Techno-economic and Monte Carlo probabilistic analysis of microalgae biofuel production system

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HIGHLIGHTS

- Microalgal oil production cost reaches $3.46 per liter.
- System can range widely from high profits to low competitiveness on biofuel market.
- Co-products have strong influence on microalgal diesel prices.
- Microalgal system has more market flexibility than traditional energy markets.

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ABSTRACT

This study focuses on the characterization of the technical and economic feasibility of an enclosed photobioreactor microalgae system with annual production of 37.85 million liters (10 million gallons) of biofuel. The analysis characterizes and breaks down the capital investment and operating costs and the production cost of unit of algal diesel. The economic modelling shows total cost of production of algal raw oil and diesel of $3.46 and $3.69 per liter, respectively. Additionally, the effects of co-products’ credit and their impact in the economic performance of algal-to-biofuel system are discussed. The Monte Carlo methodology is used to address price and cost projections and to simulate scenarios with probabilities of financial performance and profits of the analyzed model. Different markets for allocation of co-products have shown significant shifts for economic viability of algal biofuel system.

1. Introduction

Debates over the future of microalgae biofuels have focused on quantitative methods of assessing the environmental benefits and the economic feasibility of commercial-scale algae production (Chisti, 2007; Liu et al., 2012). While numerous studies have been published on the topic, results are quite divergent. Disparities among these studies can largely be attributed to inconsistency in system boundaries, scope, cultivation system architectures, and degrees of waste and co-product integration, all of which prevent agreement on environmental performance of microalgae biofuels (Benemann and Oswald, 1996; Campbell et al., 2011; Clarens et al., 2010; Kadam, 2002; Lardon et al., 2009; Luo et al., 2010; Sander and Murthy, 2010; Sialve et al., 2009; Stephenson et al., 2010). While economic analyses of photosynthetic microalgae-based biofuels are conducted in many of these studies, a reliable estimation of the cost of producing algal biodiesel remains a challenge due to the early stage of development of this technology (Benemann and Oswald, 1996; Molina Grima et al., 2003; Schenk et al., 2008). Existing economic studies present widely diverging results. These differences can be attributed to the ranges of oil yields, which vary from conservative to aggressively high, strongly affecting cost estimates (Dogaris et al., 2015; Quinn and Davis, 2015; Sharma et al., 2015). Capital costs, several coupled plants with CO\textsubscript{2} sequestration, or wastewater applications as cost lowering components and a scenario-by-scenario basis per studies do not allow direct cross-comparisons (Benemann and Oswald, 1996; Campbell et al., 2011; Davis et al., 2011; Norsker et al., 2011; Tapie and Bernard, 1988). The literature shows a continued...
lack of agreement on production costs and economic viability of microalgae based production systems (Carriquiry et al., 2011; Quinn and Davis, 2015; Sun et al., 2011).

Most studies present a traditional accounting of cost and capital investment, but few consider a more informative way of assessing and presenting the risk in microalgae-to-biofuel investment. No microalgae economic viability studies have presented a quantification of the risks and uncertainty associated with a project (Damodaran, 2007).

