Modeling and Analysis

Technoeconomic analysis of renewable aviation fuel from microalgae, *Pongamia pinnata*, and sugarcane

Daniel Klein-Marcuschamer, University of Queensland, Australian Institute for Bioengineering and Nanotechnology, St Lucia, Australia; Joint BioEnergy Institute, Emeryville, CA, USA; Lawrence Berkeley National Laboratory, Berkeley, CA, USA
Christopher Turner, University of Queensland, Australian Institute for Bioengineering and Nanotechnology, St Lucia, QLD, Australia
Mark Allen, IOR Energy Pty Ltd, Bulimba, QLD, Australia
Peter Gray, University of Queensland, Australian Institute for Bioengineering and Nanotechnology, St Lucia, Australia
Ralf G Dietzgen, Peter M Gresshoff, Ben Hankamer, University of Queensland, St Lucia, QLD, Australia
Kirsten Heimann, James Cook University, Townsville, QLD, Australia
Robert Speight, Lars K Nielsen, University of Queensland, Australian Institute for Bioengineering and Nanotechnology, St Lucia, Australia
Paul T Scott, Evan Stephens, University of Queensland, St Lucia, QLD, Australia

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Abstract: Technoeconomic analysis of renewable aviation fuels has not been widely considered, despite the increasing global attention that the field has received. We present three process models for production of aviation-fuel from microalgae, *Pongamia pinnata* seeds and sugarcane molasses. The models and assumptions have been deposited on a wiki (http://qsafi.aibn.uq.edu.au) and are open and accessible to the community. Based on currently available long-term reputable technological data, this analysis indicates that the biorefineries processing the microalgae, *Pongamia* seeds, and sugarcane feedstocks would be competitive with crude oil at $1343, $374, and $301/bbl, respectively. Sensitivity analyses of the major economic drivers suggest technological and market developments that would bring the corresponding figures down to $385, $255, and $168/bbl. The dynamic nature of the freely accessible models will allow the community to track progress toward economic competitiveness of aviation fuels from these renewable feedstocks. © 2013 Society of Chemical Industry and John Wiley & Sons, Ltd

Supporting information may be found in the online version of this article.

Key words: technoeconomic analysis; aviation fuels; biofuels; microalgae; *pongamia*; sugarcane.

Correspondence to: Daniel Klein-Marcuschamer, Joint BioEnergy Institute, Emeryville, CA, USA.
E-mail: dklein@lbl.gov

Introduction

The replacement of petroleum-derived transportation fuels with renewable alternatives is an important step in mitigating green house gas (GHG) emissions, meeting transportation needs in an oil-constrained world, and promoting local economies. Aviation fuels account for a significant fraction of global transportation needs; for example, in 2010, air transport consumed 10% of global transportation energy and this share is projected to increase to 13% by 2030.[1] In addition, aviation fuels represent a segment of the energy market that is unlikely to be met by other alternatives (e.g. battery-powered vehicles).

For that reason, the aviation industry is actively encouraging and supporting the development of drop-in (i.e. compatible with current infrastructure) renewable fuels, and it is very likely that other sectors of the transportation industry will benefit from these efforts. Proof-of-concept flights have already demonstrated that aviation biofuels from several sources meet the required performance specifications and the industry is accelerating the certification process.[2] While the opportunity of and need for developing a sustainable aviation fuel industry is recognized, there is as yet no generally accepted strategy or production process. Furthermore, controversial and often contradictory claims about the performance of various technologies and feedstocks or the advantages of some production routes over others appear frequently in the scientific and popular literature. Technoeconomic studies offer quantitative data that can help inform these debates.[3–6]

In the present study, we constructed technoeconomic models for the production of aviation fuel based on three feedstocks: photoautotrophic microalgae, *Pongamia pinnata* seeds, and sugarcane molasses (see Process Description section). The selection was made primarily because of the potential role these routes can play in the economy of Australia and other countries with bioenergy aspirations, and the work presented here is not intended to be representative or comprehensive. The goal is instead to provide a first estimate of the technical and economic performance of the three different routes and to discuss a methodology that can be followed when studying other feedstocks and fuel production technologies.

In order to accelerate progress in this nascent field, we have adhered to an earlier dissemination strategy for technoeconomic studies, in which the assumptions and the models themselves are made available to the bioenergy community.[7] The models can be accessed at http://qsafi.aibn.uq.edu.au. The aim of the dissemination strategy is to quickly bridge the gap in knowledge, establish a common ground for discussion across interest groups and provide a platform that can be used to dynamically study the economic impact of technology as it develops.

Process descriptions

Process design and technology selection was done in consultation with the members of the consortium behind this study, comprising experts from the University of Queensland, James Cook University, Amyris Biotechnologies, Boeing, IOR Energy, Mackay Sugar Limited, and Virgin Australia. The choice of technology for each step was discussed among the members of the consortium before modeling, since for several steps there are various technologies that can accomplish similar tasks (e.g. open ponds *vs.* photobioreactors for microalgae, fermentation to farnesene *vs.* other hydrocarbons for sugarcane, chemical *vs.* enzymatic degumming of microalgae and *Pongamia* oils, etc.). The technologies presented were chosen because: (i) there were sufficient data to model them in detail, either in the literature or from the consortium of companies and research groups that supported this study; and (ii) they had energetic, performance or well-documented economic advantages over other technologies. In many cases, alternatives that are potentially advantageous have been reported, but they could not be fully modeled for lack of relevant parameters. As data become available, the models can be expanded or modified to include innumerable other configurations.

