GLOBAL CHANGE BIOLOGY
BIOENERGY

GCB Bioenergy (2018) **10**, 92–107, doi: 10.1111/gcbb.12478

Biorefinery for combined production of jet fuel and ethanol from lipid-producing sugarcane: a techno-economic evaluation

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Abstract

Replacing fossil fuels with an economically viable green alternative at scale has proved most challenging in the aviation sector. Recently sugarcane, the most productive crop on the planet, has been engineered to accumulate lipids. This opens the way for production of far more industrial vegetable oil per acre than previously possible. This study performs techno-economic feasibility analysis of jet fuel production from this new cost efficient and high yield feedstock. A comprehensive process model for biorefinery producing hydrotreated jet fuel (from lipids) and ethanol (from sugars), with 1 600 000 MT yr^{-1} lipid-cane processing capacity, was developed in SuperPro Designer. Considering lipid-cane development is continuing for higher oil concentrations, analysis was performed with lipid-cane containing 5%, 10%, 15%, and 20% lipids. Capital investments for the biorefinery ranged from 238.1 to 351.2 million USD, with jet fuel capacities of 12.6–50.5 million liters (correspondingly ethanol production of nil to 102.6 million liters). The production cost of jet fuel for different scenarios was estimated $0.73 to $1.79 per liter ($2.74 to $6.76 per gal) of jet fuel. In all cases, the cost of raw materials accounted for more than 70% of total operational cost. Biorefinery was observed self-sustainable for steam and electricity requirement, because of in-house steam and electricity generation from burning of bagasse. Minimum fuel selling prices with a 10% discount rate for 20% lipid case was estimated $1.40/L ($5.31/gal), which was lower than most of the reported prices of renewable jet fuel produced from other oil crops and algae. Along with lower production costs, lipid-cane could produce as high as 16 times the jet fuel (6307 L ha^{-1}) per unit land than that of other oil crops and do so using low-value land unsuited to most other crops, while being highly water and nitrogen use efficient.

Keywords: bioethanol, biojet fuel, lipid, sugarcane, techno-economic, transgenic

Received 20 June 2017; accepted 28 July 2017

Introduction

Transportation sector, including aviation segment, consumes about one-third of total energy and causes 21% of total GHG emissions globally (Juneja *et al.*, 2013). Jet fuel is a very valuable product obtained from crude oil processing, and about 4 gallons out of each barrel of crude oil is used to produce jet fuel (Klein-Marcuschamer *et al.*, 2013; Chu *et al.*, 2016; Diederichs *et al.*, 2016). Globalization and improved international trades have resulted in increase in air travel, and subsequently aviation fuel use. About 565 109 thousand barrels (23.73 billion gal, in year 2015) of jet fuel is used in United States every year, and this demand of commercial jet fuel is expected to rise by 25% by 2035 (Natelson *et al.*, 2015; EIA, 2016a). Aviation fuel has stringent quality requirements compared to fuel used in ground vehicles and is one of the major operational cost in aviation industry. Another issue is that aviation fuels cannot be replaced by alternate energy sources, which is possible in case of ground transportation (e.g. battery operated vehicles) (Klein-Marcuschamer *et al.*, 2013; Natelson *et al.*, 2015).

Due to various reasons, market price of jet fuel fluctuated between $0.42 and $1.28/kg jet fuel over last decade (Diederichs *et al.*, 2016). Considering the large aviation industry in the United States (about 18 billion gallons jet fuel use in passenger and cargo airlines annually; 1/3rd of global use), increase in every penny in the fuel price results in an additional $180 million in annual fuel costs for U.S. airlines (Wang & Tao, 2016). The fluctuating oil prices, desire to achieve long-term energy security, and rising environmental concerns from fossil fuel burnings have led to interest in plant-derived aviation fuels. Biojet fuels derived from various crops have been successfully

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tested in proof of concept flights and could potentially reduce greenhouse gas emissions up to 75% (Shonnard *et al.*, 2010; Klein-Marcuschamer *et al.*, 2013). Biojet fuel can be produced through various chemical and biological routes, such as gasification–Fischer–Tropsch synthesis, hydroprocessed esters and fatty acids (HEFA), sugar to hydrocarbon process, catalytic hydrothermolysis, alcohol to jet, and hydrotreated depolymerized cellulosic jet (Natelson *et al.*, 2015; Chu *et al.*, 2016; Wang & Tao, 2016). The HEFA process, also known as hydroprocessed renewable jet fuel (HRJ), is considered the most mature technology and has been tested on pilot/commercial scales (Chu *et al.*, 2016; Diederichs *et al.*, 2016; Wang & Tao, 2016). ASTM (American Society for Testing and Materials) has approved 50:50 blend of petroleum-based jet fuel and hydroprocessed renewable jet fuel use on commercial and military flights (Klein-Marcuschamer *et al.*, 2013; Chu *et al.*, 2016; Diederichs *et al.*, 2016). Studies have concluded that jet fuel produced from oil crops using HEFA process is most economic among various process pathways and yield high energy efficiency (Diederichs *et al.*, 2016).

Regardless of significant efforts, the production volumes of biojet fuel are very small, and demand technology improvement and large-scale availability of low-cost feedstock to improve process economics. Federal Aviation Administration (FAA) is targeting to enable the use of 1 billion gallons of renewable jet fuel in aviation sector by 2018 (Smith *et al.*, 2017). In case of renewable jet fuel production from oil crops, the feedstock cost accounts for the major fraction of total production cost (Pearlson, 2011; Chu *et al.*, 2016; Wang & Tao, 2016). Some low-cost oil feedstocks such as waste cooking oil and animal fat can be used in the process; however, their production levels are far lower than the need. For long-term sustainability of fuels, in addition to process economics, it is also critical to use feedstock that minimizes the use of arable land through high production yields.

In last few years, using metabolic engineering and plant genetics, bioengineering of plants to divert energy from nonstructural carbohydrates (free sugars, starch) into triacylglycerides (TAGs), accumulated in plant vegetative tissues, has succeeded (James *et al.*, 2010; Vanhercke *et al.*, 2014). Using these strategies, expression of three lipid-producing genes and altered metabolism of engineered sugarcane has resulted in accumulation of 5% TAGs and 10% total fatty acids compared to only 0.05% oil in the wild-type plant (Huang *et al.*, 2015, 2016b; Zale *et al.*, 2016). In theory, with all energy from the sucrose that normally accumulates in the stem diverted to TAG, sugarcane could accumulate 20% lipid by weight in its stem. With possible yields of 60 t ha^{-1} stem dry matter and half of this sugar (Duval *et al.*, 2013), diversion of energy from sugars into lipid could allow as much as 11 700 L or 74 barrels of oil per hectare of land. Soybean is currently the largest source of green diesel. If we assume a seed oil content of 20% by mass and a seed yield of 3.5 t ha^{-1} (USDA, 2016), this would provide only about 820 liters or 5 barrels of oil per hectare. Large-scale production of the first generations of this engineered sugarcane, referred as lipid-cane in this manuscript, is under investigation in northern Florida (data not published). The high amount of lipids in this sugarcane provides huge advantages and could potentially be used for biojet fuel production to meet aviation sector fuel needs, at considerable scale. To understand the commercial viability of production of jet fuel from this 'lipid-cane' and its competitiveness crop, a comprehensive techno-economic analysis is needed to establish capital and operating cost profile of the process. It is helped in this case by the fact that planting of sugarcane through to harvest and delivery of stems to processing mills is a mature technology for which secure techno-economic figures are available, as are those for processing the stems through to ethanol. Although not conducted currently in sugarcane mills, extraction of TAGs from thin stillage is a widely used practice in the corn ethanol industry. This techno-economic analysis has a very secure foundation here. One earlier techno-economic study on biodiesel production from lipid-cane observed lower production costs (18–45% less than other reported studies) due to low feedstock costs (Huang *et al.*, 2016a).

The objective of this work was to determine the techno-economic feasibility and competitiveness of using lipid-cane as feedstock for jet fuel production. A biorefinery producing jet fuel and ethanol as main products was modeled to perform comprehensive techno-economic analysis of the process. Based on the preliminary studies and target oil yields, analysis was performed for sugarcane containing 5%, 10%, 15%, and 20% lipid (dry basis). Technical data on process specifications and efficiencies for jet fuel conversion using UOP refining process were derived from the literature studies and patents (Perego *et al.*, 2008; Kokayeff *et al.*, 2010; Klein-Marcuschamer *et al.*, 2013). To assess the viability of lipid-cane as feedstock, the unit production cost and economic profitability of this biorefinery were compared with other studies on biojet fuel production from oil crops and algae. Sensitivity analysis was performed by varying the price of feedstock, plant capacity, selling price of coproducts, and lipid recovery to investigate their effect on jet fuel selling price.

Materials and methods

A detailed process model for a biorefinery with a processing capacity of 1 600 000 MT yr^{-1} of lipid-cane was developed using SuperPro Designer (Intelligen, Inc., Scotch Plains, NJ, USA). The model platform allows the process visualization through detailed flow sheets of unit operations, comprehensive mass, and energy balance, and performs economic calculations. The biorefinery was modeled to produce jet fuel and ethanol as main products, and diesel, naphtha, and electricity as coproducts. Figure 1 illustrates a simple schematic of process.

Lipid-cane

Composition of lipid-cane for various scenarios is listed in Table 1. As the lipid-cane is in the development stage, the composition is estimated based on the sugarcane composition and energy balance (Bonomi *et al.*, 2011). The similar approach was used in earlier studies on biodiesel production from this lipid-cane (Huang *et al.*, 2016a,b). Energy density of sucrose (15.7 kJ kg^{-1}) is approximately 40% of energy density of vegetable oil (37 kJ kg^{-1}); therefore, accumulation of 1 unit of oil would require decrease in about 2.5 units of sugar. Loss of biomass (difference of 1.5 units) is compensated by increase in structural carbohydrates (fiber in Table 1) (Huang *et al.*, 2016a,b).