A number of studies have provided evidence to support the development of the modern algae biofuels production system. Benemann provides complete explanations of costs estimates, but focuses on open pond production systems and do not analyze risks (Benemann and Oswald, 1996). Tapie and Bernard conduct a review of the algae literature, describing data and costs for large-scale algae production facilities and reporting total production costs of non-processed biomass ranging from $0.15 to $4.00 per kg (Tapie and Bernard, 1988). Huntley and Redalje estimate oil production costs at $84 per barrel (2004 dollars), assuming no improvements in current technology, but because of the proprietary nature of the study, a detailed list of costs is not presented (Huntley and Redalje, 2007). Chisti evaluates the technical feasibility of microalgae for biodiesel production. In reviewing production practices, Chisti finds that the current technology in microalgal production results in a cost per liter of production of $0.78 and $1.00 for photobioreactors (PBRs) and open ponds, respectively (in 2006 dollars), but there are no details for how the author arrived at these cost estimates (Chisti, 2007). Shen reviews the practices, special features, and technical and/or economic barriers to various microalgae mass production methods, including open ponds and PBRs, but the analyzed plant is not for biofuel production. In addition, the open pond and PBR systems studied are for different locations and producing different amounts of biomass, further complicating comparison. Norsker calculates production costs under Dutch climatic conditions for three different microalgal production systems: open ponds, horizontal tubular PBRs and flat panel PBRs. Norsker evaluates the economics for a commercial 100 ha facility and calculate the capital and operating costs for a one hectare facility. His study shows the economics of scale that exist between the two different size facilities of the sensitivity of production costs to reducing mixing costs and nutrient costs, and the effect of improving irradiation and photosynthetic efficiency, which is significant for algal production (Norsker et al., 2011). Beal evaluates a 100-hectare production facility, in two locations (Texas and Hawaii), for biocrude, animal feed and ethanol. His study found a $2 per liter of biocrude for the best scenario case, with environmental and water benefits (Beal et al., 2015). Richardson analyzes the probability of success for both open pond and PBR systems, based on Davis’ model. Richardson describes scenarios with high probabilities of enterprise success wherein capital expenditures (CAPEX) and operating expenses (OPEX) are decreased to as low as 10% of their baseline values, but does not discuss what system changes would allow those reductions (Richardson et al., 2012).

Davis’ study is one of the most recent and comprehensive economic viability studies evaluating the product costs of microalgae-derived biofuel from open pond and airlift PBR systems, where both systems use an anaerobic digestion system as a coupled system with microalgae cultivation. The model was constructed with open, clear, accurate and detailed engineering data and referencing, for every part of the process (Davis et al., 2011). Based on our understanding of the literature, there are two primary requirements of a study that can contribute to the current debate. First, microalgae analyses have been more focused on open pond technologies and the few existing analyses on enclosed photobioreactors are not based on commercial scale models and system operation data. Second, techno-economic analyses (TEAs) provide production costs of microalgae products for a base case with just one or few market scenarios, not assessing the investment risks of microalgae biofuels from various outcomes and the probabilities that may impact forecasted profits.

The objective of this study is to develop a baseline model of the Solix Biosystem Generation 3 Photobioreactor cultivation model to assess the values of microalgae-derived biodiesel and co-products. As the biofuels industry continues to commercialize, it is critical to determine the value of microalgae-derived products and co-products for investors to maximize the return of their investment and to identify constraints of this microalgae-to-biofuel system (i.e. initial capital investment, operational costs or concerns, location and land costs, etc.). The first part of this TEA will provide the baseline of cost and capital investments for this microalgae-to-biofuel design, based on the detailed engineering model, following by estimation of the product and co-product values. The second part presents a risk analysis that quantifies the investment risks involved in the microalgae-to-biofuel process using Monte Carlo simulation to analyze set of variable factors that affect the economic feasibility of microalgae production of biofuel and co-products.

2. Material and methods

This study presents a dynamic accounting model that includes capital investment, multiple scenario inputs, operating and maintenance costs, as well as technical details on microalgae production rates, allowing analysis of the full range of possible economic performance and therefore the relative probability of economic success of microalgae biofuels.

The first stage of this analysis is to determine the baseline techno-economic model for a suspended PBR microalgae cultivation system, based on the Solix Biosystem Generation 3 Photobioreactor (SOLIX), scaled to a production capacity of 37.85 million (MM) of liters of raw oil per year. The Solix Biosystem engineering model is combined with the economic and accounting model developed by Davis as shown in Fig. 1 (Davis et al., 2011). The economic model developed by Davis is consistent to a framework that has been used in various biofuel techno-economic reports published by National Renewable Energy Laboratory (NREL), Pacific Northwest National Laboratory (PNNL) and Argonne National Laboratory (ANL), intended to enable studies of different systems to be comparable (Davis et al., 2013; Jones et al., 2009; Roberts et al., 2012; Swanson et al., 2010).

The Davis model is carefully constructed, based on clear, open, reliable and detailed engineering data and references. Its capital costs, land costs, site development costs and CO2 delivery system costs are based on the prior literature and standard engineering cost estimates. The model provides estimates for the capital costs for pumping systems for water, nutrient and electrical supply, general machinery, office buildings, warehouses, field expenses, contingency costs, salaries and overhead, maintenance, taxes and insurance costs. Its structure allows flexible introduction or exclusion of specific engineering process, types of equipment, or working load of equipment, all of which were decisive for adapting the model to the Solix system. Analysis of the SOLIX system provides a breakdown of the capital and operating costs to evaluate strengths and constraints of this microalgae-to-biofuel system, in a comparative basis to other alternative systems.