All models were built using SuperPro Designer software[8] and all had a production scale of 61 million liters (16 million gallons) of bio jet fuel per annum. The software allows the design of the flowsheets for each process and helps in solving the material and energy balances for the facilities, in addition to performing full cost calculations and aiding in net present value (NPV) analysis.

Microalgae process

Microalgal-derived biofuel production exploits the relatively high cellular lipid content as an oil source for refining into suitable fuel products (Fig. 1(a)). This model utilizes photoautotrophic microalgae, grown in open raceway ponds, consuming flue gas from a coal-fired power station as a carbon-enriched feed.[9]

Microalgae growth and harvesting

Specific microalgae composition and growth characteristics were modeled based on published *Nannochloropsis*

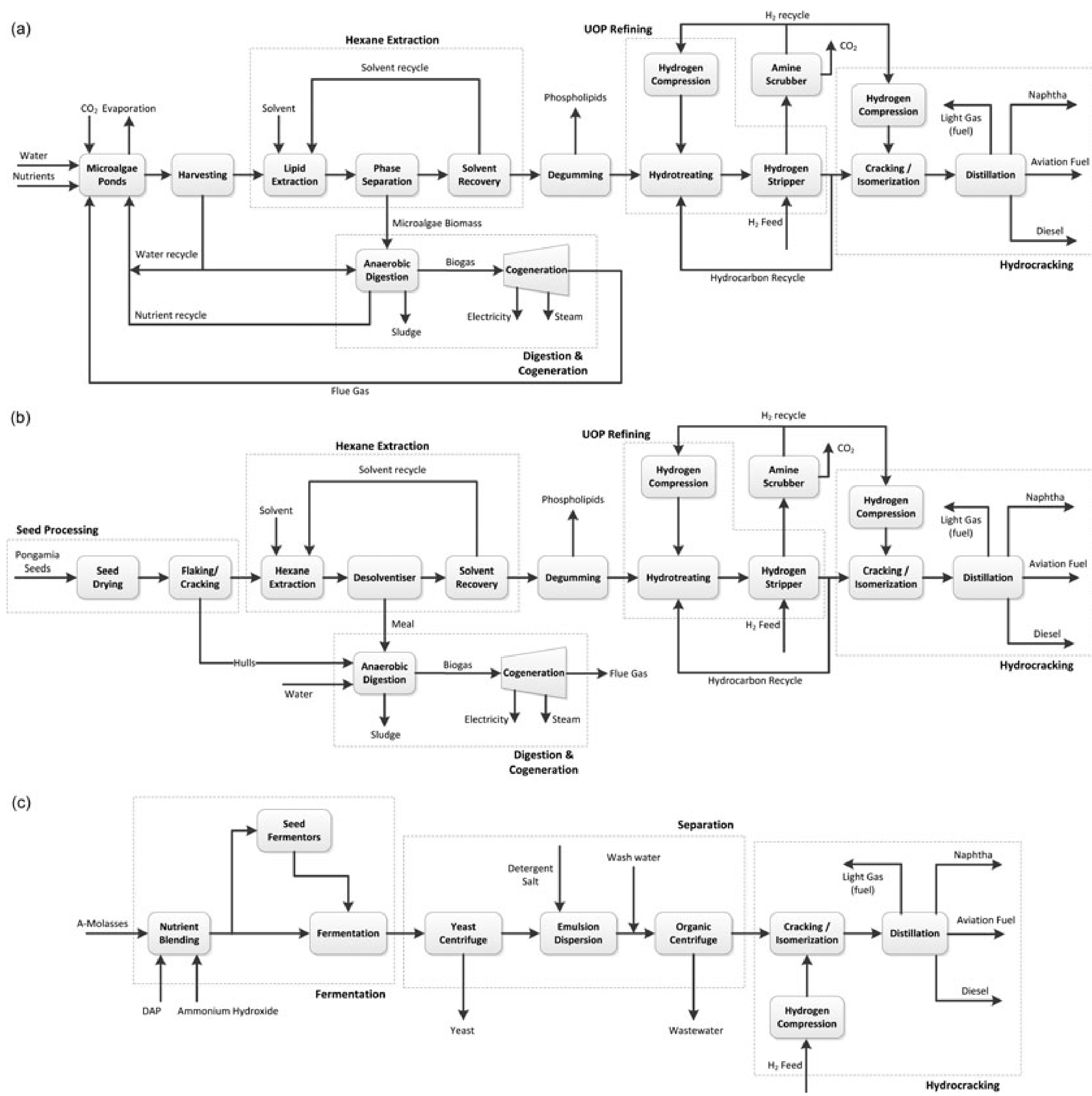

Figure 1. Process diagrams outlining the major sections of each biorefinery: (a) microalgae, (b) *Pongamia* seeds and (c) sugarcane molasses.

spp. performance. This species was selected due to (i) the availability of technical data for the entire production/processing cycle (i.e. for growth, dewatering/harvest, oil content, extraction and processing using conventional and tested technologies); (ii) its relatively high oil content; (iii) its ability to grow in saline water; (iv) its relatively high and consistent growth rate; and, importantly, (v) the availability of long-term studies that report on its performance. Though other studies have chosen to leave the species unspecified due to lack of data,[10–12] the choice of strain dictates the technologies that can be used and process parameters for various unit operations. For example, some species grow in saline waters, and others do not;[13] autoflocculation can be used to concentrate some species, but not others;[14] and the production of high-value products, which can improve the top line of a facility, is species specific.[15] Thus applying technoeconomic modeling using data for the various process configurations derived from different species cannot be used to model costs, nor can it highlight areas where strategically focused research can generate the highest impact in developing microalgae farming for economically viable aviation fuel production. Alternate production strategies like hydrothermal treatment, aqueous extraction, and secretion systems could change the output values relative to conventional dry extraction technologies, for example Vasudevan *et al.*,[16] but for the model input requirements outlined above, species specific, long term performance data must be obtained (i.e. currently long-term data for *Nannochloropsis* do not exist with these technology configurations).

