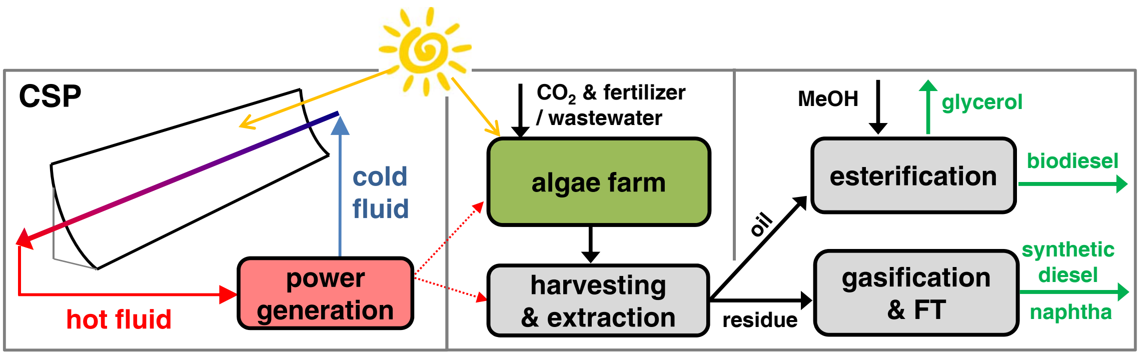


Figure 1: *Schematic process diagram of the algal biorefinery considered in this study.*

As mentioned earlier, the cost and carbon footprint of electricity can significantly affect the economics and environmental footprints of algal diesel, respectively. Since the algae farms should ideally be built in areas with high annual solar radiation, the utilisation of solar energy for providing the thermal and electricity demands of the biomass conversion process can potentially be a suitable option [1, 23]. Hence, given the level technology maturity and its ability to continuously generate power over the entire day, we assumed that a parabolic trough CSP plant with thermal energy storage system is used to meet the electricity requirements of the biorefinery. As the rate of photosynthesis and algae growth over night is substantially lower compared to the day time, a less extensive level of mixing is adequate to maintain optimal growth; which in turn, would reduce the electricity demand of the plant during that period. Considering the cost associated with the energy storage in molten salt CSP plants, a CSP plant integrated with algal biorefinery would be more cost effective due to the reduced need for energy storage.

In order to perform the global sensitivity analysis, we systematically varied the key input parameters over the ranges given in Table 4. In our view, the ranges considered here represent plausible values for such parameters over the plant lifetime, which was assumed to be 30 years. Strictly speaking, some of the parameters given in this table are somewhat dependent on each other; however, any correlations among these parameters were not considered in the analysis and they were treated as independent variables. Furthermore, there can be a level of uncertainty surrounding the performance of each technology depending upon the nature of the inputs (climate, future energy prices, etc.). Whilst the base assumption is that the technology performance is 100% the standard deviations applied to the productivities accounts for both potential inefficiencies as well as potential increases in efficiency, as listed in Table 5.

The commodity prices used in this assessment are defined as the price when the plant is constructed. The price in subsequent years is then calculated using a percentage annual increase. The only price that is not increased in this way is that of carbon which is partially controlled by governments and is predicted to increase at an approximately constant rate until 2050 [4]. The carbon credit was calculated based on the stoichiometry of diesel combustion (i.e. 3.1 kg CO_2/kg diesel), and assuming that the heating value of biodiesel is 88% of that of the petroleum diesel [24].

The estimated CAPEX and OPEX associated with the production of 1 kg of algal diesel for each of the major processes is provided in Table 3. It is important to note that although these values are normalised to 1 kg final algal diesel product they have been calculated from quotes for actual industrial-scale units. These quotes were scaled appropriately when calculating the values for a specific plant production capacity. The annual unit capacity for each of these units are also given in the table. The CAPEX of CSP plant as well as the corresponding OPEX to CAPEX ratio was obtained from [13]. The CAPEX of PBR and oil extraction unit and the specific electricity demand per unit were quoted from Subitec GmbH, Stuttgart, Germany [22], and OriginOil, Los Angeles, USA [16], respectively. The OPEX of PBR and oil extraction units were calculated based on the sum of the labour cost and maintenance, the latter of which was assumed to be equal to 2% of the CAPEX. The labour costs were estimated assuming one employee for the PBR and the extraction units installed in 10 ha. The annual salary per employee and overhead were assumed at £22,000 per year and 60%, respectively. The allocation ratio of the labour cost between the PBR and oil extraction was considered to be 2:1. The data for the transesterification and gasification-FT plants were quoted from NiTech, Edinburgh, Scotland [14], and Rentech, USA [18]. Fertiliser price and the increase rate forecast were taken from [12]. Furthermore, current and future carbon prices were calculated from [4]. The indirect costs such as engineering, installation, start up, and project contingencies are assumed to be 20% of the facility investment [10].

The economic analysis herein presented is based on the following assumptions: 25%

corporate tax rate (based on UK corporate tax rate for 2012 [5]), 5% annual depreciation rate for the equipments, and 0% cash flow discount rate which represents the minimum biodiesel production cost that one may obtain from such plants. The annual depreciation amount was used as the capital allowance of that year and subtracted from the taxable profits with unused allowance being carried into the next year.

