Queensland Sustainable Aviation Fuels Initiative

Daniel Klein-Marcuschamer^{1, 2}, Christopher Turner¹, Mark Allen³, Peter Gray¹, Ralf G Dietzgen⁴, Peter M Gresshoff⁴, Ben Hankamer⁴, Kirsten Heimann⁵, Paul T Scott⁴, Evan Stephens⁴, Robert Speight¹, and Lars K Nielsen^{*, 1}

¹University of Queensland, Australian Institute for Bioengineering and Nanotechnology, St Lucia, Australia

² Joint BioEnergy Institute, Emeryville, CA, USA; Lawrence Berkeley National Laboratory, Berkeley, CA, USA

³IOR Energy Pty Ltd, Bulimba, QLD, Australia

⁴ University of Queensland, St Lucia, QLD, Australia

⁵James Cook University, Townsville, QLD, Australia *Corresponding author

30 April 2014

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1 Introduction

1.1 Background

The Queensland Sustainable Aviation Fuels Initiative is focused on evaluating bio-fuels production, with a particular focus on environmental impact, technical feasibility, and economic viability. This study considers the production of sustainable aviation fuel from three different feed stocks (sugarcane, algae, and the oils seeds of the *Pongamia* tree) through both technoeconomic and lifecycle analyses.¹

1.2 Technoeconomic Analysis

These technoeconomic models have developed been based on open and accountable information from journal reports, patents, and industry to answer important questions about the manufacturing process for sustainable aviation fuels from the three feed stocks. A production scale of 15 million gallons per year (15,000,000 Gallons/year) has been adopted to reflect a mature, full-scale biofuels production facility.

1.3 Model Feedback

This technoeconomic model is meant to be a community-updatable tool, and we encourage and welcome suggestions, corrections, and modifications to the assumptions and parameters used. In order to ensure that the model is updated in an orderly fashion and using relevant and accurate data, we require contributors to follow the instructions below. The model will be updated with data available in peer-reviewed publications or obtained directly from equipment vendors. All data must be obtained in the conditions that are prevalent in the unit operation to be updated, and must be complete enough to describe all relevant processes in the unit operation in question and related unit operations.

- Send an email to Lars Nielsen explaining why the model should be updated and how. Cite any peer-reviewed publications that support the data provided for the update. If the information was obtained from a vendor, please provide the vendor's contact information. Please attach to the email any relevant publications. A comment will be added to the relevant page for public viewing.
- The comment can be debated for two weeks before the changes are made to the model (send any replies to the comment, which will be made public, as above). If the basis of the update is to provide evidence of an improved technology, the updated model will be checked to ensure that it results in a lower minimum selling price before it is posted in the wiki.
- When changes are made to the model, the authors of the update will be quoted, along with the reasons for the update and the associated references, in the page describing the part of the model to be updated.

¹Klein-Marcuschamer, Daniel, Turner, Christopher, Allen, Mark, Gray, Peter, Dietzgen, Ralf G., Gresshoff, Peter M., Hankamer, Ben, Heimann, Kirsten, Scott, Paul T., Stephens, Evan, Speight, Robert and Nielsen, Lars K. (2013) Technoeconomic analysis of renewable aviation fuel from microalgae, Pongamia pinnata, and sugarcane. Biofuels, Bioproducts and Biorefining, 7 4: 416-428. doi:10.1002/bbb.1404

1.4 Life Cycle Analysis

LCA on the three routes was developed by Boeing R&T - Australia.

1.4.1 Goal and Scope Definition

1.4.1.1 Goal The intended application of this Life Cycle Assessment (LCA) was to provide information on the environmental impacts of sustainable aviation fuels to the intended audience, who may wish to develop, produce or use sustainable aviation fuel.

This LCA was undertaken to provide comparative environmental data on sustainable aviation fuel that could be sourced from three types of feedstock in Queensland. The results will be used to assist in the decision whether to invest in sustainable aviation fuel plants in this State.

The intended audience for this LCA is:

- Federal Government;
- Queensland Government;
- Investors in biofuels companies;
- Research institutions such as UQ;
- Feedstock growers and producers;
- Organisations that intend to use sustainable aviation fuel, such as Boeing's commercial airline and military customers;
- Non-governmental organisations; and
- The public.

The results of this LCA will be used to compare the environmental impacts of producing sustainable aviation fuel from the following Queensland-based biomass sources:

- Molasses from sugarcane;
- Pongamia pinnata; and
- Autotrophic algae.

1.4.1.2 Scope The scope of the study was 'cradle-to-refinery gate' and included environmental impacts of production of material, and processes from the agricultural growing stage through to jetfuel available at the refinery gate.

The functional unit for the LCA study of each feedstock was the production of 1 tonne of aviation fuel at the refinery gate.

1.4.1.3 Methodology The LCA study was conducted in accordance with International Standards Organisation ISO14040 International Standard for Environmental Management – Life Cycle Assessment – Principles and Framework ².

Simapro Version 7.3.3 was used to create the models and calculate results.

1.4.2 Model Assumptions

This section includes the assumptions for the product flows, what was included and excluded from the system boundaries and why, and also any assumptions on the model construction for both the Allocation and System Expansion modelling methodologies.

According to ISO 14044, the allocation modeling methodology should be avoided, and system expansion used wherever possible in assigning impacts for processes with multiple products.²

ISO 14044 states:

Wherever possible, allocation should be avoided by:

1. Dividing the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these sub-processes; or

2. Expanding the product system to include the additional functions related to the co-products, taking into account the requirements of the system boundary.

Where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way that reflects the underlying physical

² ISO14040:2006: International Standard for Environmental Management - Life Cycle Assessment - Principles and Framework. International Standards Organisation, 2006

relationships between them; i.e. they should reflect the way in which the inputs and outputs are changed by quantitative changes in the products or functions delivered by the system.

Since both system expansion and allocation could be considered appropriate for these models, both were applied to consider the influence that either method has on the results.

1.4.2.1 Allocation

1.4.2.1.1 Sugar and Molasses Economic allocation was used to divide the impacts of the sugar mill process between the determining product, raw sugar, and its co-product, molasses. Bagasse has a calorific and market value, however bagasse combustion was considered to be a waste treatment process, with electricity and heat produced as outputs from the waste treatment process that are utilised internal to the production process. Therefore the impacts from the combustion process were assigned to the sugar mill and will flow through to the jetfuel process via the molasses, which will also have some of the impact of the cane growing and sugar milling assigned to it. Since the bagasse combustion is the most desirable form of waste disposal, surplus electricity and steam from combustion were not considered to be co-products of the sugar mill and therefore had no impacts assigned for allocation. The electricity and heat from bagasse combustion are used in the sugar mill and downstream jetfuel processes where available. The sugar mill does not require additional input of fossil-fuel energy, however electricity from coal and heat from natural gas are used to make up the remaining energy requirements for the jetfuel process.

The fermentation and hydrocracking processes produced jetfuel, diesel, naphtha and light gases. Jetfuel was the determining product of this process while diesel and naphtha were assigned impacts as co-products. The light gases were fully consumed within the sugar mill and fermentation process boilers for the purpose of heat generation, so were not considered to be co-products of the jetfuel production process.

See figure 1 for the baseline allocation model.

Variation Case

For the feed variation model, the yeast waste product from the fermentation process is no longer considered a by-product of the jetfuel refining process but rather a co-product and sold as an animal feed supplement.