The reactions used to model algal growth were derived from reported elemental compositions. Added feed nutrients consisted of diammonium phosphate and nitrate, while the flue-gas sulfur dioxide completed the elemental balance.[17–20] An open pond average biomass productivity of 20 g/m^2/day was modeled throughout the year (11 months accounting for plant downtime and maintenance), extrapolating data presented by Ben-Amotz.[21] Seasonality and downtime scheduling issues were ignored, but should be included in future studies after long-term field experiments have been performed. A cell concentration of 500 mg/L and an average algal oil content of 20.0 wt% were assumed, which correspond to the species and growth conditions modeled.[17,18,20] The product algae is harvested and concentrated to 30% solids using Evodos Spiral Plate Technology centrifuges.[22] A significant portion of the process power load is required for harvesting, with the centrifuges consuming 41% (15.8 MW) of the total power, while pond mixing consumes an additional 23% (8.9 MW).

Microalgal oil extraction and digestion

Solvent extraction of the lipid components within the algal cells first requires cell lysis to effectively release the intracellular oil.[23,24] Prior to sonication, the microalgae slurry from Evodos centrifugation is diluted with hexane solvent to allow continuous processing. The disrupted cells are treated with further hexane solvent and extracted for six hours to maximize oil recovery.[23] A decanting centrifuge recovers the organic phase, while the aqueous phase and cellular debris are separated and sent to anaerobic digestion. A three-effect evaporator flashes the hexane solvent for recycling to the extraction process. Extracted oil recovery efficiency has been reported as high as 93.8%.[23] Due to constraints in the refining process, which require minimization of phosphorus and water content, the extracted oil must be treated through a citric-acid-based degumming process.[25] Anaerobic digestion of the algae cellular debris produces a methane-rich biogas, allowing combustion and energy recovery (see Sensitivity analysis).[26] In the base case, 90% of the nutrients were assumed to be recycled after digestion and experiments will be needed to determine the validity of this number. Electricity production through biogas combustion allows a reduction in the external power demand to ~40%.

Oil refining

The refining of triacylglyceride oil into a jet fuel replacement follows the UOP Ecofining^{TM} process to produce Green Jet Fuel^{TM}. A hydrodeoxygenation reactor reduces the oil, producing saturated alkanes and propane. A three-stage packed reactor with a feed of oil and hydrogen converts the oil to hydrocarbon at 350 ^{o}C and 35 bar.[27,28] Hydrogen solubility is improved through recycling a portion of the hydrocarbon mixture through the hydrodeoxygenation reactor. The hydrocarbon mixture, mainly within the range C15–C17, needs further processing in order to be suitable as a jet fuel. A hydrocracking and hydroisomerization reactor reduces the alkane chain lengths and introduces branching. The product fraction from this reactor is rich in aviation range product (54.7 %), but also contains diesel (10.0 %) and naphtha (26.9 %) side-products.[29] These fractions are separated and recovered in an atmospheric distillation column. A propane-rich light gas stream is also recovered for use as a fuel in the refining process. Unreacted hydrogen is recycled after cleaning through an amine scrubber.[30]

Pongamia process

The seeds of *Pongamia pinnata* are rich in oil that can be refined into fuel products (Fig. 1(b)). As a fast-growing leguminous tree with abundant annual production of oil-rich seeds, *Pongamia* is a particularly suitable plant for biofuels production.[31] Seed oil extraction (mainly soybean) was used as the primary basis for modeling,[32,33] but experiments would be needed to confirm the exact performance parameters for oil extraction from *Pongamia* seeds. Continuous, year-round processing (11 months) requires storage of the dried seeds collected during the harvesting season.

The harvested *Pongamia* seeds are dried in a fluidized bed dryer prior to processing. These seeds need to be cracked and broken into smaller particles allowing separation of the thin husk from the fleshy seed. To improve extraction performance, the seeds are rolled into thin flakes to allow greater solvent exchange in the counter-current belt extractor. *Pongamia* oil extraction performance was assumed to be similar to soybean, with an oil recovery of 96%.[33] After extraction, the solvent is recovered from the meal using superheated hexane. The meal biomass is anaerobically digested similarly to the algal cell debris (see Sensitivity analysis), and the resulting biogas is combusted to produce steam and electricity for internal consumption, offsetting 28.7% of the electricity use. The oil-rich solvent is evaporated to separate the hexane for recycling, giving a triacylglyceride mixture ready for degumming and refining. These steps proceed as described for the microalgae process.

Sugarcane process

There are a number of possible methods to produce aviation fuel from sugarcane. In this study, the production of bio jet fuel from sugarcane by the fermentation of sucrose to farnesene ($C_{15}H_{24}$) and subsequent refining (Fig. 1(c)) was chosen. The process was modeled in two separate flowsheets, one for the sugar mill and one for the fermentation process, as these operate on different calendars (the fermentation operates 11 months a year, whereas the mill operates for approximately 5.5 months a year).[3,34] The material and energy balances for the sugar mill were modeled in accordance with standard industry practices,[34] with raw sugar and molasses production. However, our model alters the standard pan house from a three stage crystallization process, to a single stage.[34] While this modification decreases the raw sugar production, the molasses sucrose content is increased for use as the fermentation feedstock. Costs were only modeled for the fermentation flowsheet, as all the costs incurred by the sugar mill could be captured in the cost of molasses (see next section). This consideration also makes the model more realistic: the technology does not, and should not, require the construction of a greenfield sugar mill.