The economies of scale exponent, ϕ, controls how the price of bulk purchases of the units are discounted. If the capital cost of one plant unit, with a capacity Q_{unit}, is C_{unit} then the capital cost C a plant of that type with a capacity Q_{demand} can be calculated as

$$C = C_{\text{unit}} \left(\frac{Q_{\text{demand}}}{Q_{\text{unit}}} \right)^{\phi} . \tag{1}$$

In this paper ϕ was set to a value of 0.8 for all technologies. One should realise that Q_{unit} refers to the CAPEX values quoted for the unit sizes listed in Table 3.

The plant *Return on Investment* (ROI) is defined as follow:

$$\text{ROI}(\%) = \frac{\text{Total Profits}}{\text{Total CAPEX}} \times 100 , \tag{2}$$

where the total profit is calculated as the cumulative profit gained over the time span considered. The algal diesel production cost is calculated by subtracting the sum of gross profits from the bi-products (naphtha and carbon sequestration) as well as the relevant capital allowance from the total costs and dividing that by the total amount of algal biodiesel produced, all over the lifetime of the plant.

Table 2: *Consumption and production rates of key processes to produce 1 kg algal diesel based on 30 wt% algae oil content and 100 tonne/ha annual productivity.*

Process	Feedstock	Products	Value	Unit
CSP		Electricity	30.3	MJ
PBR	CO_2		5.33	kg
	NH_3		0.26	kg
	Electricity		28.8	MJ
		Algae	2.61	kg
Separation	Algae		2.61	kg
	Electricity		1.4	MJ
		Algae Oil	0.78	kg
		Residue	1.83	kg
Transesterification	Algae oil		0.78	kg
	Methanol		0.08	kg
	Electricity		2.8	MJ
		Biodiesel	0.79	kg
		Glycerol	0.07	kg
Gasification and Fischer-Tropsch	Residue		1.83	kg
		Synthetic diesel	0.21	kg
		Naphtha	0.09	kg
		Electricity	2.7	MJ

Table 3: *Estimated CAPEX and first year OPEX values for production of 1 kg algal diesel. The CAPEX values are calculated based on industrial quotations with unit capacities given in the last column and assuming a plant lifetime of 30 years.*

Process	CAPEX (£/kg)	OPEX (£/kg)	Annual unit capacity
CSP	2.01×10^{-1}	8.02×10^{-2}	3.25×10^{9} MJ
PBR	1.02	8.25×10^{-1}	8.87×10^{4} kg dry algae
Separation	5.38×10^{-1}	3.53×10^{-1}	1.50×10^{4} kg dry feedstock
Transesterification	1.23×10^{-3}	2.38×10^{-3}	5.34×10^{6} kg biodiesel
Gasification/FT	3.39×10^{-2}	6.56×10^{-2}	5.48×10^{5} kg dry feedstock

Table 4: *Ranges of parameters for global sensitivity analysis.*

Parameter	**Lower bound**	**Upper bound**	**Unit**
Production capacity	1,000	100,000	tonne/year
Algae productivity	80	120	tonne/ha/year
Algae oil content	20	40	wt%
Crude oil price	0.53	0.68	£/kg
Carbon price	0.013	0.028	£/kg
Fertiliser price	0.47	0.57	£/kg
Crude oil price increase rate	1	3	%/year
Carbon price increase	0.003	0.009	£/kg/year
Fertiliser price increase	1	3	%/year
CAPEX	-10	+10	%

Table 5: *The mean values and standard deviations of key input parameters used in the uncertainty analysis.*

Parameter	**Mean value**	**Std. Dev.**	**Unit**
Algae productivity	100	10	tonne/ha
Algae oil content	30	5	wt%
Crude oil price	0.60	0.04	£/kg
Carbon price	0.021	0.003	£/kg
Fertiliser price	0.52	0.02	£/kg
Diesel price increase rate	2.0	0.5	%/year
Carbon price increase rate	0.006	0.0015	£/kg/year
Fertiliser price increase	2.0	0.5	%/year
CAPEX of each unit	See Table 3	5	%

2.2 Global Sensitivity Analysis using HDMR

When assessing a techno-economic model it is often useful to know the relative effect of each input parameter on the output parameters. Such information can be obtained through a sensitivity analysis on the model. This analysis can be used to direct research towards technologies and advancements that will have the greatest effect on the overall economic viability of an algae to biodiesel plant. A specific example could be a research group developing new strains of algae may want to know whether it is more economically sensible to focus on getting a higher annual productivity or a greater oil content in the new strain. Another example would be an investor who is interested in an algae to biodiesel plant but wants to know which process in the plant has the greatest potential to contribute towards reducing the biodiesel production cost so that they can focus their efforts on finding a more cost effective technology for that process. The advantage of the global sensitivity analysis implemented here is that unlike the more commonly used methods which calculate sensitivity locally using finite differences, the sensitivities that are calculated take into account the global variation in the outputs over the whole space of input variables. This means that magnitude of the range over which each parameter is varied has a direct effect on the sensitivity to that parameter.