Product	Baseline % Variation %		References				
Sugar Mill							
Raw Sugar 64.93 64.93 ³							
Molasses	35.07	35.07	4				
	Jetfuel	Refinery					
Jetfuel	Jetfuel 47.17 41.81 ⁵						
Naphtha	40.75	36.12	6				
Diesel	12.08	10.71	7				
Yeast Feed	-	11.36	8				

See figure 2 for the variation allocation model.

 Table 1: Economic Allocation Percentages - Sugarcane and Molasses

 $^{^{3}\}mathrm{Australian}$ Bureau of Agricultural and Resource Economics and Sciences

⁴Personal communication with Sucrogen Ltd

 $^{^5 \}mathrm{International}$ Air Transport Association (IATA) Jet Fuel Price Monitor

 $^{^{6}}$ Recochem

⁷Australian Institute of Petroleum

⁸Index Mundi

1.4.2.1.2 Algae The algal oil was considered to be the determining product, with phospholipids the co-product. Impacts from the growing and processing phases were allocated to each of these products. Digestion of the algae waste product was assumed to be the preferred method of disposal. Therefore, since combustion of the resulting methane biogas into electricity and steam were bonus side-effects of the waste disposal process, they were not considered to be products of the oil mill and were not assigned an economic allocation. All combustion impacts were assigned to the oil processing plant.

The UOP and hydrocracking refining process produced jetfuel as the determining product, with diesel and naphtha as co-products. Impacts were assigned between these 3 products using economic allocation. Light gases were also produced however were fully consumed within the algae oil and UOP processes, therefore were not considered to be co-products of the jetfuel production process nor had impacts assigned through allocation.

See figure 3 for the baseline allocation model.

Variation Case

The algal phosopholipids and algae waste are combined to form algae meal which is a co-product of the raw oil extraction process and sold as an animal feed supplement. The algal oil is the determining product with algae meal as a co-product.

All electricity and steam requirements are fulfilled by electricity from the grid and steam from natural gas.

See figure 4 for the variation allocation model.

Product	Baseline %	$\texttt{Baseline \%} \mid \texttt{Variation \%}$					
Algae Pond Facility							
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $							
	Jetfuel Refinery						
Jetfuel Naphtha Diesel	47.19 40.77 12.04	$\begin{array}{c} 47.19 \\ 40.77 \\ 12.04 \end{array}$	5 6 7				

Table 2: Economic Allocation Percentages - Algae

 $^{^9\}rm Personal$ communication with Professor M. Borowitzka, Murdoch University $^{10}\rm hrefhttp://www.icis.com/chemicals/channel-info-chemicals-a-z/ICIS$

1.4.2.1.3 Pongamia Similarly to algae, phospholipids were considered to be a co-product of the pongamia oil production process, with pongamia oil the determining product. Impacts from the growing and oil production phases were allocated between these two products on an economic basis. Since the preferred method for disposing of pongamia hulls and meal is as an animal feedstock and not anaerobic digestion, it was assumed that the digestion/combustion processes were undertaken solely for the purposes of electricity and steam production. Therefore this process was not considered as a waste disposal method, but rather a service process in which steam and electricity were considered co-products of the pongamia oil production process. Economic allocation was used to assign impacts to each of these products, which then flowed through to the jetfuel process.

The UOP and hydrocracking refining process produced jetfuel as the determining product, with diesel and naphtha as co-products. Impacts were assigned between these 3 products using economic allocation. Light gases were also produced however were fully consumed within the pongamia oil and UOP processes, therefore were not considered to be co-products of the jetfuel production process nor had impacts assigned through allocation.

See figure 5 for the baseline allocation model.

Variation Case

The pongamia hulls and meals are combined to form a pongamia meal which is a co-product of the raw oil extraction process and is sold as an animal feed supplement. The pongamia oil is the determining product of this process, with pongamia meal as a co-product.

All electricity and steam requirements are fulfilled by electricity from the grid and steam from natural gas.

Product	Baseline %	Variation %	References				
Seed Processing Facility							
Pongamia Oil	98.89	78.08	11				
Phospholipids	0.81	-	10				
Pongamia Meal	-	21.92	8				
Electricity from Cogeneration	0.08	-	12				
Steam from Cogeneration	0.22	-	13				
Jetfuel Refinery							
Jetfuel	47.19	47.19	5				
Naphtha	40.77	40.77	6				
Diesel	12.04	12.04	7				

See figure 6 for the variation allocation model.

Table 3: Economic Allocation Percentages - Pongamia

¹¹Murphy, H et al. A Common View of the Opportunities, Challenges, and Research Actions for Pongamia in Australia. BioEnergy Research, 1-23, 2012

 $^{^{12}{\}rm hrefhttp://www.aemo.com.au/Australian Energy Market Operator$

 $^{^{13}}$ Lavarack, B et al. Prioritising Options to Reduce the Process Steam Consumption of Raw Sugar Mills. Proceedings of the International Society of Sugar Cane Technologists, XXV Congress, 2005



Figure 1: An allocation diagram for the baseline sugarcane model.



Figure 3: An allocation diagram for the baseline algae model.



Figure 5: An allocation diagram for the baseline pongamia model.



Figure 2: An allocation diagram for the variation sugarcane model.



Figure 4: An allocation diagram for the variation algae model.



Figure 6: An allocation diagram for the variation pongamia model.

1.4.2.2 System Expansion

1.4.2.2.1 Sugar and Molasses Bagasse has value as a fuel and a market value, however since it is disposed of via combustion in the cogeneration process; it was treated as a byproduct of raw sugar rather than a co-product. The electricity and steam generated from the combustion process were assumed to be outputs from the waste disposal process that are utilised internal to the production process, hence were not considered co-products of the raw sugar mill. Molasses has value as an animal feed and a market value and displaces the production of sorghum when used as an animal feed. Based on the calorific value of both molasses¹⁴ and sorghum¹⁵, the substitution factor was assumed to be 0.856 kg sorghum/kg molasses.

Wastewater from the raw sugar mill was assumed to be discharged to the nearby river. Mill mud and bagasse combustion ash were applied back to the cane field, and were also considered to be byproducts, since they did not displace any fertiliser application. The yeast slurry produced as a result of the fermentation process was applied back to the cane field as a biomulch. While it had a small nutritional content, it was not assumed to displace any fertiliser application and had little economic value, hence was considered to be a byproduct rather than a co-product.

See figure 7 for the baseline system expansion model.

Variation Case

The yeast slurry produced as a result of the fermentation process is no longer a by-product used as a biomulch in the sugarcane field. The yeast slurry is a co-product of the jetfuel refining process and is assumed to avoid the production of soybean meal which competes with a group of co-products and a baseline protein product, lupins, when applied as animal feed. Based on the protein content of the three products, the substitution factors were estimated to be 1.218 kg lupins/kg soybean meal and 0.616 kg soybean meal/kg yeast feed¹⁶. This gives a substitution factor of 0.75 kg lupins/kg yeast feed.

Excess electricity and steam from the bagasse cogeneration system are assumed to displace electricity from black coal and steam from natural gas with a substitution factor of 1:1.

See figure 8 for the variation system expansion model.

1.4.2.2.2 Algae Phospholipids were considered to be the co-product of algal oil production, and were assumed to displace the production of lupins to be used in the production of lecithin, a natural food additive. Based on the calorific values of both lupins and phospholipids¹⁵, the substitution factor was 0.905 kg lupins/kg phospholipid.

Electricity and steam were not considered to be co-products of the oil production process, rather as outputs from the algae waste disposal process that are utilised internal to the production process.

See figure 9 for the baseline system expansion model.