The second part of this study analyzes the probabilities of financial success for the microalgae cultivation facility by varying key inputs in a Monte Carlo (MC) framework. As a stochastic simulation technique that iteratively evaluates a deterministic model (i.e. baseline case), using random variables as inputs, MC can be used to value an investment proposition and to better understand
and manage risks (Hertz, 1979; Jackel, 2002; Razgaitis, 1999). The combination of input variables encompasses the set of scenarios and risks to which the investment could be exposed.

2.1. Baseline technical modelling

The first stage is to determine the baseline techno-economic model for the SOLIX cultivation system, scaled to a production capacity of 37.85 MM of liters of raw oil per year. The microalgae biofuel system has four processes: cultivation, dewatering (or harvesting), oil extraction and oil hydrotreating. The process flow diagram is shown in Fig. 1 and each process is detailed and described as follows.

The cultivation block is also called PBR photosynthetic facility, and it is composed of a number of photobioreactor unit of 36 m long and 0.127 mm of thick clear polyethylene bags, supported in a thermal water bath. The SOLIX system growth rates are based on the microalgae strain Nannochloropsis salina. The growth rate and lipid content are assumed as 0.15 kg m⁻² day⁻¹ and 30% in biomass weight, according to the latest updates (Quinn et al., 2012). After reaching the optimum biomass accumulation, the microalgae are harvested (or dewatered) through a centrifugal system. The concentrated biomass is submitted to solvent extraction with hexane and ethanol to separate microalgae oils, by high pressure centrifuges. The extracted oils compound the algal crude oil. The algal crude oil is upgraded to biodiesel via hydrotreating process, largely based on study of hydrotreating oils and brown grease developed by the company UOP. This hydrotreating saturates double bonds of the fatty acid chains of the triglyceride (TAG) components with hydrogen addition, removes of oxygen and cracks large molecules into smaller chains, with 80% fuel yield, distributed in 78% of diesel and 2% of naphtha (Davis et al., 2011; Marker, 2005). The remain-
• TCI = Total Capital Investment;
• FCR = Fixed charge rate;
• Yield = Annual biodiesel yield (gallons per year);

\[
FCR_{\text{Degradable}} = \frac{ROI (1+ROI)^{-j} - (1-i) \cdot NPV}{(1-i)}
\]

(2)

\[
FCR_{\text{Non-degradable}} = \frac{ROI (1+ROI)^{-j} - (1-i)}{(1-i)}
\]

(3)

where:
• ROI = Desired rate on investment;
• j = Analysis period;
• NPV = Net Present Value factor (for depreciation charges);
• i = Tax rate.

MFSP variable is an accounting concept, not a real price. A higher value of MFSP means that the final product (e.g., algal biodiesel) needs to be sold at a higher value (for revenues and inflow cash) to break even the original capital investments. A higher value of MFSP also means less competitiveness of the project when compared to a project with a lower value of MFSP. A negative value of the MFSP simply means that, even if the biodiesel is sold at a loss, the algae production facility would still be economically feasible. Details on the economic inputs for the calculation of MFSP are available in the Supplementary Material.

2.3. Financial feasibility economic model description

The financial success for the microalgal production system is analyzed through the concept of MFSP of algal diesel, with assessment of end-use of co-products and market projections. The baseline model is coupled with MC software to simulate projections of costs and MFSPs of algal biofuel for 2020. The most significant variables (identified in Section 2.2.) and their price or cost projections are randomly combined and input into the baseline techno-economic model to generate results or outputs of interest, in these case, production costs and MFSPs. These results or outputs are gathered into probability distributions to support analyses of financial performance or success of the baseline model (Hertz, 1979; Jacquel, 2002; Ragazaitis, 1999). The method approach is represented in Fig. 2.