In this paper global sensitivities are calculated from the coefficients of a High Dimensional Model Representation (HDMR) [17]. Each output from the model, y, for example biodiesel production cost, can be represented by a function, $f(x)$, of the model's inputs, x, such as annual algae productivity, oil content, etc. The main feature of HDMR is the decomposition of the full function into a sum of functions that only depend on subsets of the input variables such that:

$$y = f(x) = f_0 + \sum_{i=1}^{N} f_i(x_i) + \sum_{i=1}^{N}\sum_{j=i+1}^{N} f_{ij}(x_i, x_j) + \ldots + f_{12\ldots N}(x_1, x_2, \ldots, x_N), \tag{3}$$

where N is the number of input parameters, i and j index the input parameters, and f_0 is the mean value of $f(x)$. The expansion given in (3) has a finite number of terms and exactly represents $f(x)$, however for most practical applications terms containing functions of more than two input parameters can often be ignored due to their negligible contributions compared to the lower order terms [9, 17]. Therefore for most models/data the truncated approximation

$$y \approx f(x) = f_0 + \sum_{i=1}^{N} f_i(x_i) + \sum_{i=1}^{N}\sum_{j=i+1}^{N} f_{ij}(x_i, x_j), \tag{4}$$

is sufficient. Whilst it is possible to evaluate each of these terms using direct numerical integration a more efficient method is to approximate the functions $f_i(x_i)$ and $f_{ij}(x_i, x_j)$ with analytic functions [9]. In this paper orthogonal polynomials are used due to the ease of their calculation and broad applicability.

The separation of the contributions from each individual input parameter and each combination of parameters allows to calculate the global sensitivities. It has been described by Rabitz and Alış [17] that the contribution of each term in (4), σ_i^2 and σ_{ij}^2, to the variance of the output parameter can be related to the total variance by

$$\sigma_f^2 = \sum_{i=1}^{N} \int_{-1}^{1} f_i^2(x_i)\,\mathrm{d}x_i + \sum_{i=1}^{N} \sum_{j=i+1}^{N} \int_{-1}^{1} \int_{-1}^{1} f_{ij}^2(x_i, x_j)\,\mathrm{d}x_i \mathrm{d}x_j \tag{5a}$$

$$= \sum_{i=1}^{N} \sigma_i^2 + \sum_{i=1}^{N} \sum_{j=i+1}^{N} \sigma_{ij}^2. \tag{5b}$$

The sensitivities, S_i and S_{ij}, can then be calculated by dividing by the total variance σ_f^2 to get

$$S_i = \frac{\sigma_i^2}{\sigma_f^2} \quad \text{and} \quad S_{ij} = \frac{\sigma_{ij}^2}{\sigma_f^2}. \tag{6}$$

These global sensitivities can then be used to assess which input parameters are most influential on the variance of each of the output parameters. The HDMR models are also easy to plot allowing the user to visualise the effects of each parameter and their combined effects. Also due to the simple polynomial form of the HDMR models they can be used as surrogate models to perform further, evaluation intensive, analyses.

These surrogate models are generally faster to evaluate than the original model and allow rapid dynamic data visualisation as well as the option to perform more computationally intensive analyses.

2.3 Uncertainty Analysis

The global sensitivity analysis is useful for determining the relative importance of the input parameters in highly non-linear system. The HDMR results can be also used to investigate the effect of an input parameter while the effect of all other inputs have been averaged out over their specified range. Monte Carlo (MC) simulations of the forward uncertainty propagation differs from HDMR in the way that the sampling from the input domains are carried out: the HDMR presented here considers a uniform probability over the entire range of the input whereas the sampling in MC simulation happens through a probability function which determine the mean value and standard deviation of the input. In other words, MC simulation is more effective if the mean values of the input parameters are approximately known but there is likelihood that these values vary around the mean value. An example of this would be that a given strain of algae might be quoted as having a algae annual productivity of 100 tonne/ha but due to variations in growing conditions and other factors the actual productivity may be slightly different from this value. Uncertainty propagation can be performed to quantitatively assess the effects of such uncertainty in the input domain on the expected values of the outputs (e.g. biodiesel production cost and ROI).

Having estimated the probability distributions of the outputs, it is then possible to generate the associated cumulative distributions from which the probabilities of different scenarios can be calculated. For example the cumulative distribution for biodiesel production cost can be used to calculate the probability that, given the uncertainty in the inputs, the biodiesel production cost will be less than a given amount.

3 Results

In this section, we will first present the results obtained from the global sensitivity analysis in which the relative contributions of key input parameters to the economic viability of the described algal biorefinery are determined. Subsequently, we will demonstrate to what extent algae oil content, annual productivity, carbon price increase rate, and PBR CAPEX affect the algal diesel production cost with various production capacities. Finally, we will discuss how current economic and technical uncertainties can affect the profitability of a diesel-only algal biorefinery over its lifetime (e.g. 30 years).

3.1 Global Sensitivity Analysis

The global sensitivities of the economics of the algae conversion constructed upon the strategy schemed in Figure 1 to the key input parameters were studied using the HDMR method. There are a number of parameters that can serve as the model output, among which we focused on algal diesel *production cost* and 5- and 30-year *ROI*. It is worth mentioning that the algal diesel production cost is dependent on the crude oil and carbon prices as the revenue generated from the process byproducts (i.e. naphtha and sequestrated carbon) is subtracted from the actual cost to obtain the net production cost of the algal diesel. The ROI depends on both algal diesel production cost and the selling price of all products, including algal diesel, naphtha, and carbon. However, strictly speaking, the values associated with most of the capital and operating costs are inevitably dependent on the fossil energy prices to a variable extent. The input parameters along with the ranges over which the value of each input parameters was allowed to vary can be seen in Table 4. Since the HDMR model separately incorporates the CAPEX of each process unit listed in Table 3, there are total of 14 independent inputs to the model. Due to the global nature of this sensitivity analysis the exact range over which each parameter is varied directly affects the sensitivity to that parameter. We note that in reality there is a slight negative correlation between algae oil content and algae annual productivity for a given production configuration and algae strain [8]. Nonetheless, the highly scattered paired values of algae oil content and annual productivity in the literature allows them to be considered as independent variables, particulary as no specific strain of algae was considered in the analysis.