Variation Case

Algae meal is considered to be the co-product of algal oil production and is assumed to avoid the production of soybean meal which competes with a group of co-products and a baseline protein and energy product, lupins, when applied as animal feed. Based on the protein content of the three products, the substitution factors were estimated to be 1.218 kg lupins/kg soybean meal and 0.616 kg soybean meal/kg algae meal ¹⁶ ¹⁷. This gives a substitution factor of 0.75 kg lupins/kg algae meal. The digestion and cogeneration system is not included in the variation model and therefore there is no surplus electricity or steam.

See figure 10 for the variation system expansion model.

¹⁴Renouf M et al, Life Cycle Assessment of Australian Sugarcane Products with a Focus on Cane Processing. The International Journal of Life Cycle Assessment, 16, 125-137, 2010

¹⁵National Nutrient Database

 $^{^{16}{\}rm Frank},$ E D et al. Life Cycle Analysis of Algal Lipid Fuels with the GREET Model. Argonne National Laboratory, 2011

¹⁷Stephens, E et al. An Economic and Technical Evaluation of Microalgal Biofuels. Nature Biotechnology, 28, 126-128, 2010

1.4.2.2.3 Pongamia All pongamia pods from the on-farm depodding process were assumed to be spread back on the farm as a form of biomulch and weed control. Although the shells contain a small amount of nutrients, they did not displace any fertiliser use so were therefore considered a byproduct, rather than co-product.

Phospholipids were considered to be the co-product of pongamia oil production, and were assumed to displace the production of lupins to be used in the production of lecithin, a natural food additive. Based on the calorific values of both lupins and phospholipids¹⁵, the substitution factor was 0.905 kg lupins/kg phospholipid.

Electricity and steam were considered to be products arising from the purposeful combustion of the pongamia hull and meal biogas rather than co-products of the oil production process. Electricity and steam from the combustion process were assumed to displace electricity from coal and steam from natural gas, with a substitution factor of 1.

See figure 11 for the baseline system expansion model.

Variation Case

Pongamia meal is considered to be the co-product of pongamia oil production, and is assumed to avoid the production of soybean meal which competes with a group of co-products and a baseline protein and energy product, lupins, when applied as animal feed. Based on the protein content of the three products, the substitution factors were estimated to be: 1.218 kg lupins/kg soybean meal and 0.616 kg soybean meal/kg pongamia meal¹⁶ ¹⁷. This gives a substitution factor of 0.75 kg lupins/kg pongamia meal.

The digestion and cogeneration system is not included in the variation model and therefore there is no surplus electricity or steam.

See figure 12 for the variation system expansion model.

Jetfuel

Diesel and naphtha were the co-products of the jetfuel refining process for all 3 feedstocks, and were assumed to displace the production of diesel and naphtha from fossil fuels with a substitution factor of 1. Light gases were also produced during the refining process, however were fully combusted within the system.



Figure 7: An system expansion diagram for the baseline sugarcane model.



Figure 9: An system expansion diagram for the baseline algae model.



Figure 11: An system expansion diagram for the baseline pongamia model.



Figure 8: An system expansion diagram for the variation sugarcane model.



Figure 10: An system expansion diagram for the variation algae model.



Figure 12: An system expansion diagram for the variation pongamia model.

1.4.3 Life Cycle Inventory

The Life Cycle Inventory includes detail regarding the data used to construct the models; that is the data values, sources, pedigrees and any assumptions significant to the models.

1.4.3.1 Data Sources

1.4.3.1.1 Sugarcane LCA Data The data sources listed below are applicable for both the baseline and variation models unless specified otherwise.

Sugarcane in the Field

Agricultural Process Data - per tonne of cane delivered to the mill

Product	Data	Units	Variance	Reference
Sugarcane Yield	85	t/ha	1.21	18
Urea	3.7	kg	1.21	18
Diammonium Phosphate	1.2	kg	1.21	18
Potassium Chloride	1.3	kg	1.21	18
Ammonium Sulphate	0.5	kg	1.21	18
Lime	2.1	kg	1.21	18
Active Pesticide	24.8	g	1.21	18
Water for irrigation	37.2	kL	1.21	18
Electricity	8.1	kWh	1.21	18

 Table 4: Field Inputs

Product	Data	Units	Variance	Reference
Shipping	60.1	tkm	2.06	18
Articulated Truck	3.0	tkm	2.06	18
Rigid Truck	0.1	tkm	2.06	18
Production of farm inputs	0.02	kg	3.08	18

 Table 5: Transport - Farm Inputs

Product	Data	Units	Variance	Reference
Tractor Use	87.9	MJ	1.21	18
Tractor Production	0.08	kg	3.08	18
Shed Production	0.0003	m2	3.08	18
Trailer Production	0.02	kg	3.08	18

Table 6: Capital Goods

Product	Data	Units	Variance	Reference
Harvester Use	54	MJ	1.21	18
Harvester Production	0.02	kg	3.08	18
Rail Transport	17.5	$^{\mathrm{tkm}}$	2.05	18
Road Transport	4.6	$^{\mathrm{tkm}}$	2.05	18

Table 7: Harvesting and Transport

 $^{^{18}}$ Renouf M et al, Life Cycle Assessment of Australian Sugarcane Production with a Focus on Sugarcane Growing. The International Journal of Life Cycle Assessment, 15, 927-937, 2010

Product	Data	Units	Variance	Reference
Nitrous Oxide - Direct	39.29	g	1.86	19
Nitrous Oxide - Indirect	3.14	g	1.86	19
Carbon Dioxide from Liming	0.924	$_{\rm kg}$	1.86	20
Ammonia from Urea Volatilisation	0.10	$_{\rm kg}$	1.7	18
Nitrate via Leaching	7.73	g	1.94	19

Fal	ble	8:	Field	Emissions	-	Emissions	to	Air
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Product	Data	Units	Variance	Reference
Phosphorous via runoff Pesticides via runoff COD via runoff	$25.6 \\ 0.372 \\ 4.3$	g g kg	$1.69 \\ 1.69 \\ 1.69$	18 18 18

Table 5. Field Linissions - Linissions to Wate	Table 9. Field Emissions - Emissions to Wa
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Product	Data	Units	Variance	Reference
Methane	89.6	g	1.67	19
Nitrous Oxide	5.73	g	1.67	19
Nitrogen Oxides	331.2	g	1.67	19
Carbon Monoxide	3.494	kg	5.16	19
NMVOC	203.8	g	1.67	19

Table 10: Field Emissions - Burnt Cane Harvesting

Raw Sugar Mill Milling Process Data - per 100 tonne of cane delivered to mill

Product	Data	Units	Variance	Reference
Milk of Lime	679	kg	1.22	21
Phosphorous Pentoxide	45	kg	1.22	21
Lubricants	0.5	kg	1.32	14
Gross Electricity	5.86	MWh	1.22	21
Gross Steam	43.33	\mathbf{t}	1.22	21
Imbibition Water	42.0	\mathbf{t}	1.22	21
Wash Water	3.51	\mathbf{t}	1.22	21

Table 11: Milling Inputs

Product	Data	Units	Variance	Reference		
Wastewater	51.03	t	-	21		
COD	23.0	kg	1.57	14		
Mill mud transportation	12.56	tkm	2.05	14		
Mill mud	1.26	\mathbf{t}	-	14		
Table 12: Waste Products						

¹⁹National Inventory Report, Volume 1. Department of Climate Change and Energy Efficiency, Australian