The Solix production system generates a set of co-products: lipid-extracted algae (LEA), biodiesel and naphtha. The naphtha can be sold as a blending component in gasoline. LEA has a wider range of applications, including as a food, cosmetics, energy, and pharmaceutical input. For this study, LEA will be analyzed in two applications: (a) as fish feed for aquaculture and (b) as cofiring biomass for electricity generation.

These LEA applications have different implications for the monetary and energy valuation of the coproduct:

(a) As fish feed: Conventional fish and rotifer feed is composed of a minimum of 50% protein and of 20% oil content. The lipid extracted algae can be used to construct a feed of similar composition. The extracted biomass is composed of 36.7% protein and 5% oil on a dry weight basis. Canola oil at $0.93 per kg can be added to the extracted biomass to produce a product with the same ratio of protein to oil of fish feed. For replacement equivalency, 1.5 kg of algae-canola feed can replace 1 kg of fish feed (De Pauw et al., 1984; Lubzens et al., 1995; Metting, 1996; Pulz and Gross, 2004; Richmond, 2004). Costs relating to oil mixing and transportation are not included.

(b) As energy source: After the algal oil extraction, the LEA has its heating value reduced, but still the remaining biomass can be used as cofiring material to generate bioelectricity, with an estimated heating value of 14.2 MJ per kg (Kadam, 2002).

Projections of prices for crude oil, natural gas, fertilizers, electricity, solvents, and aquaculture feed, all up to 2020, compose the set of variables assumed to significantly impact the economic viability of the SOLIX system. Probability density functions for these inputs were constructed on the basis of projections of future prices. It was adopted triangular probability distributions, where the lower bound is related to the worst case scenario, the upper bound is related to best case scenario, and the median is approximated by the reference scenario (Damodaran, 2007; Tan et al.,

Fig. 2. Monte Carlo techno-economic and risk analysis approach diagram.
The LEA selling price as fish feed is modeled based on aquaculture production scenarios and projected fishmeal prices. The reference aquaculture scenario incorporates an annual rate of increase of 1.5% of global food fish production (Delgado et al., 2003), resulting in a modeled 18% increase in LEA price, between 2013 and 2020. The upper bound scenario assumes a rapid aquaculture expansion scenario associated with a decrease in fish price and an increase of feed price, resulting in a modeled 59% increase in LEA price between 2013 and 2020 (FAO, 2012). The lower bound assumes a slow aquaculture expansion scenario projecting a price increase for fish and 0% increase in LEA price (Delgado et al., 2003).

The LEA selling price, as a co-firing biomass to generate bioelectricity in power plants, is projected using the baseline data for 2013 and the same yearly percentage increase in price as is projected for industrial electricity rates based on U.S. Energy Information Administration forecasting until 2020 (EIA, 2013).

The input costs for high density polyethylene (HDPE) and hexane are projected on the price of crude oil and nitrogen nutrient costs are projected on fertilizer prices. The projections use the baseline data for 2013 and price forecasting from the U.S. Energy Information Agency (EIA) reference scenario, lower case scenario, and higher case scenario until 2020 (EIA, 2013; USDA, 2011). More details of these projections are available in the Supplementary Material.

MC simulations were performed with 3000 runs (determined through a convergence study), for each of the two potential markets for LEA sales. The outputs of the engineering model are used to evaluate capital and operating costs to establish a baseline of production costs for this microalgae production of biofuels and co-products.

### 3. Results and discussion

#### 3.1. Baseline model

The first results presented correspond to the characteristics of the baseline model. In this section, it is presented the breakdown of capital and operating costs, compare these costs to those of conventional biofuels, and evaluate the baseline co-product valuations.

Regarding to the final products of microalgae system, the operating costs represent the largest contribution (63%) to total production cost, the capital investment costs represent almost 30%, and land purchasing costs are only 7% of the production costs. The resulting production costs for the microalgae raw crude oil of $3.46 per liter and for refined diesel of $3.69 per liter. The breakdown of production costs of raw crude oil and refined diesel are shown in Fig. 3.