Process development

The biorefinery was designed with processing capacity of 1 600 000 MT yr^{-1} of lipid-cane, assuming 200 operating days in a year (8000 metric ton day^{-1}). The operational period (200 days) was selected based on the harvesting cycle of sugarcane (lipid-cane in this case), which is approximately 6–7 months of a year (Vanhercke *et al.*, 2014; Huang *et al.*, 2016a). Considering the sugarcane processing industries, the simulated biorefinery is of intermediate size (Sousa & Macedo, 2010). The biorefinery consisted of five major processing sections: feedstock handling, oil and sugar separation, ethanol production, jet fuel production, and cogeneration. A simple picture of complete process modeled (from SuperPro Designer software) is shown in Fig. 2, and detailed pictures of each section are provided in Figures S1–S5 of Supporting Information. Supporting information file also consists of a Table S1 that lists detailed component flows and properties of each stream of the model. Brief description of each section is provided below.

Table 1 Composition of lipid-cane used in process simulations (% wet basis; dry basis values in parentheses)

	Lipid-cane with 5% lipids	Lipid-cane with 10% lipids	Lipid-cane with 15% lipids	Lipid-cane with 20% lipids
Water	70	70	70	70
Sugars	11.2 (37.2)	7.4 (24.7)	3.65 (12.2)	0
Lipid	1.5 (5)	3 (10)	4.5 (15)	6 (20)
Fiber	15.3 (50.8)	17.5 (58.3)	19.75 (65.8)	21.9 (73)
Ash	0.6 (2)	0.6 (2)	0.6 (2)	0.6 (2)
Others	1.5 (5)	1.5 (5)	1.5 (5)	1.5 (5)

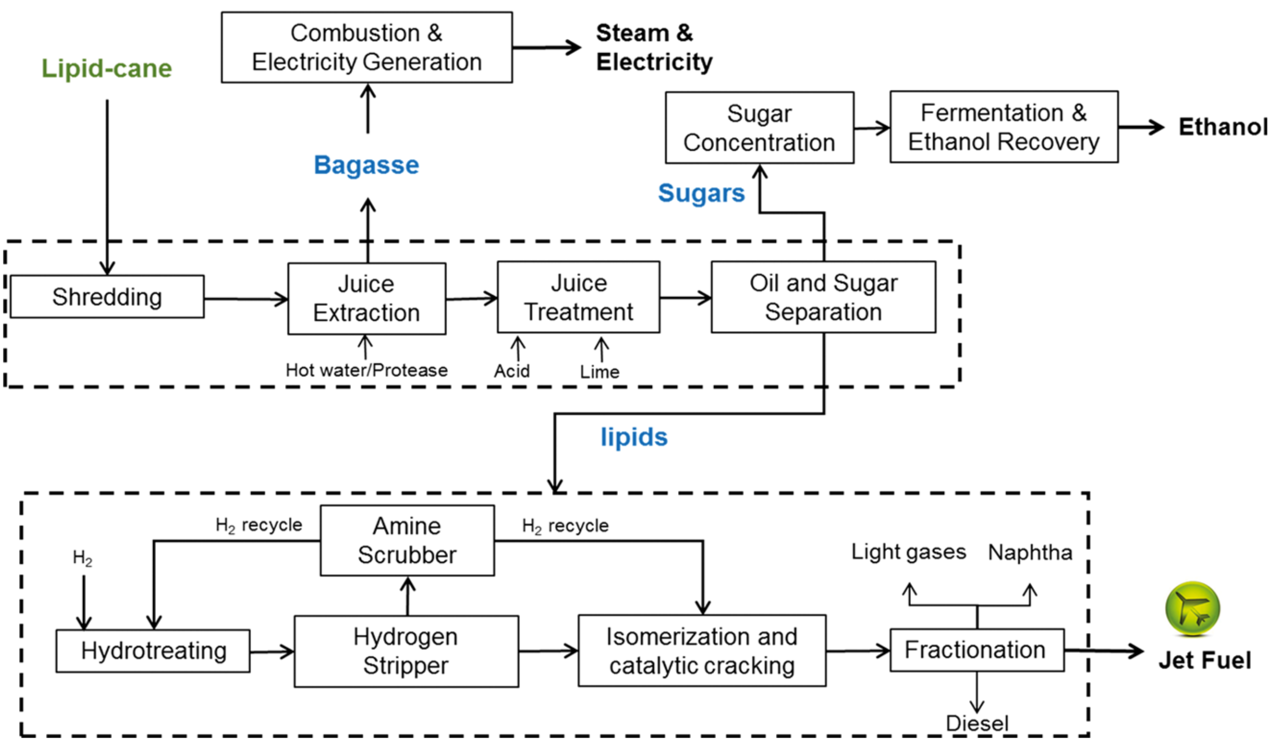

Fig. 1 Schematic diagram outlining the major sections of biorefinery. Figure illustrates the major unit operations of the biorefinery producing jet fuel and ethanol. Sugars are converted to ethanol, lipids are used to produce jet fuel, and bagasse is burnt to produce steam and electricity.

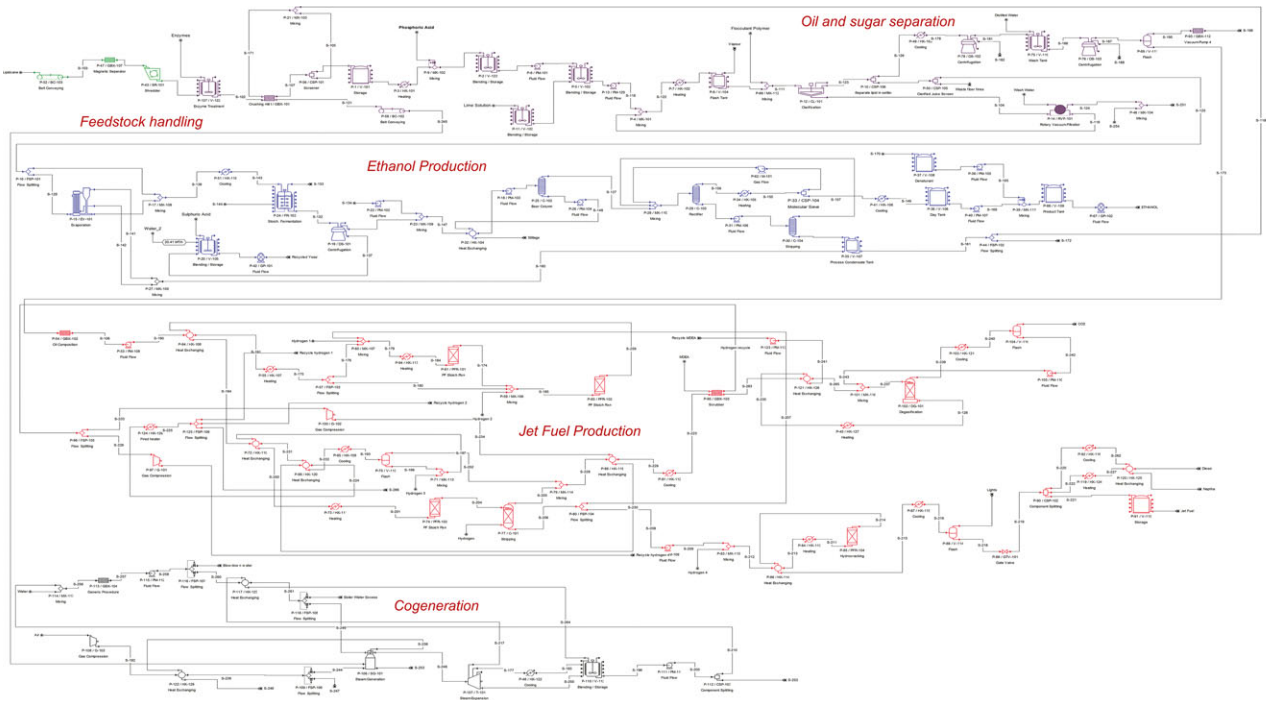

Fig. 2 Flow sheet of a process model of biorefinery developed in SuperPro. Figure illustrates the all unit operations and equipment used in the model development.

Feedstock handling. Feedstock handling section was simulated based upon current sugarcane processing facilities (Bonomi *et al.*, 2011; Huang *et al.*, 2016a). Mechanically harvested lipid-cane is transported to mill, where it is conveyed to a shredder for size reduction that improves the lipid and sugar extraction in the further processing steps. Impurities (metal residues from harvesting machines) are removed from the shredded biomass using magnetic separator before conveying it to mill tandem. Lipid-cane is not washed before crushing to minimize the loss of sugar and lipids.

Oil and sugar separation. This section includes the unit operations related to lipid-cane juice extraction and separation of sugars and lipids. Cleaned, shredded stems of lipid-cane are processed mechanically in mill tandem, a well-established method of juice extraction in the sugarcane processing industry. Addition of protease enzymes (0.5% concentration) enhances the extraction of sugars and especially lipids, by breaking down the proteins, including oleosin that surrounds the lipid bodies (Dickey *et al.*, 2011; Majoni *et al.*, 2011). This aqueous enzymatic approach to extract and separate oil from oil-rich crops and other substrates (soybean, peanut, corn germ, wheat germ, rice bran, etc.) has been successfully demonstrated by several researchers (Campbell & Glatz, 2009; Moreau *et al.*, 2009; Dickey *et al.*, 2011; Majoni *et al.*, 2011; Fang & Moreau, 2014). As shown in Fig. 2, the extracted juice is passed through rotary screens to remove solid residues (fibers) and is further guided toward clarification process. Removed solid residues are fed back to mills to recover remaining sugars and lipids. The juice is stored temporarily to match the processing of juice in the treatment section. In the first treatment step, phosphoric acid is added to the heated juice (70 °C) to bring pH 4.5 followed by addition of calcium hydroxide (lime) to bring pH again to 7. This process leads to removal of impurities by forming calcium phosphate particles. After this treatment, juice is further heated to remove dissolved air. Fine fiber fragments and soil particles are removed in the settling tank by addition of flocculent polymer. In the settling tank, juice gets separated into three parts: lipid on the top, sugar solution layer, and all solids particles at the bottom of tank (Huang *et al.*, 2016b). The mud (debris of solid particles) is washed using a rotary vacuum filter to recover all sugars, and the washed water is recycled in the process just before the settling tank. The remaining solid material on the filter, termed as filter cake, can be used as animal feed.