Fermentation of molasses to farnesene uses an engineered yeast strain from Amyris, with ammonium hydroxide and diammonium phosphate supplied as nutrients. Current reports describe farnesene yields of 16.8 g farnesene/100 g sugar and an average productivity of 16.9 g/L/d.[35] Recovery of farnesene from the fermentation broth uses a two-stage centrifugation process, with a reported 97% recovery of farnesene.[36] In the first stage, the yeast biomass and a large portion of the aqueous phase are removed. Prior to further centrifugation, the pH and salt concentration are adjusted to disrupt the emulsion created by the presence of extracellular material.[36] For applications as a bio jet fuel, farnesene needs to be further processed. Although straight hydrogenation allows the product, farnasane, to be mixed with fossil jet fuel,[37] hydrocracking and hydroisomerization were modeled in this study to be consistent across process models.[25] The resulting hydrocarbon mixture was assumed to be similar in composition to those produced in the microalgae- and *Pongamia*-based oil refining processes, and the jet fuel component was accordingly separated in a distillation column. Further experimental studies would need to be performed to confirm the exact composition of the hydrocracked product.

Economic analysis

All currencies used in the models are based on US dollars referenced to 2011. Facility-dependent costs were derived from relevant studies,[3,7,38] corrected using the Chemical Engineering Plant Cost Index (CEPCI), as well as from Aspen Process Economic Analyzer.[39] Highly-specific unit operations (e.g. Evodos centrifuges, cracking mills, hexane extractors) were priced from vendor quotes. Labor costs were calculated from the mean weekly earning statistics for factory process workers,[40] using the Wessel method for estimating process labor requirements.[41] Although this method provides a rough approximation of labor requirements, it has the clear advantage of allowing calculation of labor costs based on local salaries. Considering that labor makes up a minor fraction of operating costs, this method was deemed appropriate for the purposes of the study. Standard assumptions were used for the cost of electricity (10¢/kWh), cooling water (0.05$/MT) and process steam (12$/MT).[42] The price of *Pongamia* seeds (590 $/MT) was based on cost models communicated by the *Pongamia* researchers of the consortium (Gresshoff, unpublished results), whereas that of A-molasses (190 $/MT) was based on industry experience (Lavarack, personal communication). Modeled feed nutrients for microalgae growth and fermentation were: ammonium hydroxide (229.41 $/MT),[43] diammonium phosphate (703 $/MT),[44] and nitrate (500 $/MT). Additional processing chemicals with a significant impact on the processing cost were hydrogen (1.015 $/kg)[45] and industrial hexane (2 $/kg).

Financial assumptions were made with the expectation of low technological risk (i.e. based on an Nth plant), similar to previous studies.[3,7] The plants were financed with a 60–40 debt-equity split, assuming an interest rate of 8% for the debt and a 10% discount rate for NPV analysis (admittedly low even for more mature technologies; see Conclusions). Minimum selling price (MSP) analysis was performed assuming a project lifetime of 25 years for all cases.[7] When multiple products are sold, as is the case in this study, MSP analysis can be performed in two general ways: (i) the price of a single product is varied while others are left constant, giving the MSP of that product; or (ii) the products are varied in a constant proportion to each other. The latter approach was taken in the present study. The jet fuel (135.6 USD/barrel),[46] naphtha (1068 USD/MT),[47] and diesel (142.6 AUSc/L)[48] prices were varied in proportion to their long-term fuel:oil price ratio (i.e. using a constant average measure of the crack spread). Therefore, results are reported in terms of the MSP of a barrel of oil that would make the jet fuel, naphtha and diesel produced in the biorefinery competitive with those produced in an oil refinery. It should be noted that the data used to calculate the ratios were Australian fuel prices.

Results and discussion

Base cases

As a first step, base case scenarios were analyzed based on data found in the scientific and industry literature (see Process description). An overview of the economic results is presented in Table 1. The annual operating cost (AOC) breakdowns point to the key economic drivers in each case with raw material and facility-dependent annual costs

Table 1. Economic summary.

	Microalgae model	Pongamia model	Fermentation model
Total Capital Investment ($M)	$ 3,451	$ 506	$ 259
Annual Operating Cost ($M)	$ 984	$ 303	$ 253
Facility Costs	84.17%	31.93%	18.84%
Raw Materials	10.11%	57.86%	70.89%
Utilities	4.43%	5.56%	8.13%
Labor Cost	1.25%	4.53%	2.14%
Consumables	0.04%	0.12%	0.01%
Minimum Selling Price ($/barrel eqv.)	$ 1,343.18	$ 373.68	$ 301.35

(depreciation, maintenance, insurance, and facility overhead) being the most significant for the three processes.