This result demonstrates that microalgae diesel from SOLIX system is higher compared to soybean-based biodiesel costs, which range from $0.57 to 0.67 per liter (Tao and Aden, 2009) and to the costs of other diesel from alternative feedstocks and technologies, such as diesel from wood by hydropyrolysis, which have a minimum selling price of $0.42 per liter (Roberts et al., 2012); Fischer-Tropsch biofuels from corn stover with production cost range of $1.13 to $1.28 per liter (Swanson et al., 2010); diesel from wood chips through fast pyrolysis with production cost of $0.58 per liter (Jones et al., 2009) and, Davis assessed microalgae biodiesel from hydrothermal liquefaction (HTL) process with MFSP of $2.64 per liter of biodiesel (Davis et al., 2014).

The SOLIX microalgae biodiesel may have competitive production costs advantages over some other models of microalgae biorefineries, i.e. Richardson’s study includes single solvent extraction for algal lipid and estimated average production costs of $7.61 and $5.38 per liter of algal crude oil, respectively for open and PBR system (Richardson et al., 2014); and Brownbridge assesses microalgae biodiesel derived from Fischer-Tropsch process and with production costs between £0.8–1.6 per kg of biodiesel (Brownbridge et al., 2014).

The techno-economic analysis aims to provide a detailed and realistic analysis of each stage of microalgae biofuel system and also to identify potential process or economic hurdles that should be targeted in future research.

The capital investment costs are measured in U.S. million dollars. The harvesting (dewatering) and the lipid extraction systems represent 33% and 32% of the total direct installed capital costs, respectively. These are followed closely by microalgae cultivation system, representing almost 30% of total direct installed capital, which includes PBRs, CO2 supply, utility supply system and machinery (pumps, pipelines). The indirect installed cost, which consist of warehouse, office buildings, contingency, land costs and others, and sum up to $166.20 million of dollars, represents about 50% of total direct and indirect capital costs. The hydrotreating section, that converts algal raw oil into biodiesel, represents only 5% of total capital installed costs. The results of the CAPEX analysis are detailed in Table 1.

The operating costs are measured in U.S. million dollars per year. The microalgae cultivation, algal oil harvesting and extraction represent 96% and the biodiesel hydrotreating is only 4% of OPEX. The breakdown of OPEX shows that the solvent consumption in the lipid extraction is the major expense, about 29%. Nutrient and power supplies are other major costs, contributing as 22% and 16% of OPEX, respectively. The replacement of PBRs, with estimation of total replacement within 5 years, accounts only for 5% of OPEX. Details of the OPEX analysis are shown in Table 2.

On the techno-economic assessment, it is clear that technological research should be focused on alternatives or improvements on microalgae harvesting and lipid extraction, which have the most impact on the final production costs. Other R&D efforts could be focused on alternative nutrients to cultivate microalgae, such as sewage, wastewaters, which can decrease costs and environmental impacts.

Besides the biodiesel, the system generates LEA and naphtha, whose revenues are treated as credits in the accounting framework. The naphtha produced has equivalent energy value of gasoline, can be sold as blending component for gasoline, and sale prices are determined by gasoline retail prices. With gasoline price at $0.95 (the annual average in 2013, reported by EIA), credits for naphtha are converted to $0.03 per liter of biodiesel produced.
Operating costs.

<table>
<thead>
<tr>
<th>Capital and equipment investment costs</th>
<th>U.S. Dollars (in MM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct installed costs</td>
<td></td>
</tr>
<tr>
<td>Microalgal lipid production</td>
<td></td>
</tr>
<tr>
<td>PBR tube system material and installation</td>
<td>$35.43</td>
</tr>
<tr>
<td>CO₂ distribution system</td>
<td>$0.65</td>
</tr>
<tr>
<td>Algal harvesting system</td>
<td>$53.19</td>
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<tr>
<td>Extraction centrifuge system</td>
<td>$51.61</td>
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<tr>
<td>Utility supply system</td>
<td>$7.54</td>
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<tr>
<td>General machinery</td>
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<tr>
<td>Initial Water Charge</td>
<td>$0.88</td>
</tr>
<tr>
<td>Biodiesel production</td>
<td></td>
</tr>
<tr>
<td>Diesel hydrotreating plant</td>
<td>$8.37</td>
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<tr>
<td>Subtotal</td>
<td>$161.55</td>
</tr>
<tr>
<td>Indirect installed costs</td>
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<tr>
<td>Site development</td>
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<tr>
<td>Warehouse</td>
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<tr>
<td>Field expenses</td>
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<td>Home office and construction</td>
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<tr>
<td>Contingency</td>
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<td>Other costs</td>
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<tr>
<td>Working capital (25% of Operating Costs)</td>
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<tr>
<td>Subtotal</td>
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<tr>
<td>Non-depreciable capital</td>
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<td>Land costs</td>
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<td>Total capital costs</td>
<td>$327.74</td>
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</table>

These data are related to Solix Microalgal Biofuel System. Values are in millions of U.S. Dollars.