Government, 2009 ²⁰National Greenhouse Account Factors. Department of Climate Change and Energy Efficiency, Australian Government, 2011 ²¹Derived from UQ (AIBN) Mass and Energy Balance Process Flows, 2013

Bagasse Combustion - per tonne of bagasse

Product	Data	\mathbf{Units}	Variance	Reference
Bagasse	6.83	GJ	1.24	21

Product	Data	Units	Variance	Reference
Carbon Dioxide Biogenic	849.55	kg	1.09	21
Methane	63.52	g	1.09	19
Nitrogen Oxides	573.72	g	1.51	19
Dinitrogen Monoxide	28.0	g	1.51	19
Carbon Monoxide	11.10	kg	5.01	19
Sulfur Dioxide	250	g	1.07	22
Particulates $(<10 \text{um})$	220	g	2.0	22
PAH	0.5	g	3.0	22
NMVOC	111.33	g	1.51	19
Ash	227	kgkm	2.01	14
Transport of Ash	22.7	kg	-	14

Table 13: Combustion Inputs

Table 14: Combustion Emissions

Jetfuel Refinery Jetfuel Refining Process Data - per tonne of molasses

Product	Data	Units	Variance	Reference
Cooling Water	895.72	kg	1.21	21
Wash Water	35.99	kg	1.21	21
DAP	1.50	kg	1.21	21
Ammonium Hydroxide	24.33	kg	1.21	21
Sodium Hydroxide	2.78	kg	1.21	21
Sodium Chloride	23.48	kg	1.21	21
Hydrogen	10.20	kg	1.21	21
Tergitol	1.71	kg	1.21	21
Gross Electricity	12.12	kWh	1.16	21
Gross Steam	0.255	kg	1.16	21

Table 15: Refining Inputs

Product	Baseline Data	Variation Data	Units	Variance	Reference
Yeast Transport	0.86	100	tkm	1.16	14
Wastewater	658.68	658.68	kg	1.16	21
Carbon Dioxide Biogenic	553.53	553.53	kg	1.16	21

Table 16: Refining Outputs - Baseline

²²National Pollutant Inventory: Emission Estimation Technique Manual for Combustion in Boilers, Version 3.6. Department of Sustainability, Environment, Water, Population and Communities, Australian Government, 2011

Product	Data	Units	Variance	Reference
Wastewater	658.68	kg	1.16	21
Carbon Dioxide Biogenic	553.53	kg	1.16	21

Table 17: Refining Outputs - Variation

Sugarcane Yield Data

Product	Baseline Data	Variation Data	Units	Reference				
		In the field						
Sugarcane	18							
Sugar Mill								
Raw Sugar 6.27 6.27 t/100t cane								
Molasses	14.68	14.68	t/100t cane	21				
Bagasse	30.97	30.97	t/100t cane	21				
Bagasse Combustion								
Electricity	234.18	234.18	kWh/t bagasse	21				
Steam	1.43	1.43	t/t bagasse	21				
Jetfuel Refining								
Jetfuel	53.45	53.45	kg/t molasses	21				
Naphtha	28.85	28.85	kg/t molasses	21				
Diesel	8.07	8.07	kg/t molasses	21				
Light Gases	0.8544	0.8544	GJ/t molasses	21				
Yeast Feed	86.4	34.04	$\rm kg/t~molasses$	21				

Table 18: Sugarcane Yield Data

1.4.3.1.2 Algae LCA Data Data sources for each process are listed below. Data can be assumed to be for both the baseline and variation models unless specified otherwise.

Algae at the Pond Agricultural Process Data - per tonne of algae slurry

Product	Baseline Data	Variation Data	Units	Variance	Reference
Seawater	1.22	7.56	m3	1.27	21
Groundwater	14.7	14.7	\mathbf{t}	1.27	21
Gross electricity	90.09	90.09	kWh	1.29	21
Flue Gas	2291	2291	kg	1.59	21
Cooling Water	65.75	10.26	kg	1.27	21
Diammonium Phosophate	0.79	7.9	kg	1.27	21
Sodium Nitrate	12.5	125.03	kg	1.27	21
Vehicle Use	0.0036	0.0036	$\rm km$	2.11	23

Table 19: Pond Inputs

Product	Data	Units	Variance	Reference
Pond Production	0.0005	ha	3.15	24 25
Tractor Production	0.000151	kg	3.11	23
Harvester Production	0.106	kg	3.11	$26\ 21$
Shed Production	0.000005	m2	3.11	23

Table 20: Production of Capital Goods

Emissions to Air							
Product	Baseline Data	Variation Data	\mathbf{Units}	Variance	Reference		
Nitrous Oxides	1.68	16.84	g	1.58	19 16		

Table 21: Pond Emissions

Algae Oil Process Data - per tonne of algae slurry

Product	Baseline Data	Variation Data	Units	Variance	Reference
Cooling Water	0.560	0.560	kg	1.54	21
Wash Water	0.57	0.57	kg	1.54	21
Hexane	0.70	0.70	kg	1.25	21
Citric Acid	0.17	0.17	kg	1.54	21
Gross Electricity	3.24	3.24	kWh	1.81	21
Gross Steam	0.122	0.089	t	1.81	21
Transport of algae meal	0.0	100	tkm	2.06	21

Table 22: Algal Oil Inputs

 $^{24} Benemann \ J \ et \ al, \ Technology \ Roadmap \ for \ Biofixation \ of \ CO2 \ and \ Greehouse \ Gas \ Abatement \ with \ Microalgae.$ Second Annual Conference on Carbon Sequestration, 2003 ²⁵Weissman J C and Goebel R P, Design and Analysis of Microalgal Open Pond Systems for the Purpose of

 $^{^{23}\}mathrm{Ecoinvent}$ Database. Swiss Centre for Life Cycle Inventories, 2010

Producing Fuels: A Subcontract Report. Solar Energy Research Institute, 1987

²⁶Collet P et al, Life Cycle Assessment of Microalgae Culture Coupled to Biogas Production. Bioresource Technology 102, 207-214, 2011

Product	Baseline Data	Variation Data	Units	Variance	Reference
Hexane	0.01	0.01	kg	2.07	21
Waste purge to digestor	0.94	0.0	t	1.54	21
Wastewater	0.0	6.24	m3	1.54	21

Table 23: Algal Oil Emissions

Biodigestor Data - per tonne of waste input

Product	Baseline Data	Variation Data	\mathbf{Units}	Variance	Reference
Gross electricity	0.306	0.0	kWh	-	21
Wastewater	99.24	0.0	kg	1.54	21

Table 24: Algae Digestor

Algal Jetfuel Algal Jetfuel Data - per tonne of algal oil

Product	Data	Units	Variance	Reference
Cooling Water	683.39	kg	1.24	21
Process Water	101.19	kg	1.56	21
Hydrogen	157.86	kg	1.27	21
Gross Electricity	953	kWh	1.81	21
Gross Steam	0.591	\mathbf{t}	1.81	21

Table 25: Jetfuel Refinery

Product	Data	\mathbf{Units}	Variance	Reference		
Biogenic Carbon Dioxide	71.82	kg	1.6	21		
Table 26: Refinery Emissions						

Algae Yield Data

Product	Baseline Data	Variation Data	Units	Reference			
At the Pond							
Algae Slurry Yield	66	66	t/ha/yr	21			
	Alga	al Oil Processing					
Algal Oil	44.18	44.18	kg/t algae slurry	21			
Phospholipids	13.61	0.0	kg/t algae slurry	21			
Algae Meal	0.0	318.8	kg/t algae slurry	21			
Biogas Combustion							
Biogas	68.2	0.0	m3/t algae slurry	21			
Electricity	1.26	0.0	kWh/m3 biogas	21			
Steam	2.18	0.0	kg/m3 biogas	21			
Jetfuel Refining							
Jetfuel	467.44	467.44	kg/t algal oil	21			
Naphtha	252.3	252.3	kg/t algal oil	21			
Diesel	70.29	70.29	$\rm kg/t$ algal oil	21			
Light Gases	7.48	7.48	GJ/t algal oil	21			

Table 27: Algae Yield Data

1.4.3.1.3 Pongamia LCA Data Data sources for the Pongamia model are listed below. Data can be assumed to apply to both the baseline and variation case unless specified otherwise.