The global sensitivities of the overall algae-derived diesel production cost to the major inputs are shown in Figure 2. It was found that the production cost of algae-derived diesel is most sensitive to the algae oil content, primarily due to the substantial differences between the process efficiencies and costs of the two routes to convert the oil and oil-extracted algae into diesel (i.e. esterification and gasification-FT, respectively). The second most influential factor in the production cost was the algae annual productivity, mainly because it would considerably alter the number of PBR units and the solar power plant capacity simultaneously. Other significant factors included carbon price increase rate, plant production capacity, and PBR CAPEX. Moreover, none of the second-order sensitivities appeared to have a sizeable impact on the production cost.

The global sensitivity of 5- and 30-year ROI to the key input parameters are depicted in

Figure 3. The HDMR analysis indicated that the contribution of each input parameter to the short and long term ROIs is different. In general, it is expected the variation in input parameters that represent the future changes such as oil and carbon price increase rates have smaller impacts on the short-term performance of the plant (i.e. 5 year ROI), but would become more important when extending the analysis time span. In fact, according to presented results, the 5 year ROI is primarily sensitive to the algae oil content, crude oil price at the beginning of the plant operation, and algae annual productivity per hectare. The 30 year ROI is most sensitive to the algae oil content, crude oil price increase rate, and algae annual productivity. Expectedly, the carbon price increase rate only affects the 30-year ROI.

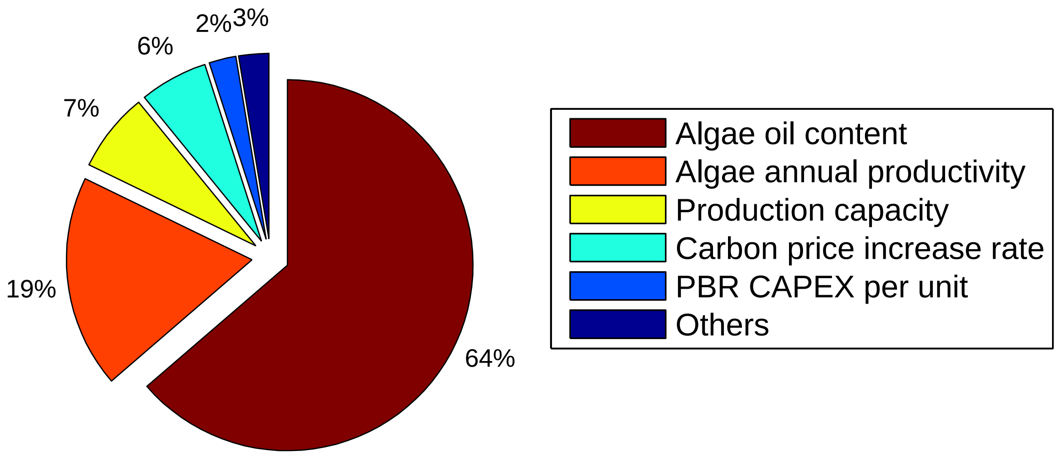


Figure 2: *Global sensitivities (S_i) algal diesel production cost to key input parameters listed in Table 4.*

Figure 4 depicts how the production cost of algae-derived diesel would vary with the plant production capacity and the four other input parameters that give the greatest contribution to the output as identified in Figure 2. The results presented in Figure 4 were generated by evaluating the surrogate model for the production cost and a secondary variable with all other inputs set to their arithmetic mean values of the ranges given in Table 4. As can be seen, the effects of production capacity somewhat levels off at values greater than 20,000 t/y. Furthermore, increasing the algae oil content from 20 to 25 wt% can reduce the biofuel production cost by almost £0.3 (Figure 4a). However, the cost saving by increasing the oil content is less pronounced at higher oil percentages, as for example only about £0.14 would be saved if the algae oil content is increased from 35 to 40 wt%. The same behaviour was observed for the effect of algae annual productivity on the biofuel production cost (Figure 4b) as this parameter also consistently becomes less influential when moving away from the lower bound of the specified range. In contrast, the variation of the production cost with the carbon price increase rate and PBR unit CAPEX were found to be more uniform throughout the ranges considered in this study (Figures 4c and 4d).