For microalgae, capital expenditure (capex) is the biggest driver, in particular the cost of harvesting equipment and the raceway ponds (Fig. 2). Raw material costs are mostly associated with water, since it is assumed that 90% of the nutrients can be recycled after anaerobic digestion and CO_2 was assumed to be freely available (i.e. a scenario where a monetary carbon credit exactly balances the cost of delivering the gas). Harvesting is the single most expensive cost of the facility and was calculated based on vendor quotes from Evodos (Brocken M, Evodos, personal communication). Indeed, harvesting was identified previously as a key cost

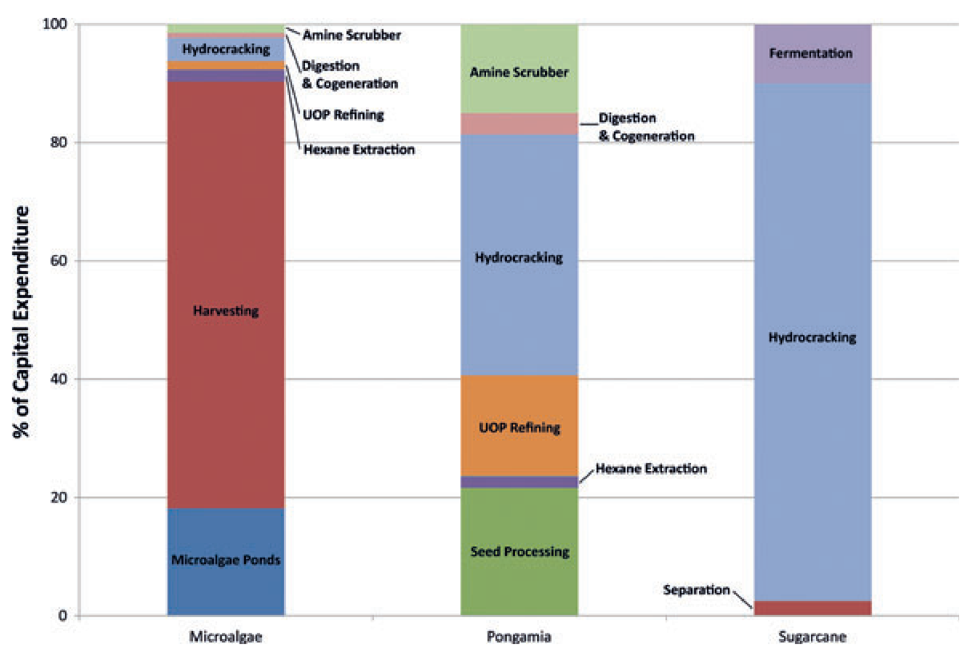

Figure 2. Installed equipment costs by section, as a percentage of total. Legend follows sections outlined in Fig. 1.

driver[49–52] and our analysis confirms what others have proposed. Even though other harvesting technologies exist,[52] Evodos centrifugation was chosen because it (i) can separate *Nannochloropsis spp.* from a 500 mg/L solution and concentrate it to the high solids required for oil extraction (30% solids; Heimann, unpublished results); (ii) does not require addition of chemicals for electrolyte or pH control, allowing the recycling of the water; (iii) works with saline water; and (iv) could be satisfactorily modeled given the information provided by the vendor. Any technology that did not enjoy these advantages could not be accurately modeled, and therefore the options were highly limited. Although no substantive information was available for the harvesting of *Nannochloropsis spp.* with dissolved air flotation (DAF), this technology has been studied before for an unspecified algal species[12] and a lumped-cost estimate was considered, after appropriate scaling, during sensitivity analysis.

For *Pongamia*, the cost of seeds (which comprises 90% of the raw material cost) is the largest share of the AOC (~60%). This observation points to the seed purchasing price and the seed oil content as important factors. Others have similarly pointed to the predominance of raw material costs in vegetable oil-based processes,[53,54] though the studies are not perfectly comparable as they use different raw materials or make different end products.

For sugarcane, the cost of sucrose is the main driver. This is generally observed for fermentation-derived commodity/bulk chemicals using a relatively mature process.[55] Most of the facility-dependent cost is related to hydrocracking, since most of the remaining equipment is comparatively simple and low cost. Cracking is needed to reduce the chain length of the farnesene and to produce a similar range of fuels compared to the other processes modeled in this study, but hydrodeoxygenation is not required. Though there is no publicly available information about how farnesene would behave in a hydrocracker, we assumed similar behavior to other hydrocarbons. The lack of experimental information on farnesene cracking raises the issue of whether less expensive hydrogenation should be modeled instead. In fact, if the refining capex is adjusted to that needed to process the farnesene through hydrogenation, with hydrogen added in stoichiometric quantities and no requirement for downstream distillation, the farnasane as a jet fuel replacement/additive, would be competitive with crude oil at ~242 $/bbl (using the same analysis as used elsewhere in this study).

Model validation

The economic estimates resulting from the base case models were validated, as far as was possible. Hydrocarbon refining equipment was validated by IOR Energy (Allen, personal communication), an Australian oil refiner with expertise on the types of equipment used for downstream processing. Other costs were verified using different sources, as discussed in the following paragraphs.

In the case of microalgae, capex is the main cost in need of confirmation, as it is the most significant. The capital costs of all sections were in line with the costs of Benneman and Oswald,[56] after adjusting for inflation, except for harvesting. Though the report by Benneman and Oswald is not current, the data are still widely quoted in the algae literature.[12,57,58] However, harvesting numbers were, according to the report itself, extremely preliminary and uncertain. By using vendor quotes for the harvesting equipment, we reduced the uncertainty in this step.

In the case of the *Pongamia* route, the capex of the facility was compared to that of a soybean processing facility (see Process descriptions). Based on our design, a *Pongamia* oil extraction facility (i.e. one including seed processing, oil extraction, and oil cleaning, but not refining or anaerobic digestion) falls within the capex ranges for soybean oil extraction facilities outlined by Soares *et al.*,[59] after appropriate scaling. As for the seed purchasing price ($590/MT), the number provided by the consortium is similar to the market price of soybean (average prices for soybean in the August 2011–August 2012 period were $500/MT).[60] Until long-term field trials for *Pongamia* plantations are conducted, this number will be difficult to more accurately specify.