Jet fuel production. The refining process for conversion of lipids to jet fuel in this study follows the UOP Ecofining™ process, and the process details were adapted from a previous comprehensive study on jet fuel production from *Pongamia pinnata* seeds (Klein-Marcuschamer *et al.*, 2013). The specific design and study was chosen because of the ample details considered in the model and further validation of process design with commercial refining companies. The composition of lipid-cane oil was assumed similar to that of soybean oil (10.58% C16:0, 4.76% C18:0, 22.52% C18:1, 53.95% C18:2, and 8.19%

C18:3) (Canakci & Van Gerpen, 2001). In the first step of conversion process, a three stage hydrodeoxygenation reactor at 350 °C and 35 bar reduces the oil in the presence of hydrogen to saturated alkanes and propane. The hydrocarbon mixture (mainly within range C15–C18) from this reactor is treated further with addition of hydrogen in the hydrocracking and hydro-isomerization reactor (335 °C and 52.7 bar) to reduce the chain lengths and isomerized (introduces branching). The product from this reactor is rich in jet fuel (49.8%, w/w) and also contains naphtha (26.9%) and diesel (7.5%). The product also contains about 16% fraction of propane-rich light gases, which provides process heat needed for the jet fuel production (Klein-Marcuschamer *et al.*, 2013). These fractions are separated and recovered in the atmospheric distillation column. Unreacted hydrogen is cleaned in the amine scrubber and recycled back in the process. More specific details of the conversion process can be found elsewhere (McCall *et al.*, 2009; Klein-Marcuschamer *et al.*, 2013).

Ethanol production. In the first step of this section, the clarified sugar solution obtained is concentrated in the multi-effect evaporators to sucrose concentration of about 20%. The concentrated sugar solution is cooled to 32 °C and transferred to fermenters maintained at 32 °C. Yeast converts sugar into ethanol and carbon dioxide, with 90% fermentation efficiency. Fermentation efficiency of 90% is in agreement with other literature studies (Dias *et al.*, 2009; Diederichs *et al.*, 2016). Yeast is separated from the fermented slurry (mixture of ethanol, water and yeast), also known as beer, through centrifugation. Separated yeast is treated with sulfuric acid solution to prevent contamination and is recycled back in the fermenters (Huang *et al.*, 2016a). Ethanol is subsequently recovered from beer using a combination of distillation columns and molecular sieves. The first column in the distillation process, known a beer column, separates ethanol as overhead vapors. The bottom stream from the beer column is used to preheat the stream entering in the column. Ethanol-enriched vapors (containing approximately same amount of ethanol and water) from the first column are further enriched in the rectification and stripper columns. The distillate from the rectification column forms an azeotrope mixture of water and ethanol that cannot be further separated using distillation. This azeotrope mixture is separated using molecular sieves to produce pure ethanol (>99% purity), which is denatured by addition of octane.

Cogeneration. Solid residues after juice extraction, known as bagasse, are primarily structural carbohydrates (cellulose and hemicellulose) and lignin, which is combusted in a fluidized bed combustor to produce process steam in the plant. Steam produced from bagasse is usually more than the steam requirement of plant, so the excess steam is used to generate electricity that can be sold to the local grid. Major equipment in this section includes a combustor, a boiler for steam generation, and a turbogenerator to generate electricity. Process design, technical details, and equipment costs were used from the cellulosic ethanol process model developed by the National Renewable Energy Laboratory (NREL), where lignin-rich solids are used to produce steam and electricity (Kazi *et al.*, 2010; Humbird *et al.*, 2011). The solid stream going to combustor contains about 50% moisture. Heating value of the stream was calculated based on the elemental composition and model-embedded combustor modules, and the boiler efficiency for steam generation was assumed as 80% (Mani *et al.*, 2010). Flue heat from the boiler is used to preheat the bagasse. The turbogenerator in the model uses a multistage turbine with two steam extraction ports and a final condenser. The first steam is extracted at 1.48 MPa and 268 °C, and is mainly used to preheat the water before entering the boiler. The second extracted steam (0.44 MPa and 152 °C) is used for process heating in the plant. The extraction fractions were adjusted based on the steam demand of the plant. Rest of the steam is condensed at 10 kPa (45.8 °C) to maximally increase the electricity production. The condensed steam is again recirculated in the boiler for steam generation.

Economic analysis

All economic calculations were performed for the year 2016, and all costs reported are in US dollars (USD). Costs of specific equipment (reactors, molecular sieves, distillation columns, steam turbine) for biomass handling, oil–sugar separation, ethanol production, and cogeneration were calculated based on cost models of earlier biofuel studies in the literature (Kazi *et al.*, 2010; Bonomi *et al.*, 2011; Humbird *et al.*, 2011; Kumar & Murthy, 2011; Huang *et al.*, 2016b). Cost of highly specific equipment used in jet fuel production section was obtained from the process model of jet fuel from *Pongamia pinnata* seeds and vegetable oil (Klein-Marcuschamer *et al.*, 2013; Diederichs *et al.*, 2016). The cost of equipment for the size required for current process was calculated using the exponential scaling equation (Eq. (1)).

$$\text{New Cost} = \text{Base Cost} * \left(\frac{\text{new size}}{\text{base size}}\right)^{\text{exp}} \quad (1)$$

Costs of other general and smaller equipment (pumps, heat exchangers, tanks, etc.) were calculated based on the built-in cost models in SuperPro Designer. Other than equipment purchase costs, several additional costs, classified as direct costs: installation, piping, electrical, and insulation, and indirect costs: design work, building construction, and project contingencies, need to be considered in the calculation of direct fixed capital cost (DFC). These costs were calculated using Lang factor of 3.0, which is in agreement with other biofuel techno-economic studies in the literature (Haas *et al.*, 2006; Kwiatkowski *et al.*, 2006; Humbird *et al.*, 2011; Zhao *et al.*, 2015; Huang *et al.*, 2016a). Total capital investment was sum of direct fixed capital cost and working capital (assumed as 5% of the DFC). Construction period was assumed as 24 months. Total project life was assumed 20 years (Table 2). Depreciation was estimated using modified accelerated cost recovery systems (MACRS) 7-year depreciation schedule with a 0% equipment salvage value. Direct fixed cost was distributed over first 2 years (40% and 60%, respectively).

Operating costs consists of variable cost (raw materials, utilities, coproducts, etc.) and fixed operating cost (labor and various overhead items). Variable operating costs occurs only

Table 2 Financial assumptions for profitability analysis of biorefinery

Parameter	Value
Project lifetime	20 years
Construction period	2 years
Salvage value of equipment	No value (0)
Distribution of capital investment	40% in 1st year and 60% in 2nd year
Depreciation life	MACRS 7-year depreciation schedule*
Working capital	5% of fixed cost
Income tax	35%
Minimum acceptable IRR	10%

*MARCS, Modified Accelerated Cost Recovery Systems.

when plant is operating. Price of lipid-cane at the refinery gate was assumed to be $35 per metric ton, similar to average price of sugarcane (Huang *et al.*, 2016a,b). Cost of other consumables was either estimated based on recent studies or market values in year 2016. Cost of electricity, process steam, and water was assumed $ 0.1/kWh, $17/MT, and $0.353/MT, respectively (Klein-Marcuschamer *et al.*, 2013; Huang *et al.*, 2016a,b). Although hydrogen can be produced from steam reforming or naphtha to gasoline reformer in the biorefinery itself, however, considering the high capital costs, on-site hydrogen production was not considered in this model. Hydrogen was assumed to be purchased externally at cost of 1.015 per kg (Klein-Marcuschamer *et al.*, 2013). This approach has been used in several studies on techno-economic evaluation of renewable diesel and jet fuels (Wright *et al.*, 2010; Pearlson, 2011; Veriansyah *et al.*, 2012; Klein-Marcuschamer *et al.*, 2013). Sensitivity analysis was performed by varying the hydrogen purchase cost.

Although the biorefinery produces jet fuel and ethanol as main products, however, to calculate unit cost of jet fuel production, ethanol was considered as a coproduct with selling price of $1.42/gal, (CARD, 2016). Some studies have used allocation methods for distributing the operating and capital costs and calculating unit production cost of two main products; however, in those cases, results are highly dependent on the allocation method used (market value, energy basis, or mass basis). The selling price of diesel was assumed $1.65/gal (after excluding 20% tax and 19% distribution cost from the retail price) (EIA, 2016b). Selling price of another coproduct naphtha was assumed $1.607 per kg (Diederichs *et al.*, 2016). Due to fluctuations and uncertainties about fuel prices and government policies (incentives, subsidies), calculation of minimum fuel selling price with an acceptable investor return is a common method for an economic comparison and profitability analysis of the plant (Kazi *et al.*, 2010; Humbird *et al.*, 2011; Pearlson, 2011; Klein-Marcuschamer *et al.*, 2013; Natelson *et al.*, 2015; Crawford *et al.*, 2016; Diederichs *et al.*, 2016; Wang & Tao, 2016). The minimum jet fuel selling price (MJSP) was calculated using discounted cash flow rate of return (DCFROR) to obtain zero net present value (NPV) of zero at minimum acceptable internal rate of return (IRR) of 10%, an approach used in most of techno-economic studies including NREL project reports (Kazi *et al.*, 2010; Humbird *et al.*, 2011; Pearlson, 2011; Natelson *et al.*, 2015; Crawford *et al.*, 2016; Diederichs *et al.*, 2016). The calculated minimum selling price is the minimum price at which fuel must be sold to in order to breakeven for the assumed discount rate (10% in this case) (Humbird *et al.*, 2011; Klein-Marcuschamer *et al.*, 2013; Diederichs *et al.*, 2016). Selling price higher than MSJP will result in higher rate of return and vice versa. Economic sensitivity analysis was performed by varying the most influential parameters of the process.

Split biorefinery scenario

As mentioned earlier, considering sugarcane harvesting characteristics, the biorefinery was modeled with 200 operating days. To improve the capital utilization efficiency, a split biorefinery scenario was modeled as described in Fig. 3. In this case, lipid-cane processing, ethanol production, and cogeneration were modeled to operate only during the harvesting season of 200 days, while the jet fuel production section throughput was decreased to process same amount of lipids in 330 days instead of 200 days. Excess lipids produced daily are stored in storage tanks for continuous supply to jet fuel conversion section during off-season. The whole process was modeled in two separate flow sheets, one for the lipid-cane processing, ethanol production, and cogeneration, and other for the jet fuel process, as these operate on different calendar days. This case would potentially lead to small size equipment use in the jet fuel section and lower overall capital investment.