Operating costs.

<table>
<thead>
<tr>
<th>Operating costs</th>
<th>U.S. Dollars (in MM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microalgal lipid production</td>
<td></td>
</tr>
<tr>
<td>Power consumption</td>
<td>$13.46</td>
</tr>
<tr>
<td>Nutrients (N,P)</td>
<td>$18.96</td>
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<tr>
<td>CO₂ supply</td>
<td>$5.92</td>
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<tr>
<td>Solvent consumption</td>
<td>$24.03</td>
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<tr>
<td>PBR 5-year replacement</td>
<td>$7.09</td>
</tr>
<tr>
<td>Waste disposal</td>
<td>$1.36</td>
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<tr>
<td>Utilities (cooling water, steam)</td>
<td>$2.92</td>
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<tr>
<td>Labor and overhead</td>
<td>$3.82</td>
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<tr>
<td>Maintenance, tax, insurance</td>
<td>$5.43</td>
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<tr>
<td>Diesel hydrotreating plant</td>
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</tr>
<tr>
<td>Hydrogen consumption</td>
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<tr>
<td>Steam consumption</td>
<td>$0.01</td>
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<tr>
<td>Labor and overhead</td>
<td>$0.76</td>
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<tr>
<td>Maintenance, tax, insurance</td>
<td>$1.09</td>
</tr>
<tr>
<td>Total operating costs ($/YR)</td>
<td>$86.52</td>
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</tbody>
</table>

These operating costs are related to Solix Microalgal Biofuel Systems. Values are in millions of U.S. Dollars per year.

The co-product LEA revenues can vary highly depending on its final application.

### 3.1.1. LEA application to aquaculture feed

The current commercial market value of fish feed for aquaculture is US $1.53 per kg. Costs relating to oil mixing and transportation are not included in this study, as further investigation is still required for accurate estimation of costs. The microalgae system produces 99.8 metric tonnes of LEA per year, and its revenue credits can provide equivalent to $4.13 per liter of microalgae biodiesel produced. The combined revenue of LEA and naphtha provides credit of $4.16 per liter.

The final MFSP of algal diesel, with the revenue credits from LEA and naphtha sales, is $–0.47 per liter.

### 3.1.2. LEA application to energy

LEA has an estimated heating value of 14.2 MJ per kg (Batan et al., 2010). The price of biomass as a combustion fuels for electricity generation is $1.89 per GJ of heating value capacity (Brown and Baek, 2010). The revenue credit from LEA as co-firing biomass is $0.007 per liter of biodiesel. The combined revenue of LEA and naphtha is equivalent to $0.03 per liter of biodiesel produced.

The final MFSP of algal biodiesel, with the resulting revenue credits, is $3.66 per liter.

### 3.2. MFSP sensitivity analysis

The MFSP sensitivity analysis aims to point out, among a large number of factors, those that impact significantly the selling prices of microalgal diesel. For this analysis, every input factor has its value incremented ±30%, while all other input factors remain constant, to detect its effect on the algal MFSP. The same procedure is performed independently for each input factor. Changes in output associated with an increase of input values are indicated on each side of the centerline (baseline case) using blue shading; while decrease of input values are indicated with red shading.

The change in the selling prices of the co-product LEA as fish feed has the greatest influence on the MFSP. The variation on the selling price of the co-product causes a 270 percent change in the minimum selling price for biodiesel. It is worth to reassert that MFSP is an accounting value, in which negative value means that the product can be sold even with loss, while supplementary revenues can make the project profitable.

The price of hexane, HDPE, electricity and nitrogen fertilizer affects the MFSP in the range of 20–34 percent. For all other input cost variables, the sensitivities are less than 17 percent change in the MFSP of algal biodiesel. The results of this sensitivity analysis are presented as a tornado plot (see Fig. 4).