Pongamia in the Field Agricultural Process Data - per tonne of seed

Product	Data	Units	Variance	Reference
Pesticides	1.0	kg	1.54	27
Herbicides	0.114	kg	1.54	27
Gross electricity	67.81	kWh	1.27	27
N Fertiliser	0.22	kg	1.54	27
P Fertiliser	0.13	kg	1.54	27
K Fertiliser	0.13	kg	1.54	27
S Fertiliser	0.013	kg	1.54	27
Water	$66,\!667$	kg	1.54	27
Transport	100	tkm	2.06	27

Tal	ole	28:	Field	Inputs
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Product	Data	Units	Variance	Reference
Tractor Use	0.27	km	1.58	27
Tractor and Trailer Production	0.007	kg	3.29	23
Harvester Use	643.3	MJ	1.58	27 28
Harvester Production	0.007	kg	3.29	23
Depodder Use	5.0	kWh	1.61	21 27
Depodder Production	0.0051	kg	3.3	23
Shed Production	0.00044	m2	3.29	27 23

Table 29: Capital Goods

	Nitrous	Oxides		
Product	Data	Units	Variance	Reference
Fertiliser Application	0.465	g	1.76	19
Biological Fixation	656.23	g	1.76	19
Atmospheric Deposition	3.49	g	1.76	19

Table 30: Field Emissions to Air

Pongamia Oil Process Data - per tonne of seed

Product	Baseline Data	Variation Data	Units	Variance	Reference
Degumming Water	3.04	3.04	kg	1.54	21
Cooling Water	50.9	50.9	kg	1.54	21
Hexane	1.95	1.95	kg	1.54	21
Citric Acid	0.455	0.455	kg	1.56	21
Gross Electricity	69.24	69.24	kWh	1.54	21
Gross Steam	0.752	0.749	t	1.54	21

 Table 31: Process Inputs

 $^{27}\mathrm{Personal}$ communication with Peter Gresshoff and Paul Scott, March 2012

²⁸BioEnergy Plantations Australia

Product	Baseline Data	Variation Data	\mathbf{Units}	Variance	Reference
Hexane	2.17	2.17	$_{\rm kg}$	2.26	21
Waste purge to digestor	508.8	0.0	kg	1.54	21

Table 32: Emissions to Air

Pongamia Digestor Process Data - per tonne of meal input

Product	Data	Units	Variance	Reference
Gross Electricity	8.09	kWh	-	21
Water	31.56	t	1.53	21

 Table 33: Process Inputs

Product	Data	Units	Variance	Reference
Wastewater	32.33	\mathbf{t}	1.54	21
	Table	24. Weat	Qutputa	

 Table 34: Waste Outputs

Pongamia Jetfuel Refinery Refinery Data - per tonne of seed oil

Product	Data	\mathbf{Units}	Variance	Reference
Cooling Water	701.46	kg	1.27	21
Process Water	118.42	kg	1.56	21
Hydrogen	166.05	kg	1.27	21
Gross Electricity	968.86	kWh	1.81	21
Gross Steam	0.608	t	1.81	21

Table 35: Process Inputs

Product	Data	Units	Variance	Reference
Biogenic Carbon Dioxide	65.91	kg	1.6	21
Table 36: Emissions to Air				

Table 36: Emissions to Air

Pongamia

Yield

Product	Baseline Data	Variation Data	Units	Reference
		In the field		
Pongamia Seed Yield	18	18	t/ha/yr	29
	Pongar	nia Oil Processing	r 5	
Pongamia Oil	286.89	286.89	kg/t seed	21
Phospholipids	22.32	0.0	kg/t seed	21
Pongamia Meal	0.0	531.15	kg/t seed	21
	Biog	gas Combustion		
Biogas	150.6	0.0	m3/t seed	21
Electricity	0.67	0.0	kWh/m3 biogas	21
Steam	6.74	0.0	$\rm kg/m3~biogas$	21
Jetfuel Refining				
Jetfuel	480.31	480.31	kg/t pongamia oil	21
Naphtha	259.25	259.25	kg/t pongamia oil	21
Diesel	72.23	72.23	kg/t pongamia oil	21
Light Gases	7.69	7.69	$\mathrm{GJ/t}$ pongamia oil	21

Table 37: Algae Yield Data

²⁹Jensen et al. Legumes for Mitigation of Climate Change and the Provision of Feedstock for Biofuels and Biorefineries: A Review. Agronomy for Sustainable Development, 2011

Product	Data	Units	Variance	Reference
Nitrous Oxides	0.83	g	1.84	20
Biogenic Carbon Dioxide	1.77	kg	1.58	21

1.4.3.1.4 Common Process Data Digestor Combustion Emissions

Table 38: Emissions to Air - per m3 of biogas

Light Gas Combustion Emissions

Product	Data	Units	Variance	Reference
Methane	35.91	g	1.84	19
Dinitrogen Monoxide	30.26	g	1.84	19
Carbon Monoxide	2.72	g	5.33	19
Nitrous Oxides	19.36	g	1.84	19
Particulates $(<10 \text{um})$	18.49	g	2.29	22
PAHs	5.30	g	3.29	22
NMVOC	40.35	g	1.84	19
Sulfur Dioxide	116.0	g	1.58	19
Biogenic Carbon Dioxide	0.88	t	1.56	20

Table 39: Emissions to Air - per tonne of gas

1.4.3.2 Data Assumptions

1.4.3.2.1 Foreground Data Foreground data includes all feedstock specific processes such as agricultural, biomass and jetfuel refining process data as well as field and combustion emissions calculations.

The foreground data assumptions for each of the feedstocks are listed below.

Product	Assumption
Farming fertilisers	Fertilisers are bought locally
Active pesticides	Produced and bought locally
Water for irrigation	A range of water sources such as river, bore, scheme channel/pipe and dam
-	are used in the QLD region for sugarcane irrigation. Assume that bore
	water is used for all irrigation since the model characterisation factors are
	equal across all water sources
Field emissions	Based on IPCC Tier 1 and 2 methodology, with default fraction and emis-
Burnt cane harvesting	sion factors Assume 26.3%. Based on Queensland specific value from 2009 from the
Durnt concerningions	National Inventory Report 2009
Burnt cane emissions	only emissions from the current National inventory Report have been
	from the model as they are not listed in the surrent literature as contribut
	ing to burnt cano omissions
Molasses vield	A-grade molasses is assumed to be the co-product output of the milling
inorassos yrora	process
Sorghum Production	Based on Australian specific process data for cultivation of irrigated sweet
<u> </u>	sorghum grains in NSW
Mill Lubricants	Based on Swiss econvent data for generic lubricants
Transport of mill mud	The mill is assumed to be 10km from the cane field
Mill mud	Mill mud is assumed to be a byproduct of the sugar milling process and
	is applied back to the field
Bagasse ash	Bagasse combustion ash is assumed to be a byproduct of the combustion
	process and is applied back to the field
Bagasse boller	Boller assumed to have a wet scrubber filter
Bagasse boller emissions	Nitrogen oxides and dinitrogen monoxide emission factors are based on a
Vosst for formontation	Yeast input included for completeness however a particular process for
reast for termentation	reast input included for completeness nowever a particular process for yeast production has been excluded from the Simapro model due to the
	regligible contribution this amount makes to the final model result
Sodium Chloride	Based on sodium chloride of natural origin
Phosphorous Pentoxide	Based on solid chemical form from natural origin
Co-location	The mill, refinery, bagasse combustion plant and fermentation plant are
	all co-located. The farm is located next to the existing cane rail and road
	network which is located approximately 10km from the mill and other fa-
	cilities. The water treatment plant is located onsite with the fermentation
	plant.