Results

The developed process models were simulated to conduct thorough material and energy balances for the biorefinery and to estimate process yields, capital costs,

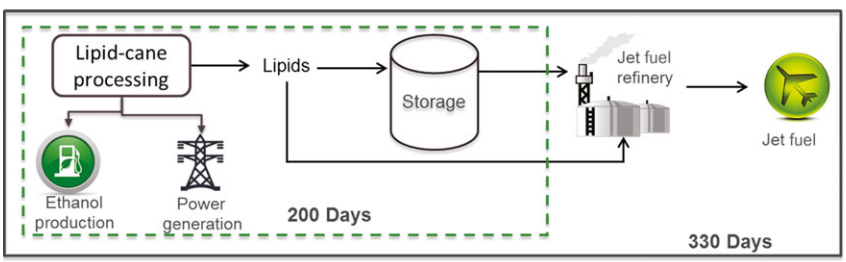

Fig. 3 Schematic of modeled split biorefinery scenario for jet fuel and ethanol production.

operating costs, chemicals, and utilities used in the plant.

Process yields

The jet fuel production capacities were calculated 12.62, 25.24, 37.86, and 50.55 million liters (3.34, 6.68, 10.02, and 13.35 million gal) for plants processing lipid-canes with 5%, 10%, 15%, and 20% lipid, respectively. Due to diversion of sugars toward oil accumulation, with increase in lipid content, jet fuel yield increases and ethanol yield decreases. Ethanol yields were calculated in the range of nil to 102.66 million liters (nil to 27.16 million gal). It was assumed in the case of 20% lipids that there were no free sugars from which ethanol could be produced, and therefore, that jet fuel was the only major product. Fuel and surplus electricity yields per unit feedstock are illustrated in Fig. 4. For 20% lipid case, jet fuel production was 31.6 L MT^{-1} of lipid-cane (wet basis, 70% moisture in lipid-cane). In terms of conversion efficiency, the jet fuel yield in this study was estimated 478.83 kg MT^{-1} of oil (lipids), which is similar to those (480–494 kg MT^{-1} oil) reported in other literature studies (Pearlson, 2011; Klein-Marcuschamer *et al.*, 2013; Diederichs *et al.*, 2016). These results confirm the validity of the data and the assumptions considered in the model. Bagasse is burnt to produce steam and electricity. This makes sugarcane process self-sustainable in energy, and extra electricity (if available) can be sold to grids. For all cases (lipid content 5–20%), electricity produced after extracting the process steam (steam requirement in plant) was sufficient to meet the electricity requirement of the process, and surplus electricity (83–156.9 kWh MT^{-1} lipid-cane) was considered as coproduct credits.

As mentioned earlier, due to limited land and water resources, challenge of low oil yields per unit land is a major obstacle in the growth of industry producing biofuel derived from oil crops. Relatively very high yields of sugarcane compared to oil crops can potentially address this issue. Jet fuel production from processing of lipid-cane with 5%, 10%, 15%, and 20% lipids was calculated 1577, 3155, 4732, and 6307 L ha^{-1}, respectively. More details are provided in Discussion Section of the manuscript.

Process economics

Capital costs. Table 3 gives an overview of the process economics, including capital and operating costs. The capital costs of biorefinery processing lipid-cane with 5–20% lipid were estimated in the range of \$238 to \$351 million, with jet fuel production capacities in the range of 3.34–13.35 million gal yr^{-1}. Capital costs were observed increasing with increase in lipid content in the lipid-cane. This rise was mainly attributed to high cost of equipment used in the jet fuel production and cogeneration sections. Figure 5 illustrates the equipment cost breakdown for all major sections of the plant processing lipid-cane with 5–20% lipids. In every case, the contribution of jet fuel section in process economics was significantly higher than that of ethanol production section. Even at low lipid content of 5%, jet fuel section facility accounted for about 27% cost contribution compared to 12% by ethanol production. Among the equipment used in jet fuel section, amine scrubber (hydrogen cleaning and recycling) unit was most expensive followed by the hydrocracking reactor (Fig. 6). Share of cogeneration system in total capital cost ranged from 38.5–43.5%, depending on the lipid content of feedstock.

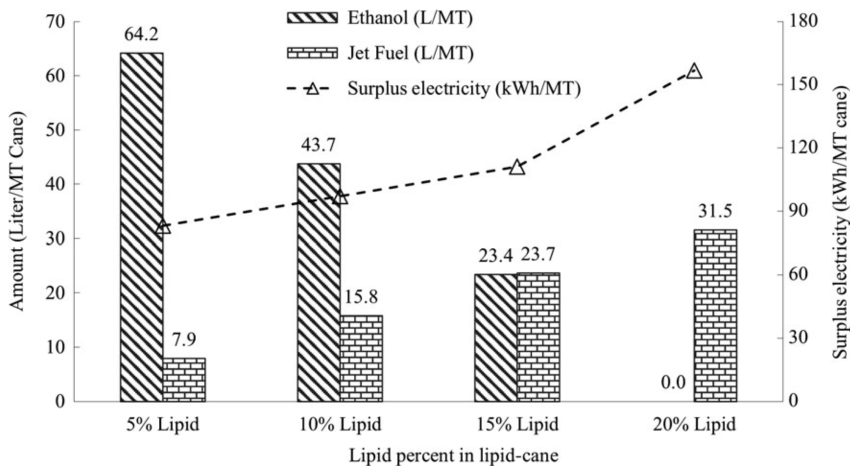

Fig. 4 Process yields of jet fuel, ethanol, and surplus electricity. Figure illustrates the amounts of jet fuel, ethanol, and surplus electricity (after meeting process demand) production per unit (MT) of lipid-cane (wet basis; 70% moisture).

Table 3 Process economics and yields of the biorefinery processing lipid-cane with different lipid percentages

	Lipid content (%)			
	5%	10%	15%	20%
Total Capital Investment (million USD)	238.1	288.1	332.6	351.2
Gross Operating Cost (million USD)	84.1	90.6	96.7	100.3
Ethanol (million gal yr^{-1})	27.16	18.51	9.89	0
Jet Fuel (million gal yr^{-1})	3.34	6.68	10.02	13.35

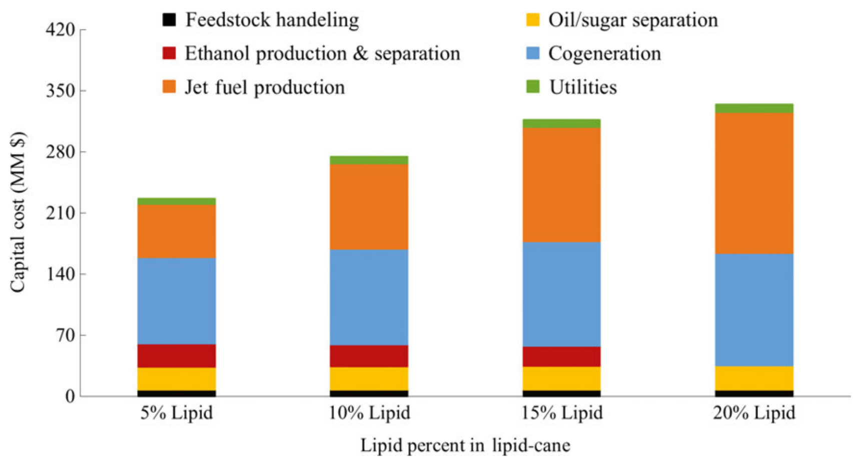

Fig. 5 Breakdown of capital cost in various sections of biorefinery. Figure illustrates the capital cost requirement of various sections of plant for all scenarios (lipid-cane with 5%, 10%, 15%, and 20% lipids). MM$ means million USD.

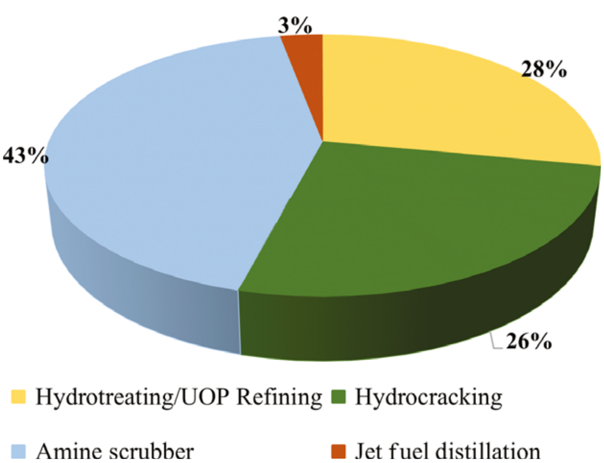

Fig. 6 Equipment price breakdown in jet fuel production section. The figure illustrates the contribution of major equipment used in the jet fuel production section for 10% lipid-cane scenario.

In case of 5% and 10% lipids, equipment costs associated with cogeneration section were maximum among all sections in the plant.

Due to multiple products in this case, it is difficult to compare capital cost of all cases with other literature studies. For the 20% lipid case (with only jet fuel as main product), capital cost ($ 26.3/gal jet fuel) was in the range of reported values ($8.8–$215.7/gal) (Klein-Marcuschamer *et al.*, 2013; Crawford *et al.*, 2016; Diederichs *et al.*, 2016; Wang & Tao, 2016). Except for costs for microalgae and *Pongamia* oil conversion, the capital cost in this study is on the higher side of reported values in the literature. There are several factors that can explain these differences in costs and are discussed in detail in Discussion Section of the manuscript.