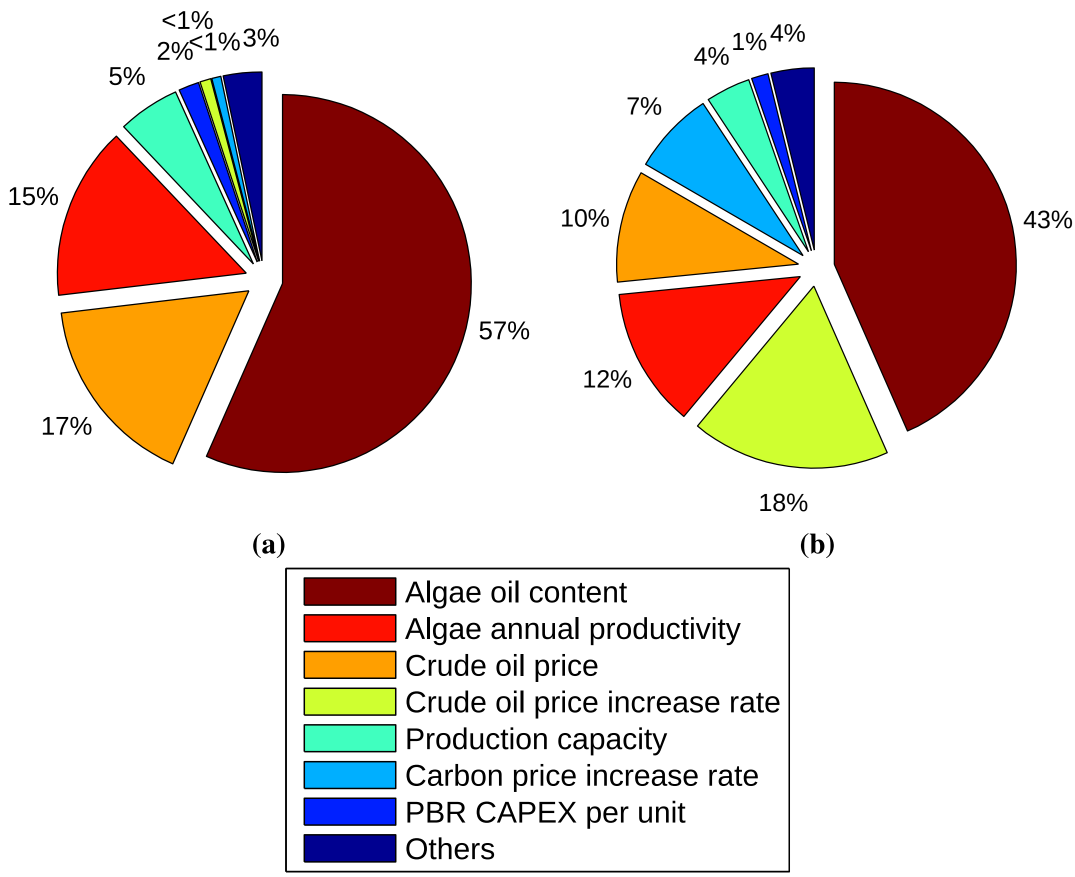
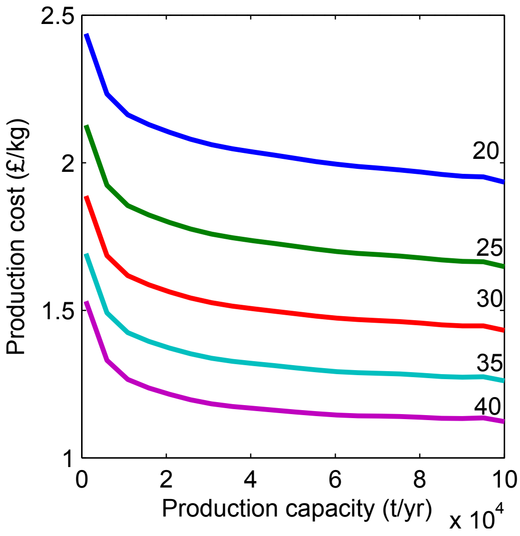


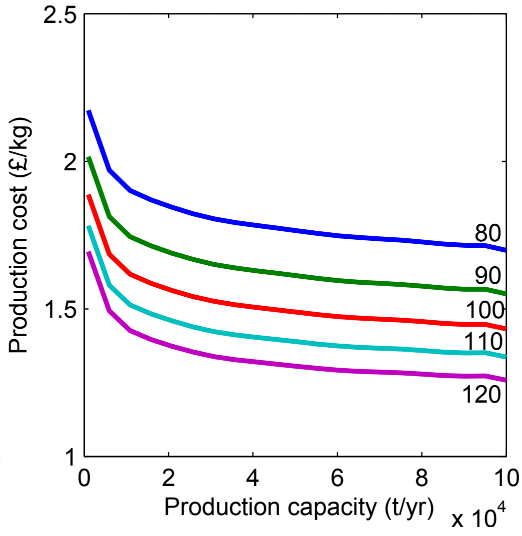
Figure 3: *Global sensitivities (S_i) of ROI to key input parameters listed in Table 4 for a) 5 years, and b) 30 years. The order in the key was calculated from the average of the two sensitivities.*