Table 40: Foreground Data Assumptions - Sugarcane

Product	Assumption
Algae yield	20g/m2day, operating at 330 days per year. Algae slurry contains 30wt%
	algae solids in liquid.
Pond size	10.67ha
Total pond farm	10061ha
Total ponds per farm	943
Pond construction	Assumed to be 20cm deep clay compacted pond in raceway configuration
	with stainless steel paddlewheels
Water use	Ground and seawater are assumed to be pumped to the ponds
DAP	Sourced locally
Sodium Nitrate	Based on Swiss econvent data for sodium nitrate from a natural source
Vehicle usage	Assume 2 hours of general tractor/vehicle use per day for general mainte-
	nance activities on the farm, for 2 vehicles
Algae harvesting	Harvesting process includes centrifuge process, which is assumed to be
	equivalent to the Evodos process
Digester input	The biomass residue left as a result of hexane extraction is sent to the
	digester as well as the saline purge from the algae pond
Biogas combustion emis-	Derived from National Pollution Inventory - Combustion in Boilers Man-
sions	ual based on default emission factors for landfill gas boilers. Also assume
	complete chemical combustion of methane with no leakage or flue emis-
Diana and an and a state	sions
Biogas energy content	Assumed to be equal to Mass and Energy Balance derived value
Co-location	The point, processing farm and reintery are co-located. The point is also
	co-located with the coal fired electricity plant and a dedicated pipe is
	used to feed the flue gas from the plant to the algae pond. The anaerobic
	digester and boiler are co-located with the pond and processing farm, as
	well as the onsite wastewater treatment plant for processing the settled
	digester muds

Table 41: Foreground Data Assumptions - Algae

Product	Assumption
Plantation design	Assume the plantation spacing will be approx 4m between trees and 5m
~	between rows. This gives optimum plantation size of 500 trees/ha
Seed definition	The seed is located inside a thick, outer pod. Within the pod, the seed is
Seed Yield	encased in a thin husk 20,000 seeds per tree, 1.8g per seed (not including outer pod). The seed
	yield is 46wt% of the entire seedpod
Growth phases	The pongamia trees are assumed to have an initial growing phase of 5
	years before yielding seeds. The plantation then produces seeds for the
	to the applicable growth phase data to account for the potential zero yield
	in the first 5 years of growth
Fertiliser application	Nitrogen fertiliser can be applied during the initial growing stages and
	some plantations will then have reduced application over life of the trees.
	Fertiliser use is a general estimate for all regions. Some plantations have
	shown to grow without any fertiliser application. Assume Nitrogen fer-
	tiliser is applied for first 5 yrs of growing stage then not required thereafter
	for the last 25 years of the plantation
Pesticide application	Regional estimate used for amount of pesticide since areas with higher
Harbieida	rainfall will most likely require more pesticides than those with low rainfall Harbicide will be used as required during the life of the plantation. It
Herbicide	is assumed that for the first 10 years of the life cycle, herbicide will be
	applied twice a year. For the last 20 years of the life of the plantation
	the herbicide will only be required once a year due to the larger tree
	size and seedpod mulch both providing extra cover to limit weed growth.
	The amount of herbicide required is based on a generic product such as
	roundup
Tractor use	Assume tractor is required to be used on average twice a year for gen-
	eral maintenance of the plantation, including application of herbicides,
XX7- +	pesticides and fertiliser, and pruning activities
water use	Crops located in tropical areas will have sufficient rainfail that no irrigation
	system is required. Crops located in more and rand areas will assume the
	Energy trials at Spring Gully At farms where the average annual rainfall
	is not sufficient, a drip irrigation system will be required
Harvester use	Harvesting equipment is assumed to be a small modified tractor with an
	umbrella shaker, harvesting at rate of 2 trees per minute
Depodder use	Assume depodding equipment similar to that of peanut shelling machine,
	for example 6BH-880C. The depodding equipment is located on the farm,
Pod disposal	and the seeds are transported by truck to the drying and crushing mill Assume pode are spread back on field as biomulch
Digestor input	The seed meal which is leftover after the pressing process is sent to the
Digestor input	digester and combined with the seed husks
Biogas combustion emis-	Partially derived from National Pollution Inventory - Combustion in Boil-
sions	ers Manual based on default emission factors for landfill gas boilers. Also
	assume complete chemical combustion of methane with no leakage or flue
Diama anone contant	emissions
Colocation	Assumed to be equal to Mass and Energy Balance derived value
CO-IOCATION	farm and depending area is located within 100 200km of the good process
	ing plant and transport occurs via road
	I IIIS Plant, and transport occurs via toad

Table 42: Foreground Data Assumptions - Pongamia

1.4.3.2.2 Background Data Background data includes all other higher level data such as capital goods production, fertiliser and pesticide production, and electricity, steam and fuel production data.

Background data assumptions for all feedstocks can be found below.

Product	Assumption
Electricity	Queensland specific electricity mix predominantly from black and brown
Steam	coal Australian specific steam from natural gas
Farming Capital Goods	Based on Swiss econvent data for production of generic farming equip-
Production	ment, including tractors, trailers, general tillage equipment, harvesters,
	algae pond and sheds. Data has been modified to suit Australian pro-
	cesses wherever possible
Truck transportation	Australian specific 28 tonne load on 30 tonne truck, with 90% rural oper-
Tractor Use	ation Australian tailored data for tractor engine use in low population area
Cane rail track produc-	Australian specific process developed for the production of the cane rail
tion	tracks, based on major materials used
Wash water	Wash water for the milling and refining processes is assumed to be Queens-
	land specific tap water
Hydrogen	SMR Hydrogen is assumed to be equivalent to Australian specific hydrogen
m :/ 1	from natural gas
Tergitol	Based on Swiss econvent process for generic surfactant production
Citric Acid	Based on Global econvent process for generic organic chemicals
Hexane	Based on Australian specific process for hexane production
Wastewater treatment	Wastewater treatment plant assumed to be onsite. Based on existing
T. 1, 1, .	Brisbane specific three stage treatment plant
Light gas combustion	100% of the light gases produced by the jettuel refining process are com-
	busted back in boilers within the system. Only combustion emissions are
Light gas combustion	recorded in the model Derived from National Inventory Report and Pollution Inventory – Com-
emissions	bustion in Boilers Manual. Emission factors based on default factors for
	refinery gas
Cooling water	Cooling water is a utilities use and not a continual water source, therefore
	this is a one-off amount which has been amortized over the life of the
	process. Cooling water is assumed to be from a natural origin

Table 43: Background data assumptions

1.4.4 Life Cycle Impact Assessment

1.4.4.1 Impact Categories The impact categories used in this study are detailed below.

Impact Categories:		
Global Warming	100 year greenhouse impacts based on 2009 data	kg CO2-eq
Potential	CMI Model average nutrients released into metamore which	Irg DO4 og
Eutrophication	cimulate further plant growth	kg r 04-eq
Land Use Zero weighting land use		Ha_a
Water Use Zero weighting water use		m3
Cumulative Energy Total energy flows based on lower heating value		MJ LHV
Demand Human Toxicity Australian toxicity impact assessment method developed by		DALY
	Lundie et Al 2008, that considers both carcinogenic and non-	
Ecotoxicity	Australian toxicity impact assessment method developed by	DAY
	Lundie et Al 2008, that considers aquatic, freshwater and ter-	
	restrial impacts	

Table 44: Impact Categories

The Global Warming Potential category provides weighted characterization factors for each substance that contributes to greenhouse impacts. Biogenic carbon dioxide has a characterisation factor of 0 to exclude any carbon that is released during the natural uptake and release cycle of agricultural processes. All natural carbon dioxide sinks have also been excluded from this category.