Operating costs. Operating costs of the plants processing lipid-canes with 5%, 10%, 15%, and 20% lipid were estimated $84.1, $90.6, $96.7, and $100.3 million, respectively. Operating costs include material costs, facility-dependent costs, utility costs, labor costs, and other supplies costs. Breakdown of operating cost for all scenarios is illustrated in Fig. 7. Raw material was major cost in all the cases and accounted for about 72–76% of total operating cost of the process. Figure 8 illustrates the share of different raw material inputs in the total material costs for the cases of 5% and 20% lipids. Similar to other literature studies, lipid-cane cost was the major share (77–88%) of total material cost in all cases. Contribution of feedstock cost in the total material cost was found decreasing with increase in oil content, mainly due to rise in hydrogen use. Costs associated

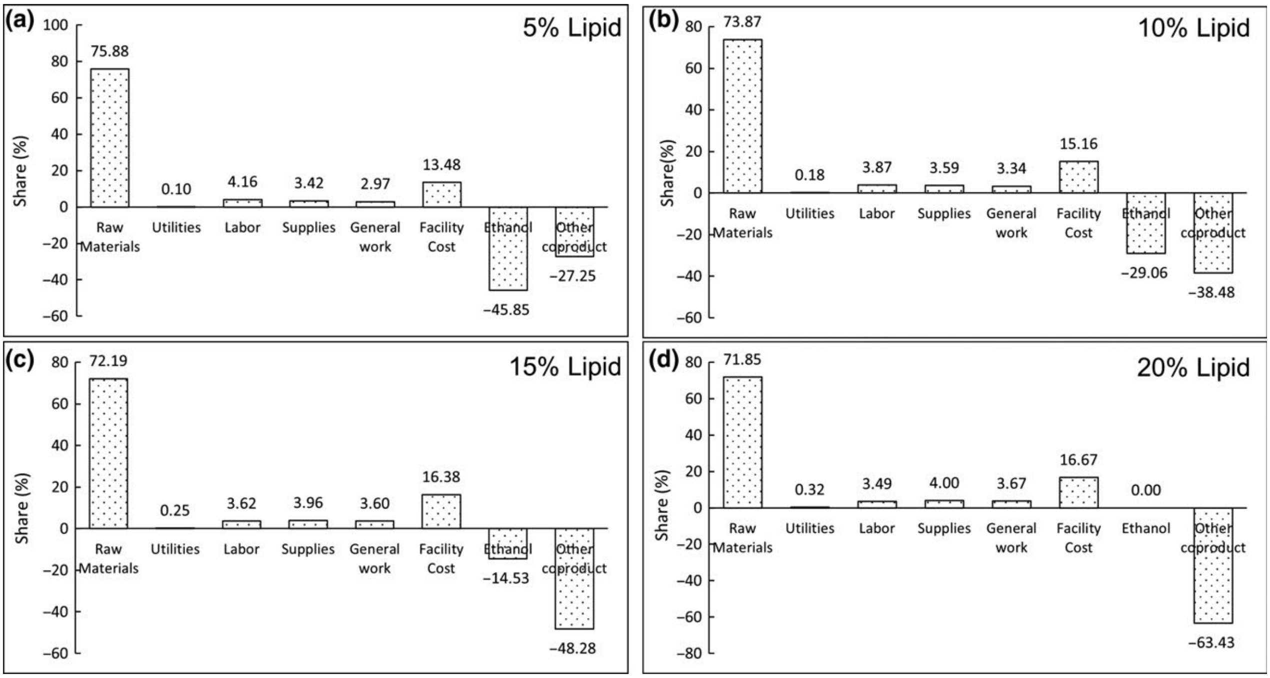

Fig. 7 Operating cost breakdown during jet fuel production from lipid-cane. Figure illustrates various types of cost and their share in total operational cost of the plant for all scenarios (lipid-cane with 5%, 10%, 15%, and 20% lipids). Negative values for coproducts indicate income instead of costs.

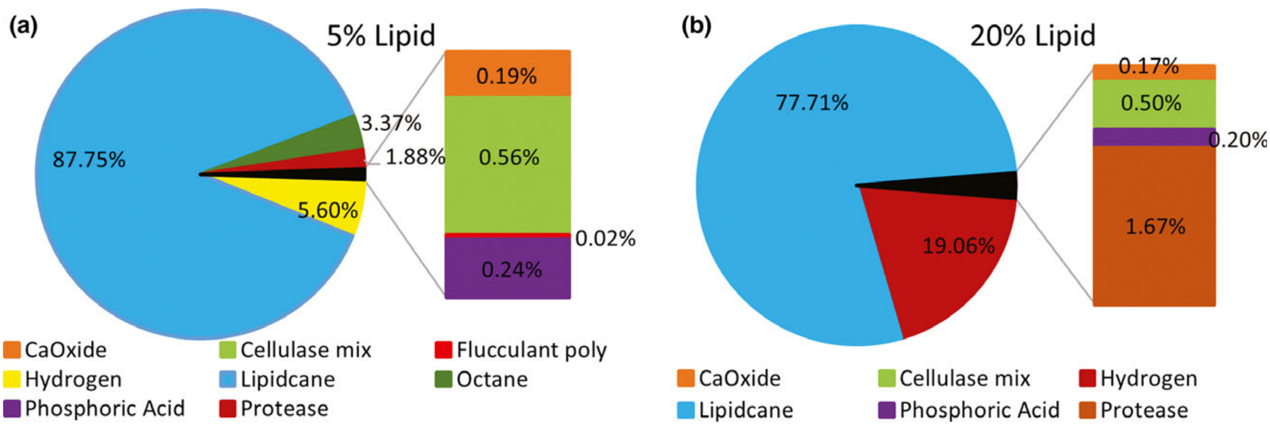

Fig. 8 Fraction of various inputs in total raw material costs. Figure shows the fraction of various inputs in total raw material costs for two cases: (a) 5% lipid-cane, (b) 20% lipid-cane.

with hydrogen increased from about 6% to 19% with change in oil content from 5% to 20%. Facility-dependent costs were observed as second most significant economic driver in the process that ranged from 13.5% to 16.7% of total operating cost. Equipment cost in the cogeneration section increased from 32.9 to 42.9 MM$ with change in lipid content from 5% to 20%, accordingly maintenance and depreciation costs were increased.

Unit production cost ($/liter of fuel) was calculated as ratio of net operating cost (total operating cost – coproduct cost) and jet fuel produced. The unit production costs of jet fuel for various scenarios were calculated in the range of $2.74–$6.76/gal ($0.73 to $1.79 per liter) of jet fuel (Fig. 9). Unit production cost decreased with increase in lipid content, and minimum cost of $2.74/gal ($ 0.73/L) jet fuel was observed in case of 20% lipid content. The decrease in the production cost was observed due to increase in oil content and surplus electricity available corresponding to higher fiber content, as illustrated in Fig. 4. Other coproducts (naphtha and diesel) revenue also increased with rise in oil content. Figure 9 also illustrates the comparison of

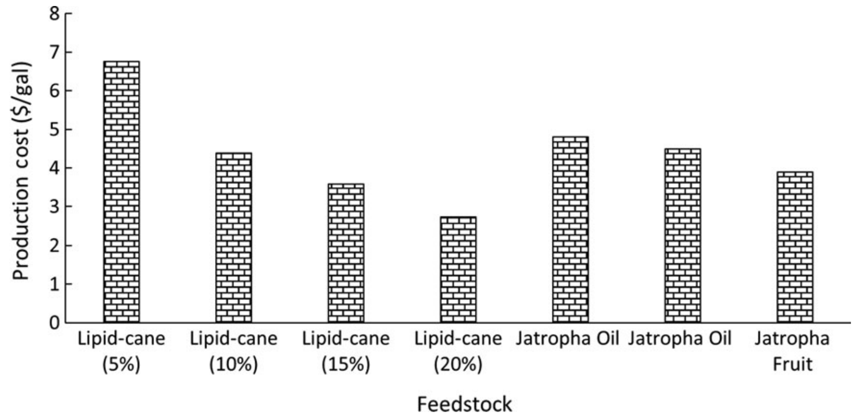

Fig. 9 Jet fuel unit production costs from lipid-cane and other feedstocks. Figure illustrates the production cost of jet fuel ($/gal) for all scenarios (lipid-cane with 5%, 10%, 15%, and 20% lipids) and also show their comparisons to jet fuel production costs from other oil crops (Diederichs *et al.*, 2016; Wang, 2016).

jet fuel production costs with those from other literature studies. The production cost for cases of 15% and 20% lipid-cane is lower than production cost from other oil-based feedstock.

Coproducts (naphtha, diesel, and surplus electricity) play a critical role in the final production cost. As presented in Fig. 6, revenue from selling the coproducts (excluding ethanol) was estimated in the range of 27.3–63.3% of gross operating cost of the process. Amounts of utilities and coproducts for all four cases are summarized in Table 4. Electricity production increased with increase in lipid content because of higher fiber content. In case of 20% lipids, surplus electricity was about 157 kWh MT^{-1} of lipid-cane. Total electricity used in this study, ranged from 70 702 to 145 186 MW (44.2–90.7 kWh MT^{-1} lipid-cane processed), was significantly higher than that of biodiesel production from lipid-cane (31–33 kWh MT^{-1} lipid-cane). Correspondingly, the surplus electricity produced (maximum 156.9 kWh MT^{-1} lipid-cane with 20% lipid) was also less than that of biodiesel production from lipid-cane (maximum 217.2 kWh MT^{-1} lipid-cane with 20% lipid) (Huang *et al.*, 2016a). This was observed because of significant electricity used for hydrogen compression in the jet fuel conversion process.

Figure 10 shows the minimum jet fuel selling price in this study and other literature studies on jet fuel production from oil-based feedstock (Pearlson, 2011; Klein-Marcuschamer *et al.*, 2013; Diederichs *et al.*, 2016; Wang, 2016). The MSJP of $3.63/L ($13.72/gal) was higher than all literature studies except jet fuel production from microalgae ($32.97/gal) (Klein-Marcuschamer *et al.*, 2013).