In the case of sugarcane, the price for A-molasses (i.e. after A-sugar is crystallized) was validated by Mackay Sugar Limited (Lavarack, personal communication), one of the major sugar producers in Australia and a member of the consortium behind this study. Capex numbers for farnesene production are proprietary, and thus it was difficult to assess our design in the same manner as was done for the microalgae and *Pongamia* processes. However, we modeled the production of farnesene from molasses by eliminating all unit operations necessary for refining, and arrived at a MSP of $2.22 per kg of farnesene. This cost of production is in line with the target price of similar molecules produced by Amyris and expected for sale in the near future.[61]

Sensitivity analysis

Sensitivity analyses were performed to test parameters that were found to significantly affect the economics and/or that were notably uncertain (Fig. 3). In all cases, low and high cost points were chosen, which were then combined to give an estimate of the accumulated effect of the various param-

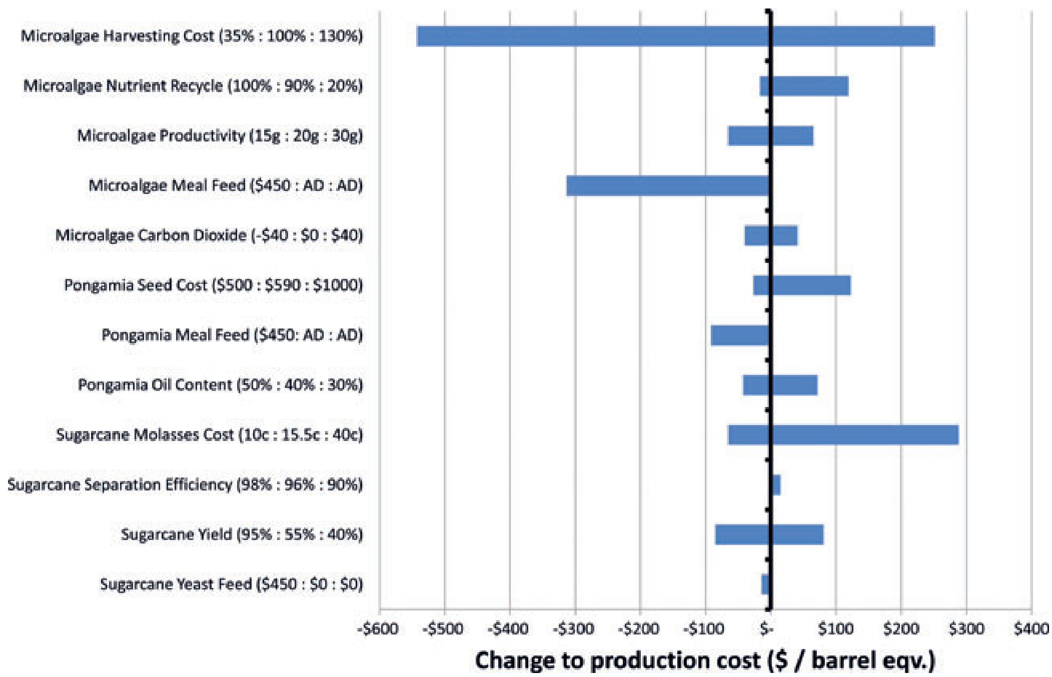

Figure 3. Sensitivity of MSP per barrel of oil equivalent to different parameters. The high and low points outlined in the text and summarized in Table 2 were used for the extreme values in most cases. Scenarios including anaerobic digestion of waste biomass for energy recycle are marked AD.

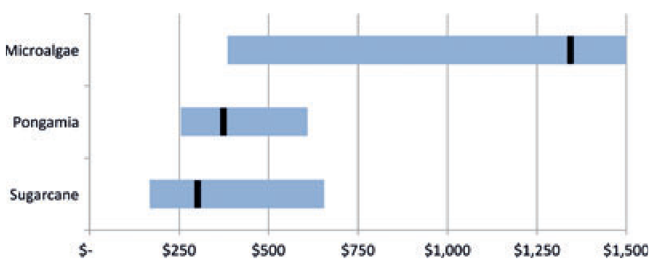

Figure 4. Accumulated effect of the sensitivity parameters described in Table 2. The base cases are included for reference as a vertical bar.

eter changes on the MSP (Fig. 4). The parameters chosen for the low and high points are summarized in Table 2.

Given the economic drivers for the microalgae process discussed above, two aspects were the focus of analysis. First, we varied the cost of the harvesting equipment, as there is significant uncertainty regarding harvesting costs and these have a particularly large influence on the final cost of fuel production. The cost of the Evodos centrifuges was estimated based on vendor quotes, but this can decrease in the future, or other technologies can enter the market that decrease the cost of this operation. The high point was unmoved with respect to the base case as it is unlikely that the cost of harvesting will escalate with time, though other factors can increase its contribution. For instance, performance of the machines in a large scale operation can fall below specification, requiring many spare units or frequent downtime (Fig. 3). The low point was estimated based on a potentially more frugal technology, dissolved air flotation (DAF). We did not model this technology as part of the base case because the literature lacks the engineering details needed to design a DAF system for *Nannochloropsis spp.* The low point used for Figs 3 and 4, which corresponds to a DAF system, is instead based on a previous lumped estimate,[12] after appropriate scaling. This number is likely to be itself inaccurate, but can serve as a first estimate of the cost of DAF applied to *Nannochloropsis spp.*

As the cost of harvesting decreases, the cost of the open ponds becomes significant. In fact, if harvesting costs were assumed to be zero, the cost of ponds would represent ~70% of the capital cost and the MSP would be ~$500/bbl. Instead of manipulating the cost of the ponds directly, we instead studied the effect of algae productivity (g/m^2/day), which impacts the area needed to grow the biomass and in turn affects the cost of the ponds. The pond design is already austere compared to other growth systems, and thus the capital cost per hectare is unlikely to be reduced significantly for this operation. In addition, there are currently various research groups that aim at increasing the productivity of microalgae through modern strain engineering techniques (for a review on the topic, see Radakovits *et al.*).[62] The high

Table 2. Basis for the sensitivity analysis illustrated in Figure 4.