Land and Water Use both utilize zero weighting, where a characterization factor of 1 is applied regardless of the source or compartment. Therefore each land and water source has an equal impact on final results.

Solid Waste has been excluded as an impact category since the results will be negligible for this study.

Further details on the impact categories and associated characterisation factors can be found in the Simapro Database V7.3.3.

1.4.4.2 Uncertainty Analysis Uncertainty ranges and pedigree values were assigned to each data value in the models before a Monte Carlo analysis was conducted to determine a 95% confidence interval over 500 iterations. The pedigree system assesses data sources based on six characteristics and each is assigned a quality level from 1 to 5. An uncertainty value is then calculated for the data point based on the quality levels of each characteristic.

The six pedigree characteristics are:

- Reliability
- Completeness
- Temporal Correlation
- Geographical Correlation
- Technological Correlation
- Sample size of collected data.

The process of assigning pedigrees to each datapoint can be subjective and this may influence the results. Further details on the pedigree matrix can be found in the Swiss Ecoinvent Overview and Methodology report.³⁰

 $^{^{30}{\}rm Frischknecht}$ R et al. Overview and Methodology: Eco
invent Report No.1. Swiss Centre for Life Cycle Inventories, Dubendorf, 2004

2 Model Downloads

2.1 SuperPro Designer

These models have been developed in SuperPro Designer and to use the model please follow the following steps:

- 1. Download the SuperPro software. A free demo version can be dowloaded here. If you own a license to the software, feel free to use it. The model runs on version 8.5. For more information about the software requirements or specifications, please contact Intelligen directly.
- 2. Download the relevant flowsheet file (see below).
- 3. Open the SuperPro Software, and then open the file you downloaded in step 2.
- 4. You can explore the data populated in the flowsheet, or can change the parameters and run the model again.
- 5. If you want to UPDATE the model, please follow the instructions found here.

Questions or comments can be directed to Lars Nielsen.

Please note that the models were built in SuperPro Designer v8.5. If errors with other versions occur, please contact INTELLIGEN customer support.

2.2 Sugarcane Fermentation Process Model

These models are updatable, and therefore subject to change. Please ensure you have the latest version of the model.

This model has been divided into two separate models to allow accurate modelling of the different operating bases.

Please note that the Sugarcane Mill Process does not include accurate costing information. This model was an exercise on M&E balances. Please refer to the manuscript 1 for an explanation.

Sugarcane Mill Model Fermentation Model Current Model Version: v2.0

2.3 Algae Based Process Model

These models are updatable, and therefore subject to change. Please ensure you have the latest version of the model.

Algae Model

Current Model Version: v2.0

2.4 Pongamia Based Process Model

These models are updatable, and therefore subject to change. Please ensure you have the latest version of the model.

Pongamia Model

Current Model Version: v2.0

3 Costs

3.1 Materials and Labor

3.1.1 Labor Costs

Labor costs were calculated from the mean weekly earning statistics for factory process workers,³¹ using the Wessel method (Equation 9-7) for estimating process labor requirements.³²

Labor Costs:		
Operator Supervisor	$\begin{array}{c c} 23.42 \ \$/hr \\ 46.84 \ \$/hr \end{array}$	31 32 31 32
Table 45: Labor Costs		

3.1.2 Material & Utility Costs

Feedstock, nutrient and utilities were costed using a combination of industry quotes and published cost history.

Feedstock Costs:		
Pongamia Seeds	590 /MT	33
A-Molasses	$190 \ M T$	34
Utility Costs:		
Electricity	$10 \mathrm{~c/kWh}$	
Cooling Water	$0.05 \ \text{MT}$	
Process Steam	$12 \ \text{MT}$	35
Feed Nutrients:		
Ammonium Hydroxide	$229.41 \ \text{MT}$	36
Diammonium Phosphate	$703 \ \mathrm{MT}$	36
Nitrate	$500 \ MT$	
Processing Chemicals:		
Hydrogen	$1.014 \ \text{/kg}$	37
Industrial Hexane	$2 \$ kg	

Table 46: Material & Utility Costs

³⁶ CRU News, Fertilizer Week Article.

 $^{^{31}{\}rm Employee}$ Earnings, Benefits and Trade Union Membership. Canberra (ACT): Australian Bureau of Statistics 6310.0: 2011

³²Perry RH and Green DW, Perry's Chemical Engineers' Handbook. McGraw-Hill New York, 2008

³³Gresshoff PM. unpublished results. 2012

 $^{^{34}\}mathrm{Lavarack}$ BP. personal communication. 2012

³⁵Patel M, Crank M, Dornburg V, Hermann B, Roes L, Husing B, et al., Medium and Long-term Oppurtunites and Risks of the Biotechnological Production of Bulk Chemicals from Renewable Resources (BREW). Utrecht (NL): Utrecht University: (2006).

³⁷Molburg JC and Doctor RD. Hydrogen from Steam-Methane Reforming with CO2 Capture. 20th Annual International Pittsuburgh Coal Conference; Pittsburgh (PA) 2003.

3.2 Capital Expenses

Facility-dependent costs were derived from relevant studies and corrected using the Chemical Engineering Plant Cost Index (CEPCI), as well as from Aspen Process Economic Analyzer. Highlyspecific unit operations (e.g. Evodos centrifuges, cracking mills, hexane extractors) were priced from vendor quotes.

3.2.1 Unit Operation Costing

- Evodos Centrifuge ³⁸
- Pumps, Hydrogen Stripper, Distillation Column ³⁹
- Compressors, Fired Heaters, Hydroisomerization/Hydrocracker, HDO Reactors ⁴⁰
- Vessels, Heat Exchangers/Coolers/Heaters, Anaerobic Digestor, Methane Boiler, Turbogenerator ⁴¹
- Amine Scrubber ⁴²
- Sonicator ⁴³
- Algae Pond ⁴⁴
- Fermentors ⁴¹
- Cracking Mill, Flaking Mill, Hexane Extractor ⁴⁵

3.3 Financial Assumptions

Financial assumptions were made with the expectation of low technological risk (i.e. based on an Nth plant), similar to previous studies.⁴¹ 46

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. Minimum selling price (MSP) analysis was performed assuming a project lifetime of 25 years for all cases.

 $^{^{38}}$ Quotation: Evodos BV

³⁹Aspentech. Aspen Process Economic Analyzer. 7.0 ed. Burlington (MA) 2008.