Table 4 Overall annual utilities used and coproducts produced in the biorefinery processing lipid-cane with different lipid contents

	Lipid content (%)			
	5%	10%	15%	20%
Utilities				
Electricity (MW)	70 702	96 681	122 691	145 186
Steam (MT)	665 539	647 443	631 009	98 565
Steam (High pressure) (MT)	87	73	61	49
Cooling water (000 MT)	109 337	132 045	154 760	173 911
Chilled water (MT)	200 916	401 831	602 738	803 240
Light gases fuel (MT)	3061	6123	9183	12 202
CoProducts				
Naphtha (MT)	5491	10 982	16 474	21 953
Diesel (million L)	1 838 869	3 677 727	5 516 514	7 351 591
Surplus Electricity (MW)	132 836	155 409	177 794	250 959

Split biorefinery

For efficient use of machinery and process optimization, a split biorefinery scenario was simulated considering storage of a fraction of lipids produced from cane processing (200 days operational) and provides a continuous feed to jet fuel processing section (330 days operational). The model was simulated only for plant processing lipid-cane containing 10% lipids. The results from the analysis are presented in Fig. 11. The fixed capital cost in this case was estimated $265.6 million, which was $8.8 million less than that of base case. Due to smaller equipment size, capital cost of jet fuel section decreased by about 30% ($98.1–$68.1 million). However, there was extra capital investment of $20.4 million for lipid storage, which reduced the over savings to $8.8 million. Correspondingly, there was about 14 ¢ decrease

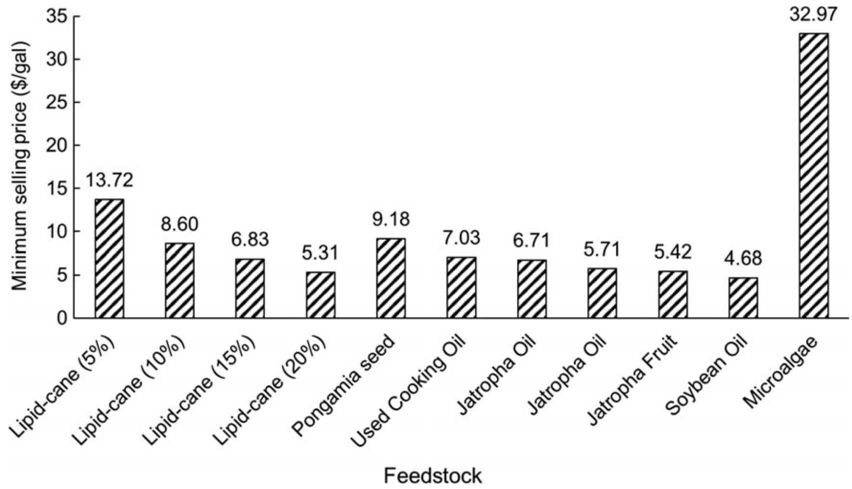

Fig. 10 Minimum jet fuel selling price from lipid-cane and other oil feedstocks. Figure illustrates the minimum jet fuel selling prices with a 10% discount rate for all (lipid-cane with 5%, 10%, 15%, and 20% lipids) and also compares these values with other reported values in the literature.

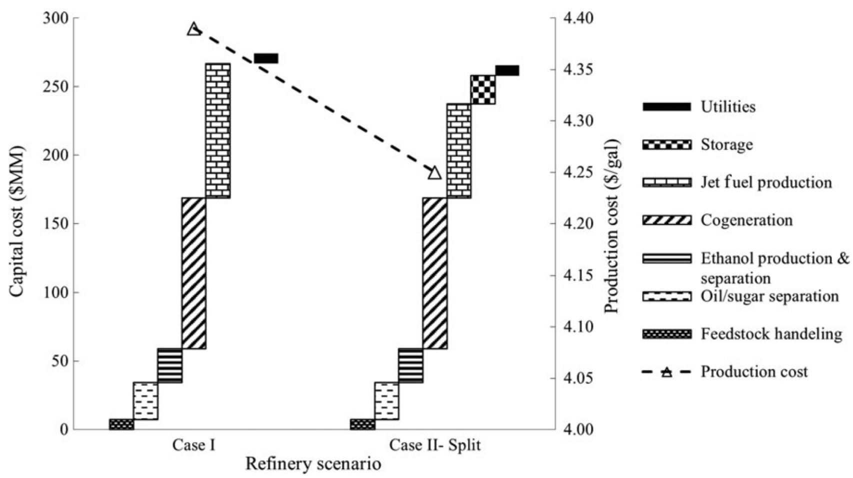

Fig. 11 Comparison of fixed capital costs and production cost for base case and split refinery scenario. Figure illustrates the change in capital cost and jet fuel production cost ($/gal) with use of split refinery scenario instead of base case.

in production cost per gallon jet fuel ($4.39–$4.25/gal). Due to less capital investment and lower operational cost, minimum jet fuel selling price for 10% IRR decreased from $8.60 to $8.31/gal ($2.28 to $2.20/L) of jet fuel.

Sensitivity analysis

Considering the uncertainty in technology, fluctuating oil prices and assumptions used in the analysis, it is important to understand the sensitivity of the results by varying the process parameters that are either particularly uncertain or could significantly affect the process economics. Effect of oil content in the feedstock, a major uncertain parameter for lipid-cane, has already been discussed throughout the manuscript. All other sensitivity analysis was performed for only 10% lipid case, which is close to current concentrations (8%) in the lipid-cane. Based on the cost contributions in the process economics, feedstock price was considered as a critical parameter for sensitivity analysis. Feedstock price of $35/MT (similar to that of sugarcane) was assumed for development of actual models. In the developmental stage, there are uncertainties in the final lipid-cane price. Price of genetically modified lipid-cane could be relatively higher because of high oil contents and research investment. Lipid-cane price will also be influenced by the final biomass yields. The lower biomass yield would probably cause relatively higher lipid-cane price to balance farmer's income. However, there are

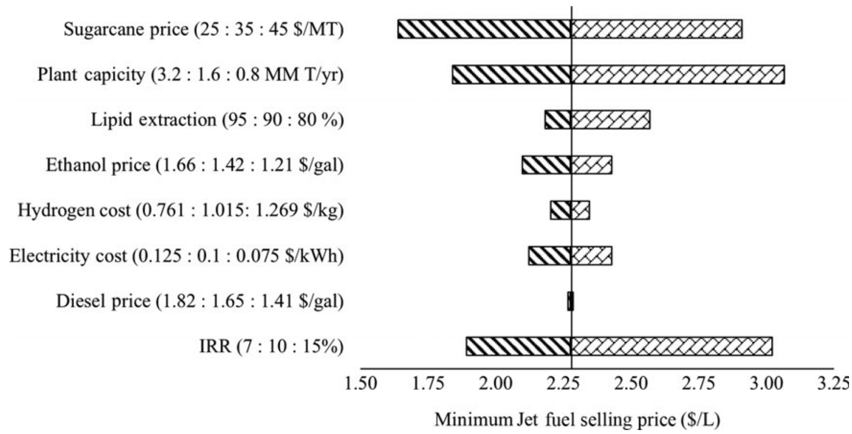

Fig. 12 Sensitivity of minimum jet fuel selling price to different parameters. The numbers in brackets in *Y*-axis are the potential low, base, and high values of each parameter.

also good possibilities of yield increase due to the synergistic effect of lipid accumulation and carbon assimilation and current research on photosynthesis improvements in crops (Vanhercke *et al.*, 2014; Huang *et al.*, 2016a). Therefore, sensitivity analysis was performed using a large variation of lipid-cane price ($25–$45/MT). Decrease in lipid-cane cost to $25/MT resulted in lowering the contribution of raw material in the operating cost from 74% to 68%, which brought the minimum jet fuel selling price to only $1.64/L ($6.2/gal). Similarly, raising the lipid-cane price to $45/MT resulted in about 18% increase in total operational cost, with minimum jet fuel selling price of $2.91/L ($11.00/gal) (Fig. 12). The jet fuel production costs at lipid-cane prices of $25 and $45 were calculated $0.53/L ($2.0/gal) and $1.79/L ($6.78/gal), respectively. These results are in agreement with other studies on jet fuel production from oil crops that also found feedstock cost to be the most sensitive parameter in price of jet fuel (Pearlson, 2011; Klein-Marcuschamer *et al.*, 2013; Diederichs *et al.*, 2016; Wang & Tao, 2016).

Another major factor that influenced the process economics was the size of plant (crushing capacity), which was shown to have considerable effect on price of jet fuel (Fig. 12). The jet fuel selling price was estimated $1.84/L (19.07% decrease) and $3.07/L (34.78% increase) for double (3.2 million ton lipid-cane annually) and half (0.8 million ton lipid-cane annually) of base plant capacity, respectively. This inverse relationship between plant size and unit production cost has been observed in several other biofuel techno-economic studies (Huang *et al.*, 2009; Pearlson, 2011; Wang & Tao, 2016). Production cost and minimum selling price increase by lowering the plant capacity to 50% were more than the cost drop for doubling the plant processing capacity. This was observed because many equipments have a limit to their capacity (maximum size) and with increase in throughput, sometimes number of units also increases that result in high capital cost. Effect of hydrogen cost was investigated by changing the cost by 25%. The jet fuel minimum selling price varied between $2.2 and $2.35 per liter of jet fuel. Lipid extraction efficiency, assumed 90% in base case, is another uncertain parameter and could be important factor in process viability. The sensitivity of lipid extraction efficiency on jet fuel price was investigated by varying the efficiency from 80 to 95%. At 80% efficiency, the minimum selling price was estimated $2.57/L (production cost of $1.31/L), which decreased to $2.18/L (production cost of $1.12/L) at 95% efficiency. Price of ethanol and other coproducts is market-driven and could influence the process economics. Sensitivity analysis was performed by varying the ethanol and diesel price between maximum and minimum market price in 2015. Due to relatively smaller production volumes, the change in price of diesel did not have as large impact as that from changing the ethanol price (Fig. 12). Furthermore, electricity prices had significant influence on the jet fuel production costs because of large amount of surplus electricity produced (Fig. 3). By changing electricity prices by 25%, the minimum selling price ranged between $2.12 and $2.43 per liter of jet fuel (production costs 1.01 and 1.32/L jet fuel). The minimum jet fuel selling price is highly dependent on the IRR value considered in the calculations (10% in the base case). Selling price decreased to $1.89/L (17% decrease) for minimum 7% IRR and increased to $3.02/L (33% increase) for minimum 15% IRR.