	Maximum case	Base case	Minimum case
Microalgae	Evodos Harvesting 20% Nutrient Recycle 15 $g.m^{-2}.day^{-1}$ Productivity Anaerobic Digestion 40 $/MT CO_2	Evodos Harvesting 90% Nutrient Recycle 20 $g/m^2.day$ Productivity Anaerobic Digestion	DAF Harvesting 90% Nutrient Recycle 30 $g/m^2.day$ Productivity 450 $/MT Protein Feed
Pongamia	1000 $/MT Pongamia Seed 30% Oil Content Anaerobic Digestion	590 $/MT Pongamia Seed 40% Oil Content Anaerobic Digestion	500 $/MT Pongamia Seed 40% Oil Content 450 $/MT Protein Feed
Fermentation	40 c/lb Sucrose Equivalent 55% Theoretical Yield 85% Recovery Efficiency	15.5 c/lb Sucrose Equivalent 55% Theoretical Yield 85% Recovery Efficiency	10 c/lb Sucrose Equivalent 95% Theoretical Yield 96% Recovery Efficiency

cost point is based on a long-term study that reports seasonal variation of productivity in *Nannochloropsis spp.*,[17] whereas the low point is assumed based on values from other species[63] (i.e. it assumes that productivity traits are transferrable or at least can be engineered). It must be noted that some short-term studies in laboratory conditions report equivalent productivities close to 20 $g/m^2/day$.[63,64] It must also be noted that the curve for MSP vs. productivity saturates above ~30–35 $g/m^2/day$, pointing to the need to improve this parameter simultaneously with others, as diminishing marginal returns on productivity are encountered otherwise. Sensitivity to other parameters – including nutrient recycle and CO_2 purchasing price – was explored, but the effects were not as significant as for harvesting costs and biomass productivity (Fig. 3).

In the case of the *Pongamia* seed process, the purchasing price of seeds and their oil content were the main targets for sensitivity analysis. Both parameters are influential and uncertain, though the former is significantly more uncertain than the latter. In the case of oil content, and even though studies have reported on the composition of *Pongamia* seeds,[65,66] it remains to be seen whether the oil content can be replicated in large-area field trials with consistency year-on-year. To remain conservative, the seed oil content was not assumed to increase beyond 40% for the low cost point, even though several instances of seeds with higher oil contents have been reported.[66] The low point in purchasing price was $500/MT, similar to recent average soybean prices,[60] whereas the high point was somewhat arbitrarily set to double that cost.

For the sugarcane process, where most of the cost of production is associated with the cost of sucrose, the price of molasses and the yield were the main focus of study. The purchasing price of molasses, on a cent per pound of sucrose basis, was varied between a low point of 10 ¢/lb and a high point of 40 ¢/lb. In general, the cost of molasses, on a sucrose mass basis, is lower than the crystalline sugar market price, since crystallization adds to the cost. The cost of molasses assumed for the base case, at 15 ¢/lb of sucrose, is thus justifiably lower than the sugar market price (~20 ¢/lb in August 2012).[60] The purification efficiency, i.e., the fraction of farnesene that enters refining compared to that produced in fermentation, was also studied because of the potential effect of this parameter on production costs. For both yield and efficiency, the reduction in MSP slows down as the 100% value is approached. At low values of both these parameters the same costs are incurred to produce less product, and at high values other factors limit further reductions in MSP.

In all cases, drying and selling of high-protein meal as feed was considered as a potential avenue to increase revenues and decrease the fuel MSP (yeast meal in the case of sugarcane and left-over meal post hexane extraction for microalgae and *Pongamia* seeds). Feed markets are highly local and aspects such as nutritional value, toxicity and customer adoption are of central importance, thus selling of the meal was not considered in the base cases as these were intended to be of general applicability. As Fig. 3 suggests, the impact of selling algae meal is greatest, as this process produces 43.84 kg meal per gallon of jet fuel, whereas the *Pongamia* and sugarcane processes produce 10.94 and 1.80 kg/gal, respectively. Therefore, for modeling aviation fuel economics of microalgae farms adjacent to feedlots, selling of the meal can have a significant impact and should be modeled where relevant.

Figure 4 shows the accumulated effect of the low and high cost scenarios, as well as the base cases. The range of MSP values for microalgae is widest both because many parameters influence the economic viability of this technology, and because of the uncertainty in these parameters. As technology develops, alternative routes are ruled out and data become consistent, the high and low points are expected to converge. The sugarcane route has a narrower range, since most of its cost is derived from a tradable commodity (molasses) and because the technology is closer to being commercialized. Uncertainty in the fermentation model is chiefly due to lack of data, most of it being proprietary and thus unavailable for public release. Lastly, the range for *Pongamia* is slim primarily because a single factor – the cost of seeds – was found to drive the economics of this process. Though different factors contribute to the observed ranges in the different processes, all models will be improved and refined as more and better quality data become available.