3.2 Uncertainty Analysis

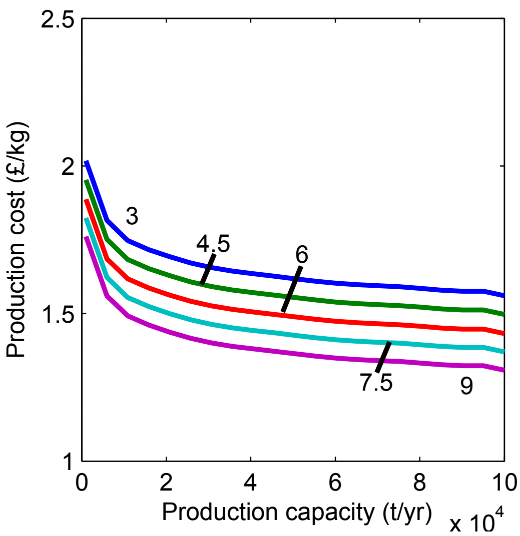
In this section, we present the results of Monte Carlo uncertainty analysis on the economic feasibility of the described algal biorefinery. These results help to provide a better understanding of how the current uncertainties surrounding the algae conversion processes can affect the cost of algal biofuel production; and in a more general scope, how these uncertainties affect the economic viability of such algal biorefineries. To this end, we assumed a normal probability distribution for each of the 14 parameters listed in Table 5 centred around their mean values. The mean of each parameter corresponds to a reasonable current estimate of its value, and the standard deviation represents the uncertainty associated with that value. The plant production capacity was treated as a known input with no associated uncertainty and the analysis was run three times with its value set to 1,000, 10,000, and 100,000 tonnes of biodiesel per year. Figure 5 shows the probability densities of the major input parameters to the model with the means and standard deviations given in Table 5. These parameters (i.e. annual productivity, oil content, crude oil price and its annual increase rate, PBR CAPEX, and carbon price increase rate) have been previously identified as the most important inputs in the HDMR analysis (see Figures 2 & 3). The width of each curve in Figure 5 is normalised by the mean value of the parameter. This shows that,



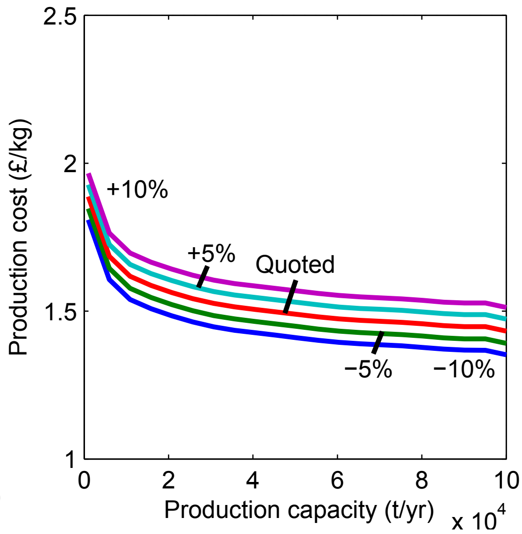
(a) *Algae oil content (wt%).*



(b) *Algae annual productivity (t/ha/yr).*



(c) *Carbon price increase rate (£/t/yr).*



(d) *PBR unit CAPEX (relative to the quoted value, Table 3).*

Figure 4: *The algal diesel production cost vs. plant production capacity and four other key input variables identified by global sensitivity analysis.*

albeit based on the assumptions made in this study, the diesel and carbon price increase rates have the highest ratio of standard deviation to mean value, reflecting the higher level of uncertainty in the price of diesel and carbon in the future.

The results of MC analyses are presented in terms of probability densities and cumulative probabilities for the production cost (Figure 6), 5-year ROI (Figure 7), and 30-year ROI (Figure 8). It is clear from Figure 6 that increasing plant production capacity will considerably reduce the mean expected value for the production cost. However, even at the largest production capacity considered here (i.e. 100,000 tonne/year), there is 20% probability that the production cost can be reduced below £1.0 per kg. It was also found that for a average-sized plant (e.g. 10,000 tonne/year), there is 50% probability that the production cost of algae-derived diesel exceeds £1.3 per kg.

The probability results for 5- and 30-year ROI in Figures 7 and 8 suggest that the plant production capacity has a similar effect on the ROI probability over both time periods. The probability of a higher ROI over either period increases significantly when increasing the plant production capacity. It is also evident that the uncertainty in the value of 30-year ROI is around a factor of ten greater than that of the 5-year ROI.