Discussion

Capacity limitations and challenges of low oil yields per unit land are major obstacles in the commercial growth of biojet fuel production from oil crops. Use of current oil crops such as soybean and jatropha to produce jet fuel could never meet aviation sector fuel needs, at considerable scale. Newly developed and genetically modified sugarcane, also known as lipid-cane, can accumulate up to 20% oil and potentially address this issue to a large extent. For the modeled biorefinery processing 1 600 000 MT lipid-cane, the jet fuel production capacities were calculated in the range of 12.6–50.5 million liter (correspondingly ethanol production from nil to 102.6 million liter) annually, depending on the lipid content in plant. Due to diversion of all sugars toward oil accumulation, ethanol production was zero in case of lipid-cane with 20% lipids. In terms of fuel yield per unit land, the jet fuel production was estimated in the range of 1577 to 6307 L ha^{-1}, depending on the lipid content in the cane. Considering average soybean yield of 3.5 MT ha^{-1}, and jet fuel yield of 29.9 gal dry^{-1} MT soybean, the jet fuel produced from one hectare of land was only 395 L ha^{-1} (USDA, 2016; Wang & Tao, 2016). These would indicate that at crop yield of 60 t ha^{-1} stem dry matter (Duval *et al*., 2013), lipid-cane even with only 5% lipids will produce about four times jet fuel per hectare of land, and yet it still provides an additional 12830 liter (per ha) of ethanol. In case of 20% lipids, the jet fuel yield per unit land could be more than fifteen times that of soybean. Similarly, for Jatropha, another highly studied feedstock for jet fuel production, only about 477 liter of jet fuel, can be produced per hectare of land (considering 480 kg jet fuel MT^{-1} jatropha oil, and yield of 741 L oil ha^{-1} of land) (Mata *et al*., 2010; Diederichs *et al*., 2016). Although jet fuel yield/ha for Jatropha is relatively higher than that of soybean, it is significantly less than that of lipid-cane. Other than production of two sustainable biofuels (jet fuel and ethanol), this biorefinery provides a unique advantage of self-sustainability in energy (from bagasse burning), which is not possible for other oil crops. After meeting the process demands, surplus electricity (83–156.9 kWh MT^{-1} lipid-cane) produced from bagasse burning can be sold to grids to replace electricity produced from fossil fuels.

Due to high front-end processing costs, estimated capital costs (238.1–351.2 million USD) were relatively higher than those from jet fuel production from other oil crops. Another major reason for high capital costs was significant high cost of cogeneration system, which is not required in processing of oil crops such as soybean. Capital cost is highly affected by type of feedstock. Due to significantly high front-end (algae growth and harvesting) costs, Klein-Marcuschamer *et al.* (2013) observed the capital cost of plant producing jet fuel from microalgae was about seven times higher than that of plant using *Pongamia* oil seeds. Compared to oil crops, in case of lipid-cane, relatively higher amount of feedstock needs to be handled for same fuel production capacity, which requires high capacity equipment on the front end of process. Similar results were observed in case of economic analysis of biodiesel production from lipid-cane compared to soybean diesel (Huang *et al*., 2016a). Diederichs *et al.* (2016) also reported significantly high front-end (sugarcane to ethanol, 30.9%) cost in case of sugarcane to jet fuel process (biochemical conversion to ethanol with upgrading) compared to that of oil crop processing. Also, it is important to note that the oil refining design was based on the work of Klein-Marcuschamer *et al.* (2013), which presented three stage process in contrast to single or two-stage process use in other studies. According to Klein-Marcuschamer *et al.* (2013), this design simulates more realistic commercial scale conditions, and the design has been verified with several academic researchers and industry experts (Klein-Marcuschamer *et al*., 2013). Costs of sugarcane processing facilities (refinery excluding jet fuel production section) were confirmed by simulating a case of processing lipid-cane with 0% lipids (similar to sugarcane). Total capital cost was observed $159 million, which is similar to reported values ($140–$ 170 million) for similar size plants (Dias *et al*., 2010, 2011; Bonomi *et al*., 2011). High cost of cogeneration system is another big difference compared to other literature studies. The cost of cogeneration system is high in current case due to use of high-pressure, extraction-condensed turbogenerators, which allows for the production of significant high electricity (Sousa & Macedo, 2010; Dias *et al*., 2011). Also, the equipment cost data for cogeneration system in this study were based on the comprehensive analysis conducted by the NREL, which would be more close to actual commercial costs (Humbird *et al*., 2011). Using same data for cogeneration system, similar results (relatively high cogeneration section cost) were observed in other studies on cellulosic ethanol and biodiesel production (Kazi *et al*., 2010; Kumar & Murthy, 2011; Huang *et al*., 2016a). Although high capital cost, however, high-pressure cogeneration system significantly increases the boiler and turbogenerator efficiency. So, the extra capital cost of system could be compensated by selling surplus electricity after meeting the process demand (Fig. 4). Other than cost credits, efficient electricity generation from bagasse would potentially replace the electricity generated from fossil sources, hence provide significant environmental benefits by reducing GHG emissions and fossil energy use. Those benefits can be analyzed in detail through life cycle assessment analysis.

Operating costs of the biorefinery were in the range of $84.1–100.3 million. In all cases, the cost of raw materials caused more than 70% of total operational cost, and feedstock cost was the major contributor in the operational costs. These observations were in agreement with other studies on jet fuel production (Pearlson, 2011; Klein-Marcuschamer *et al*., 2013; Diederichs *et al*., 2016; Wang, 2016; Wang & Tao, 2016). As mentioned earlier, high cost of feedstock is a major hurdle in the commercialization of biojet fuel production process. Klein-Marcuschamer *et al*. (2013) observed that *pongamia* seeds cost about 90% of the raw material cost, which is similar to the case of 20% lipid-cane (only jet fuel production) in current study. Similar to other literature studies, facility-dependent costs (13.5–16.7% of total operating cost) were observed as other significant economic driver in the process. Facility-dependent costs that include depreciation and maintenance are directly proportional to total fixed cost. Klein-Marcuschamer *et al*. (2013) observed that due to high capital costs ($ 3451 million for 16 million gal jet fuel plant) in case of jet fuel production from microalgae, facility-dependent costs were as high as 84% of total operating costs. In current study, facility-dependent costs were maximum for 20% lipid-cane because of relatively high equipment cost of jet fuel section compared to ethanol production section and high capacity of cogeneration section.

Jet fuel production costs were calculated in the range $0.73/L (for 20% lipids) to $1.79/L (for 5% lipids). The decrease in production cost with rise in lipid content was observed because of higher coproduct credits (especially surplus electricity) at high lipid contents (Fig. 9). Jet fuel production costs from processing of lipid-cane with 15% and 20% lipids were lower than production cost from other oil-based feedstock. The lower production cost of jet fuel in current study is primarily attributed to the relatively lower cost of lipid-cane compared to other oil crops, and in-house generation of steam and electricity from bagasse (reduced utilities cost). Wang (2016) reported that jet fuel production cost could decrease from $4.5 to $3.9/gal of jet fuel using jatropha fruit (low-cost feedstock) instead of jatropha oil (higher cost) as feedstock, however, that leads to high capital cost due to extra front-end processing. Due to similar reasons (front-end processing), the capital costs were relatively higher in current study. Similarly, although high capacity cogeneration system added big capital costs in the process, it resulted in self-sustainability in terms of steam and electricity and low utilities costs in all cases. Amount of steam and electricity generated from bagasse was more than the plant requirement in all cases, and hence, the costs of steam and electricity were set to zero. Extra electricity was assumed to be sold to the grid to generate coproduct credits. Klein-Marcuschamer *et al*. (2013) estimated 5.6% operating costs associated with utilities (steam, electricity, natural gas, etc.), whereas the utilities costs in current study (0.1–0.32% of total operating cost) were mainly associated with chilled water only. It is worth notice that steam use in case of plant processing feedstock with 20% lipid was significantly lower compared to other processes. This was observed because in this case, all sucrose was believed to be converted to TAGs, and there was no heat requirement in the sugar concentration, ethanol production, and distillation sections. However, due to additional hydrogen gas compression, electricity usage was maximum in case of 20% lipid feedstock.

Although an important parameter, however, in any production plant, only production cost cannot directly indicate the economic viability of the process. A better approach of conducting economic performance is to estimate minimum jet fuel selling price (MSJP) for a break-even point, which considers multiple financial parameters such as capital investments, operational costs, taxes, and other financial assumptions. Most of the literature studies, including all type of feedstocks (oil, lignocellulose, sugars), have reported biojet fuel selling price higher than that of petroleum-based jet fuel, and concluded the economic difficulty of the biojet fuel process without policy support. Chu *et al*. (2016) performed financial risk analysis on biojet fuel production from oil crops and concluded that only with an incentive of $0.2/L ($0.76/gal), jet fuel production from Camelina and Carinata (*Brassica carinata*) can yield positive net present values with probabilities of 85% and 75%, respectively. Similar to other literature studies, minimum selling jet fuel prices in current case ($5.31–$13.72 per gallon) were considerably higher than that of wholesale market price of petroleum-based jet fuel ($2.71/gal, average of last five years). Similar to operational cost, MSJP was found decreasing with increase in oil content and was found minimum of $1.40/L ($5.31/gal) for case of 20% lipid-cane, lower than most of the literature studies. These lower MSJP values along with relatively very high fuel yield per unit of land indicate that lipid-cane is a high potential feedstock for biojet fuel production. In addition to quantitatively examining the techno-economic feasibility of the process, this analysis helped in identifying the major cost affecting inputs/operations and high energy demanding processes in the whole process. Other than changes in market price of coproducts, potential for significant jet fuel cost reductions exists by crop improvement, increasing plant capacity, or splitting the biorefinery for efficient use of machinery.

Overall, although process require relatively high capital cost, it provides huge benefit in terms of production costs, high fuel yield per unit land (up to 15 times than that from other oil crops), and surplus electricity that can displace fossil fuel electricity and provide environmental benefits. As this crop can be grown locally, it provides a means to produce jet fuel at remote locations and in countries that lack oil reserves.

Acknowledgement

The information, data, or work presented herein were funded in part by the Advanced Research Projects Agency-Energy (ARPA-E), U.S. Department of Energy, under Award Number DE-AR0000206. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

References

Bonomi A, Mariono A, de Jesusa D *et al*. (2011) Virtual Sugarcane Biorefinery Report. Brazilian Bioethanol Science and Technology Laboratory (CTBE)

Campbell KA, Glatz CE (2009) Protein recovery from enzyme-assisted aqueous extraction of soybean. *Biotechnology Progress*, **26**, 488–4959.

Canakci M, Van Gerpen J (2001) Biodiesel production from oils and fats with high free fatty acids. *Transactions-American Society of Agricultural Engineers*, **44** , 1429–1436.

CARD (2016) *Historical Ethanol Operating Margins*. Center for Agricultural and Rural Development, Iowa State University, Ames, Iowa.

Chu PL, Vanderghem C, MacLean HL, Saville BA (2016) Financial analysis and risk assessment of hydroprocessed renewable jet fuel production from camelina, carinata and used cooking oil. *Applied Energy*, **198**, 401–409.