### 3.3. Probability distributions of minimum fuel selling price using Monte Carlo

The MFSP sensitivity analysis aims to point out, among a large number of factors, those that impact significantly the selling prices of microalgal diesel. For this analysis, every input factor has its value incremented ±30%, while all other input factors remain constant, to detect its effect on the algal MFSP. The same procedure is performed independently for each input factor. Changes in output associated with an increase of input values are indicated on each side of the centerline (baseline case) using blue shading; while decrease of input values are indicated with red shading.

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The five most sensitive variables, identified in Section 2.2, that affect MFSP are: LEA selling price, polyethylene, hexane, electricity, and nitrogen fertilizer costs. In this results section, the MC simulation analysis is used with models of the variations in these sensitivity variables to model the probabilistic distribution of MFSP, in 2020, without and then with coproduct valuation.

![Fig. 4. MFSP sensitivity analysis. Tornado plot demonstrated the extent to which algal MFSP changes with ±30% of input parameters. The center line represents the baseline case. The blue and red shading bar represents the direct and reverse relationships. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)](image-url)
The first step of the MC probability distribution analysis to determine the distribution of algal diesel MFSP, based on the projections of costs of the four variables to which costs are most sensitive – polyethylene, hexane, electricity and nitrogen fertilizer costs. Any co-product revenues or credits are excluded. The MC simulations generate a probabilistic projection of 2020 production costs with an average of $4.57 ± 0.23 per liter of algal diesel. These results demonstrate that without significant revision to the algae cultivation technology and processes, the algal diesel projected production cost will increase relative to the 2013 baseline result of $3.69 per liter.

The second step of the MC probability distribution analysis uses projections of all five sensitivity variables, where the LEA is simulated as a fish feed input. Coproduct revenues from sales of algae-derived naphtha as gasoline blending component are also considered. The combined revenues are significant enough to shift the probability distribution of MFSPs of algal to negative values. The negative value of MFSP, as an accounting value, only means that applying LEA into aquaculture feed can allow algal diesel to be sold even at loss. The co-products add an average credit of $0.25 per liter of algal diesel, which brings down the average MFSP to $−0.68 ± 0.56 per liter. The resulting distribution of MFSPs also shows a large standard deviation, which is mostly due to the large revenue from sale of LEA and the wide variation in its projected selling price, ranging from 0% to 59% of the 2013 baseline value. See the distribution data in blue in Fig. 5.

The final step of the MC probability distribution analysis uses projections of all five sensitivity variables, where the LEA is simulated as co-firing biomass. Coproduct revenues from naphtha as gasoline blending component are also accounted. The combined revenue of LEA and naphtha adds small average credit of $0.04 per liter, that reduces slightly the average MFSP to $4.53 ± 0.23 per liter of refined diesel. The resulting distribution of MFSPs has a much smaller standard deviation, due to narrower projected range of selling prices for LEA sold as co-firing biomass, varying from 15% to 19% from the 2013 baseline value. See the distribution data in red in Fig. 5.

The MC simulations demonstrate that the economic performance of the microalgae to biofuels process is dependent on access to co-product markets. Microalgae facilities that only produce fuels and electricity will be forgoing value that is available through sales of co-product to higher value markets.

4. Conclusions

The microalgae biodiesel from the proposed photosynthetic bioreactor-based algae production system is demonstrated to have high production costs, increasing out to 2020, based on reference scenarios of inputs and material costs. The financial feasibility of microalgae based biofuels is dependent on access to co-product markets with higher added values. Research to enable commercial scale of microalgae biofuels and to enhance financial sustainability should be focused on overcoming technological hurdles to harvesting, on lipid extraction techniques that are appropriate to microalgae systems, as well as expensive and alternative nutrient sources for cultivation.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.biortech.2016.07.085.

References


Fig. 5. Microalgal diesel MFSP probability distributions from Monte Carlo simulations. Blue distribution: microalgal diesel average MFSP, where LEA is sold as fish meal replacement, is $−0.68 ± 0.56 per liter. Red distribution: microalgal diesel average MFSP, where LEA is sold as co-firing supply, is $4.53 per liter. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)