Conclusion

The results of our analysis suggest that, whereas none of the studied routes for bio-jet fuel production can compete with fossil fuels today, there are several technology and market developments that can significantly improve the economics of the modeled processes. If oil prices continue to rise and societies begin to place a meaningful monetary burden on carbon-intensive technologies, these developments could accelerate the adoption of sustainable aviation fuels. It must be noted that the results of any analysis depend on the assumptions made, and it is difficult to accurately capture the potential of a particular enterprise or process with a general model based on non-proprietary data. If literature data is conservative in that it does not present the newest developments brought about by specific efforts, it is aggressive in that it ignores huge technical risks and financing hurdles associated with scale-up from the laboratory into the real world. General models, such as the ones presented here, can provide a ballpark of costs and, more importantly, indicate the process steps that challenge economic viability. The models can also quantify the potential impact of various innovations, market developments and policies on the cost of production for a given route. The effect of various factors was evidenced in the present study through sensitivity analyses.

The results of any forward-looking technoeconomic study may be open to interpretation even when the assumptions are open and transparent. While some dispute the economic potential of various innovations, public and private monies have flooded into the bioenergy field in recent years, both for R&D and for technology commercialization. A closer look at the nature of the investments reveals that these have generally not sought immediate reward, consisting mostly on angel and venture funds (as opposed to private equity, pension funds, bank debt, etc.) from the private sector and on research grants from the public sector. Yet regardless of time horizons, technology commercialization necessitates progress toward economic viability, and that progress can be misguided without proper analysis and evaluation tools. Open models and a more critical approach to economic evaluation can help in focusing efforts and in managing expectations. We hope that others will join our efforts by supplying more detailed data and their own open models and tools. A realistic and open stance is important, because the booms and busts of excitement can hurt the entire community in the long term, as sequential disappointments beget reluctance to invest.

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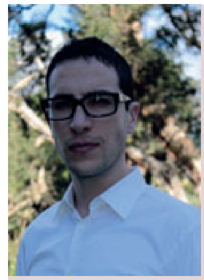


Daniel Klein-Marcuschamer

Dr. Daniel Klein-Marcuschamer is a Scientist at the Lawrence Berkeley National Laboratory, and the Director of Technoeconomic Analysis at the Joint BioEnergy Institute. He holds a B.S. from the University of Texas at Austin and a Ph.D. from the Massachusetts Institute of Technology, both in Chemical Engineering.

Chris Turner

Chris Turner is currently a Research Engineer at the Australian Institute for Bioengineering and Nanotechnology having previously received a dual BE/BSc at the University of Queensland in chemical engineering and chemistry respectively.

Mark Allen

Mark Allen is a Senior Process Engineer with IOR Energy Pty Ltd. He has over twenty years' experience in process and environmental engineering roles within the oil refining and mineral processing sectors. His process engineering experience includes work on hydrotreating units, hydrogen network optimisation and evaluation of third generation biodiesel technology.

Ralf G. Dietzgen

Associate Professor Ralf G. Dietzgen is Principal Research Fellow in the Centre for Plant Science, Queensland Alliance for Agriculture and Food Innovation institute, The University of Queensland. His research interests are in renewable biofuels, *Pongamia pinnata*, tropical and subtropical crop improvement and molecular interactions between plants, viruses and insect vectors.

Peter Gray

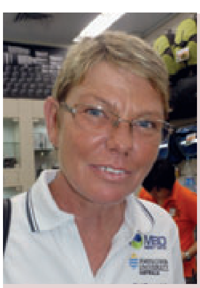
Professor Peter Gray was appointed inaugural director of the Australian Institute of Bioengineering and Nanotechnology (AIBN) at the University of Queensland in August 2003. Before joining AIBN, Professor Gray held appointments at the University of New South Wales and the Garvan Institute of Medical Research.

Peter M. Gresshoff

Prof Gresshoff is Professor of Botany at UQ in Brisbane. He also is the Director of the Australian Research Council's Centre of Excellence in Integrative Legume Research. He received his PhD in Genetics from ANU (Canberra) in 1974. During his career in plant science he has developed deep interests in plant development and its genetic control.

Ben Hankamer

Ben Hankamer moved from Imperial College London (2002) to take up a Chief Investigator position at the Institute for Molecular Bioscience, at The University of Queensland. He is a founding Director of the Solar Biofuels Consortium and was awarded an Eisenhower fellowship (2009) and ARC Discovery Outstanding Researcher Award (2012).



Kirsten Heimann

Heimann leads the microalgal bioproducts and methane remediation projects at JCU. The biomass is used for commercial production of algal co-products. She has published in high ranking journals including Nature. Her research and teaching has won many awards, the latest being the North Queensland Corporate Business Women Award 2011.

Paul T. Scott

Paul Scott has a B.Sc. (hons) *University of Sydney*, a M.Sc. (biotech) *University of New South Wales* and a PhD *Monash University*. Since 2001 Paul has worked as a research fellow at the University of Queensland. Currently his research focuses on *Pongamia pinnata*, a candidate biofuel and bioenergy feedstock.

Robert Speight

Robert Speight's background is in industrial biotechnology and he was the Founder, Operations Director and Head of Biotechnology at the UK company Ingenza before moving to an operational, commercial and research management role at The University of Queensland. His scientific interests include the sustainable production of biofuels, proteins and chemicals.

Evan Stephens

Evan Stephens is the manager of the University of Queensland's Solar Biofuels Research Centre (SBRC), established by the Solar Biofuels Consortium - managing an international team in addressing the obstacles towards commercialisation of microalgal biotechnology and environmental applications, with a primary focus on microalgal biofuels.

Lars K. Nielsen

Professor Nielsen heads the Systems and Synthetic Biology Group at the Australian Institute for Bioengineering and Nanotechnology. Using thermodynamic principles, novel approaches are developed for the rational design of complex pathways and bioprocesses as diverse as the production of blood cells for transfusion and the production of industrial biopolymers.