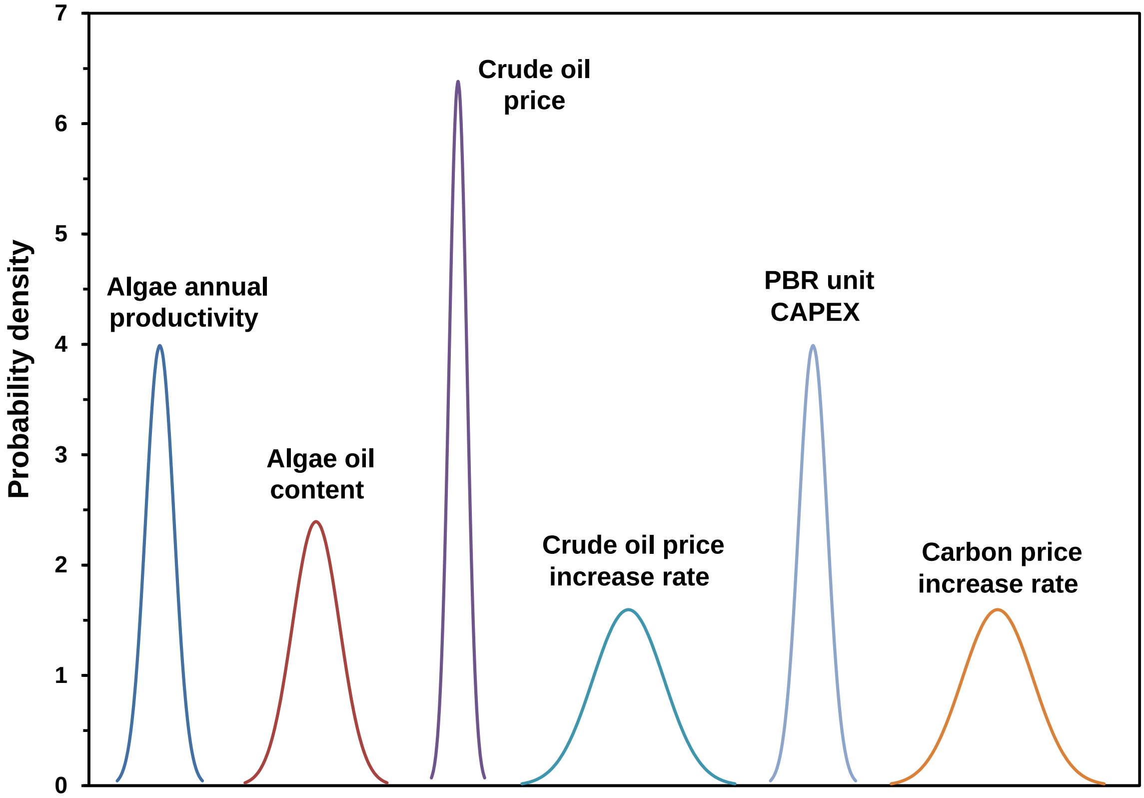
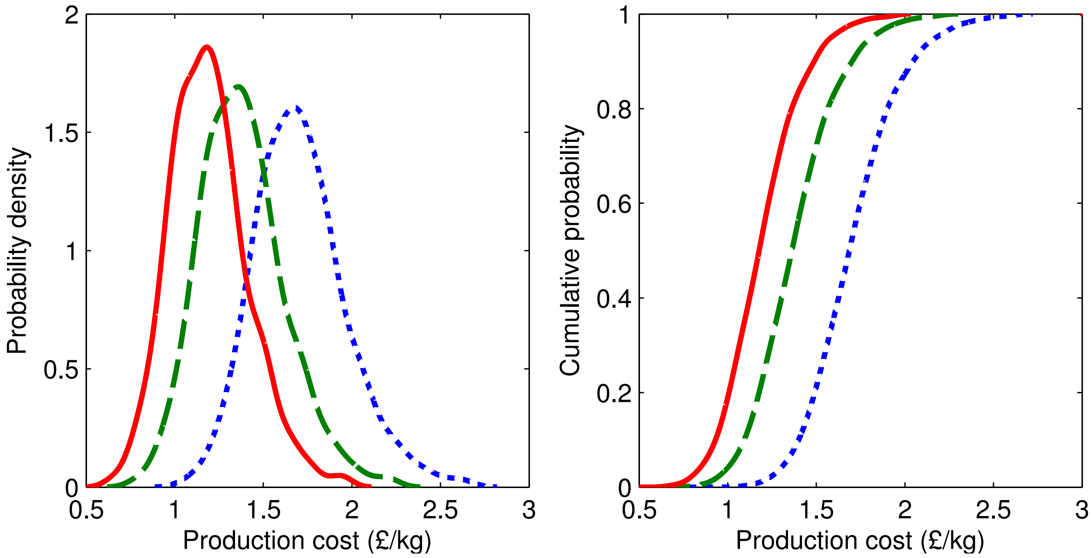


Figure 5: *Normal distributions of the most important inputs identified in the global sensitivity analysis. In order to allow comparison of the relative uncertainty of different inputs, the probability densities $\mathcal{N}(\mu,\sigma^2)$ are transformed to $\mathcal{N}(0,\sigma^2/\mu^2)$ and shown from $-3\sigma/\mu$ to $+3\sigma/\mu$.*

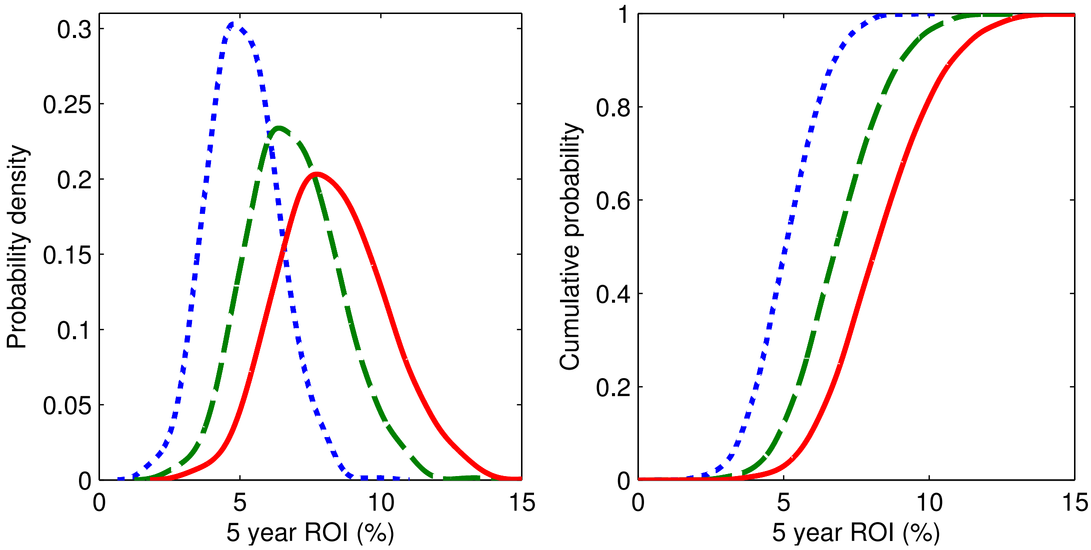
4 Conclusions

We developed a techno-economic model for the assessment of algae-derived biodiesel production under economic and technical uncertainties currently associated with algal biorefineries. The proposed strategy was comprised of photobioreactor (PBR), harvesting, oil extraction, oil esterification, and integrated gasification/Fischer-Tropsch units. In order to fully realise the environmental benefits of algal biofuels, a concentrated solar power (CSP) system was considered to provide the biorefinery with decarbonised electricity. High Dimensional Model Representation (HDMR) method was implemented to study the