Crawford JT, Shan CW, Budsberg E, Morgan H, Bura R, Gustafson R (2016) Hydrocarbon bio-jet fuel from bioconversion of poplar biomass: techno-economic assessment. *Biotechnology for Biofuels*, **9** , 141.

Dias MO, Ensinas AV, Nebra SA, Maciel Filho R, Rossell CE, Maciel MRW (2009) Production of bioethanol and other bio-based materials from sugarcane bagasse: integration to conventional bioethanol production process. *Chemical Engineering Research and Design*, **87** , 1206–1216.

Dias MO, Cunha MP, Jesus CD, Scandiffio MI, Rossell CE, Maciel Filho R, Bonomi A (2010) Simulation of ethanol production from sugarcane in Brazil: economic study of an autonomous distillery. *Computer Aided Chemical Engineering*, **28**, 733–738.

Dias MO, da Cunha MP, Maciel Filho R, Bonomi A, Jesus CD, Rossell CE (2011) Simulation of integrated first and second generation bioethanol production from sugarcane: comparison between different biomass pretreatment methods. *Journal of Industrial Microbiology & Biotechnology*, **38** , 955–966.

Dickey LC, Johnston DB, Kurantz MJ, McAloon A, Moreau RA (2011) Modification of aqueous enzymatic oil extraction to increase the yield of corn oil from dry fractionated corn germ. *Industrial Crops and Products*, **34** , 845–850.

Diederichs GW, Mandegari MA, Farzad S, Görgens JF (2016) Techno-economic comparison of biojet fuel production from lignocellulose, vegetable oil and sugar cane juice. *Bioresource Technology*, **2016**, 331–339.

Duval BD, Anderson-Teixeira KJ, Davis SC, Keogh C, Long SP, Parton WJ, DeLucia EH (2013) Predicting greenhouse gas emissions and soil carbon from changing pasture to an energy crop. *PLoS ONE*, **8** , e72019.

EIA (2016a) Jet fuel consumption, price, and expenditure estimates, U.S. Energy Information Administration Washington, DC. Available at: https://www.eia.gov/state/seds/sep_fuel/html/pdf/fuel_jf.pdf (accessed 30 March 2017).

EIA (2016b) U.S. No 2 Diesel Retail Prices, Energy Information Administration. Washington, DC. Available at: https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=pet&s=emd_epd2d_pte_nus_dpg&f=a (accessed 30 March 2017).

Fang X, Moreau RA (2014) Extraction and demulsification of oil from wheat germ, barley germ, and rice bran using an aqueous enzymatic method. *Journal of the American Oil Chemists' Society*, **91**, 1261–1268.

Haas MJ, McAloon AJ, Yee WC, Foglia TA (2006) A process model to estimate biodiesel production costs. *Bioresource Technology*, **97** , 671–678.

Huang H-J, Ramaswamy S, Al-Dajani W, Tschirner U, Cairncross RA (2009) Effect of biomass species and plant size on cellulosic ethanol: a comparative process and economic analysis. *Biomass and Bioenergy*, **33** , 234–246.

Huang H, Long S, Singh V (2015) Ultra-oil producing sugarcane and sweet sorghum. *AOCS Inform*, **26** , 278–282.

Huang H, Long S, Singh V (2016a) Techno-economic analysis of biodiesel and ethanol co-production from lipid-producing sugarcane. *Biofuels, Bioproducts and Biorefining*, **10**, 299–315.

Huang H, Long SP, Clemente TE, Singh V (2016b) Technoeconomic analysis of biodiesel and ethanol production from lipid-producing sugarcane and sweet sorghum. *Industrial Biotechnology*, **12** , 357–365.

Humbird D, Davis R, Tao L *et al*. (2011) Process design and economics for biochemical conversion of lignocellulosic biomass to ethanol: dilute-acid pretreatment and enzymatic hydrolysis of corn stover. National Renewable Energy Laboratory (NREL), Golden, CO.

James CN, Horn PJ, Case CR *et al*. (2010) Disruption of the Arabidopsis CGI-58 homologue produces Chanarin–Dorfman-like lipid droplet accumulation in plants. *Proceedings of the National Academy of Sciences*, **107** , 17833–17838.

Juneja A, Kumar D, Murthy GS (2013) Economic feasibility and environmental life cycle assessment of ethanol production from lignocellulosic feedstock in Pacific Northwest US. *Journal of Renewable and Sustainable Energy*, **5** , 023142.

Kazi FK, Fortman JA, Anex RP, Hsu DD, Aden A, Dutta A, Kothandaraman G (2010) Techno-economic comparison of process technologies for biochemical ethanol production from corn stover. *Fuel*, **89**, S20–S28.

Klein-Marcuschamer D, Turner C, Allen M *et al*. (2013) Technoeconomic analysis of renewable aviation fuel from microalgae, *Pongamia pinnata*, and sugarcane. *Biofuels, Bioproducts and Biorefining*, **7** , 416–428.

Kokayeff P, Marker TL, Petri JA (2010) Production of fuel from renewable feedstocks using a finishing reactor, (Ed.) U.S.P.a.T. Office, Vol. 0 133 144 A1.

Kumar D, Murthy GS (2011) Impact of pretreatment and downstream processing technologies on economics and energy in cellulosic ethanol production. *Biotechnology for Biofuels*, **4** , 27.

Kwiatkowski JR, McAloon AJ, Taylor F, Johnston DB (2006) Modeling the process and costs of fuel ethanol production by the corn dry-grind process. *Industrial Crops and Products*, **23** , 288–296.

Majoni S, Wang T, Johnson LA (2011) Physical and chemical processes to enhance oil recovery from condensed corn distillers solubles. *Journal of the American Oil Chemists' Society*, **88** , 425–434.

Mani S, Sokhansanj S, Tagore S, Turhollow A (2010) Techno-economic analysis of using corn stover to supply heat and power to a corn ethanol plant–Part 2: Cost of heat and power generation systems. *Biomass and Bioenergy*, **34** , 356–364.

Mata TM, Martins AA, Caetano NS (2010) Microalgae for biodiesel production and other applications: a review. *Renewable and Sustainable Energy Reviews*, **14** , 217–232.

McCall MJ, Kocal JA, Bhattacharyya A, Kalnes TN, Brandvold TA (2009) Production of aviation fuel from renewable feedstocks, (Ed.) U.S.P.a.T. Office, Vol. 0 283 442 A1.

Moreau RA, Dickey LC, Johnston DB, Hicks KB (2009) A process for the aqueous enzymatic extraction of corn oil from dry milled corn germ and enzymatic wet milled corn germ (E-Germ). *Journal of the American Oil Chemists' Society*, **86**, 469–474.

Natelson RH, Wang W-C, Roberts WL, Zering KD (2015) Technoeconomic analysis of jet fuel production from hydrolysis, decarboxylation, and reforming of camelina oil. *Biomass and Bioenergy*, **75**, 23–34.

Pearlson MN (2011) A techno-economic review of hydroprocessed renewable esters and fatty acids for jet fuel production. *Biofuels, Bioproducts and Biorefining*, **7**, 89–96.

Perego C, Sabatino LMF, Baldiraghi F, Faraci G (2008) Process for producing hydrocarbon fractions from mixtures of a biological origin, (Ed.) W.I.P. Organization, Vol. 2008/058664 A1.

Shonnard DR, Williams L, Kalnes TN (2010) Camelina-derived jet fuel and diesel: sustainable advanced biofuels. *Environmental Progress & Sustainable Energy*, **29** , 382–392.

Smith P, Gaffney M, Shi W, Hoard S, Armendariz II, Mueller D (2017) Drivers and barriers to the adoption and diffusion of Sustainable Jet Fuel (SJF) in the US Pacific Northwest. *Journal of Air Transport Management*, **58**, 113–124.

Sousa E, Macedo I.D.C. (2010) *Ethanol and Bioelectricity: Sugarcane in the Future of the Energy Matrix*. UNICA, São Paulo.

USDA (2016). Crop Production 2015 Summary, Vol. 2016, United States Department of Agriculture – National Agricultural Statistics Service. https://www.usda.gov/nass/PUBS/TODAYRPT/cropan16.pdf (accessed 15 March 2017).

Vanhercke T, El Tahchy A, Liu Q *et al*. (2014) Metabolic engineering of biomass for high energy density: oilseed-like triacylglycerol yields from plant leaves. *Plant Biotechnology Journal*, **12** , 231–239.

Veriansyah B, Han JY, Kim SK *et al*. (2012) Production of renewable diesel by hydroprocessing of soybean oil: effect of catalysts. *Fuel*, **94**, 578–585.

Wang WC (2016) Techno-economic analysis of a bio-refinery process for producing hydro-processed renewable jet fuel from Jatropha. *Renewable Energy*, **95**, 63–73.

Wang WC, Tao L (2016) Bio-jet fuel conversion technologies. *Renewable and Sustainable Energy Reviews*, **53**, 801–822.

Wright MM, Daugaard DE, Satrio JA, Brown RC (2010) Techno-economic analysis of biomass fast pyrolysis to transportation fuels. *Fuel*, **89**, S2–S10.

Zale J, Jung JH, Kim JY *et al.* (2016) Metabolic engineering of sugarcane to accumulate energy-dense triacylglycerols in vegetative biomass. *Plant Biotechnology Journal*, **14** , 661–669.

Zhao L, Zhang X, Xu J, Ou X, Chang S, Wu M (2015) Techno-economic analysis of bioethanol production from lignocellulosic biomass in China: dilute-acid pretreatment and enzymatic hydrolysis of corn stover. *Energies*, **8** , 4096–4117.

Supporting Information

Additional Supporting Information may be found online in the supporting information tab for this article:

Figure S1. Flowsheet of "feedstock handling" section of the process model of biorefinery developed in SuperPro.
Figure S2. Flowsheet of "oil and sugar separation" section of the process model of biorefinery developed in SuperPro.
Figure S3. Flowsheet of "ethanol production" section of the process model of biorefinery developed in SuperPro.
Figure S4. Flowsheet of "jet fuel production" section of the process model of biorefinery developed in SuperPro.
Figure S5. Flowsheet of "cogeneration" section of the process model of biorefinery developed in SuperPro.
Table S1. Properties and component flow rates of all streams of the process model of biorefinery producing ethanol and jet fuel using lipid-cane with 10% lipids.