(a) **(b)**

Figure 6: *Distribution of biodiesel production cost. The dotted, dashed, and solid curves correspond to production capacities of 1,000, 10,000, and 100,000 tonnes per year, respectively.*



(a) **(b)**

Figure 7: *Distribution of 5 year ROI. The dotted, dashed, and solid curves correspond to production capacities of 1,000, 10,000, and 100,000 tonnes per year, respectively.*

relative sensitivities of biodiesel production cost and ROI to 14 independent inputs to the above process units, aiming to cover the key technical and economic assumptions. The ranges over which these inputs were allowed to vary were chosen in such way to cover the current uncertainties as well as the plausible developments in the future.

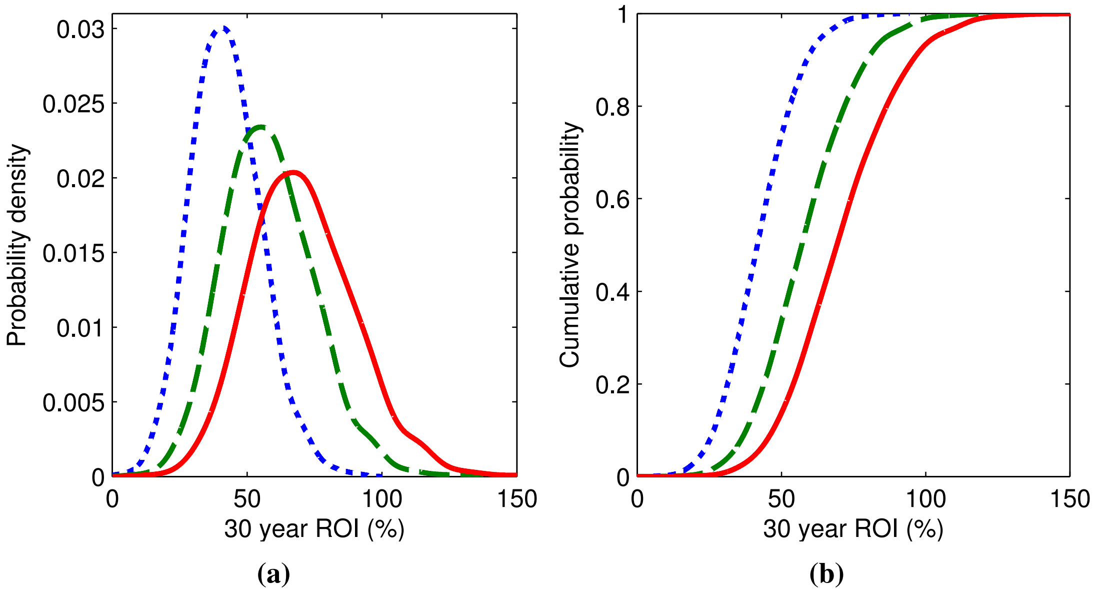


Figure 8: *Distribution of 30 year ROI. The dotted, dashed, and solid curves correspond to production capacities of 1,000, 10,000, and 100,000 tonnes per year, respectively.*

The global sensitivities calculated in this paper take into account the range over which the input parameter values can vary. The HDMR analysis revealed that the sensitivity of the production cost of algae-derived diesel to the key input parameters decreases in the following order: algae oil content > algae annual productivity per unit area > plant production capacity > carbon price increase rate > PBR unit CAPEX. It was also shown that the contribution of input parameters to short-term and long-term Return on Investments (ROIs) are somewhat different. The input parameters that represent the future changes, such as the crude oil and carbon price increase rates, were found to have negligible impact on the short-term performance of the biorefinery plant (as represented by 5 year ROI), but become substantially more important when extending the analysis time span (as represented by 30 year ROI). Our analysis indicated that the 5 year ROI is primarily sensitive to algae oil content, crude oil price at the beginning of plant operation, and annual productivity; whereas the 30 year ROI is most sensitive to algae oil content, crude oil price increase rate, and algae annual productivity.

From the uncertainty analysis presented here it can be seen that with current technologies, prices, and forecasts it is unlikely that a plant that has algal biodiesel as it's primary product can be commercially feasible. This in fact highlights the need for developing technologies to produce other value-added products, both from the algae and from the oil-extracted algae, in order to turn the production of low carbon biofuels economically viable. Furthermore, that the variance of the ROI increases by about a factor of 10 from year 5 to year 30 further demonstrates the importance of the uncertainty in price increase rates and other forecast values when calculating the future values of outputs. Such information can be subsequently used by investors and policy makers to identify the risks associated with the considered algae conversion route.

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 No. 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. Sebastian Mosbach and Dr. Jethro Akroyd for their generous help throughout this project.

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