⁴⁰Jones SB, Holladay JE, Valkenburg C, Stevens DJ, Walton CW, Kinchin C, et al., Production of Gasoline and Diesel from Biomass via Fast Pyrolysis, Hydrotreating and Hydrocracking: A Design Case. Richland (WA): Pacific Northwest National Laboratory PNNL-18284: (2009).

⁴¹Aden A, Ruth M, Ibsen K, Jechura J, Neeves K, Sheehan J, et al., Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis for Corn Stover. Golden (CO): National Renewable Energy Laboratory NREL/TP-510-32438: (2002)

 ⁴²White, C.W. ASPEN Plus Simulation of CO2 Recovery Process. (DOE/NETL-2002/1182: 2002)
 ⁴³Quotation: Hielscher Ultrasonics GmbH

⁴⁴Benemann J and Oswald WJ, Systems and economic analysis of microalgae ponds for conversion of CO2 to biomass: United States Department of Energy. Pittburgh Energy Technology Center (1996)

 ⁴⁵Quotation: Crown Iron Works
 ⁴⁶Klein-Marcuschamer D, et al. (2010) Technoeconomic analysis of biofuels: A wiki-based platform for lignocel-

lulosic biorefineries. Biomass Bioenerg 34:1914-21

4 Sugarcane

Production of bio-jet fuel from sugarcane has been divided into two models, the first modelling a industry standard sugarcane mill which extracts and purifies the sucrose from the harvested sugarcane. Only a single crystallization pass is modelled with the molasses directed to the fermentation model. The fermentation model is based upon Amyris technology for farnesene production in yeast. The product farnesene is recovered as an organic phase prior to refining. UOPTM refining processes have been modelled, which hydrogenates and isomerizes farnesene to produce a hydrocarbon product with a rich aviation fraction. A atmospheric distillation column is used to recover the aviation fuel, along with side-products including naptha and diesel.

Design Basis: 16,000,000 gallons per year of Jet A-1 blend or drop in substitute.

4.1 Sugarcane Mill Unit Operations

4.1.1 Cane Preparation

4.1.1.1 Shredding Mill The sugarcane stalks are processed to allow efficient recovery of the sugars. A shredding mill is modelled, reducing the size of the pieces of cane to a size suitable for extraction.

Need for review: low Need for innovation: low

4.1.1.2 Cane Mill The shredded cane is further processed in a 5 mill tandem, mass balance based upon a Bundaberg high extraction mill.⁴⁷ A counter-current flow of imbibition water is added to carry the extracted sugars.

Need for review: low Need for innovation: low

4.1.2 Juice Clarification

4.1.2.1 Raw Juice Heater The raw juice is heated in a plate heater (higher heat transfer coefficient) to $75^{\circ}C.^{47}$

Need for review: low Need for innovation: low

4.1.2.2 Lime Mixing Tank Intermediate Liming, using a lime-saccharate mixture of evaporator syrup combined with A 15° Baum (13.26 wt% CaO) solution. This is added at a rate of 0.9 kg CaO / tonne of sugarcane.⁴⁷

Need for review: medium

Need for innovation: low

4.1.2.3 Juice Flash Vessel The limed juice is heated in a plate heater and flashed to 100°C to removed entrained or dissolved air.

Need for review: low

Need for innovation: low

4.1.2.4 Juice Clarifier The raw juice is purified, decolorized and clarified in a SRI Rapid clarifier. Phosphorous Pentoxide $(300 \text{ mg/kg cane juice})^{47}$ is added as a flocculant.

Need for review: low

Need for innovation: low

4.1.3 Juice Concentration

4.1.3.1 Juice Evaporator The sucrose is concentrated in a 5 effect evaporator, operating at 10 kPa.⁴⁷ The resulting syrup has a concentration of 67 $Brix^{47}$ (67 wt%) and is fed to the crystallization pans.

Need for review: low

Need for innovation: low

⁴⁷ Rein, P. Cane Sugar Engineering. (Verlag Dr. Albert Bartens KG: Berlin, 2007).

4.1.3.2 Vapor Condenser The water vapour from the juice evaporator is condensed using a contacting condenser with 20 water/vapour flowrate ratio of $20.^{47}$

Need for review: low

Need for innovation: low

4.1.3.3 Rotary Vacuum Filter The rotary vacuum filter recovers water from the clarifier muds. The muds are filtered and washed to recover fine sugarcane material called bagacillo which is recycled to the x while the water is recycled to the x. A typical wash water rate of 200g/100g of cake is modelled with a cake LOD of 70% and solids retention of 85%.⁴⁷

Need for review: low

Need for innovation: low

4.1.4 Pan House

4.1.4.1 Syrup Heater The evaporated syrup is heated to $65^{\circ}C^{47}$ using low pressure steam (144 kPa⁴⁷) before being feed to the crystallization pans.

Need for review: low

Need for innovation: low

4.1.4.2 A Pans The sucrose is crystallized from the concentrated syrup using a continuous, unstirred, crystallization pan. The mass balance is based upon a single crystallization stage with the crystallized sugar being sold as product while the molasses is fed onto the fermentation process. The crystallization mass balance is based upon the A Pans from a conventional three-boiling scheme.⁴⁷

Need for review: medium Need for innovation: low

4.1.4.3 A Centrifuge High grade continuous centrifugal. Wash with condensate.

Need for review:

Need for innovation:

4.1.4.4 Molasses Storage Tank Molasses needs to be stored to account between year-round fermentation and fuel production, and seasonal processing of cane.

Need for review: low Need for innovation: low

4.1.5 Cogeneration

4.1.5.1 Bagasse Boiler Waste bagasse from the 5 mill train is combusted in a fluidized bed boiler⁴⁷ to generate high pressure (80 bar) steam for use in covering process electricity and steam requirements.

Need for review: low Need for innovation: low

4.1.5.2 Turbogenerator A multi-stage turbogenerator is used to generate electricity and generate the processes requirement for process steam.

Need for review: low

Need for innovation: low

4.2 Fermentation Mill Unit Operations

4.2.1 Fermentation

4.2.1.1 Growth Fermentor Chain The growth chain uses a series of fermentors to produce the yeast concentration in the main fermentor. Growth performance was based on reported yields by Amyris ⁴⁸. The nutrient A farnesene productivity of 16.9 g/L/d, biomass yield of 40g/100g of sugar, and 25% molar excess of nutrients is modelled.

Need for review: medium

Need for innovation: medium

4.2.1.2 Main Fermentor Assumed 25% molar excess of nutrients Farnesene Titer 104.3 g/L, Farnesene Productivity 16.9 g/L/d, Operating Temperature 35 °C, assumed negligible biomass production.⁴⁸

Need for review: medium Need for innovation: medium

4.2.2 Fermentation Separation

4.2.2.1 Yeast Centrifuge The whole broth product from the fermentation will have a combination of aqueous and organic phases with an emulsion formed due to the presence of extracellular materials. The cellular biomass (and some aqueous phase) is removed first in a continuous disk stack centrifuge. Farnesene losses in this centrifuge are reported at 10 wt%.⁴⁹

Need for review: medium

Need for innovation: medium

4.2.2.2 Blending Tank The clarified broth (without yeast cells) is treated to breakdown the emulsion. Effective conditions have been reported as solution pH of 9.5, salt concentration 1.2M, and 0.5 % by volume Tergitol (a non-ionic surfactant with emulsion stabilization applications).⁴⁹ After 1 hour emulsion breakdown was reported at 90-95%.

Need for review: medium

Need for innovation: medium

4.2.2.3 Organic Centrifuge The remaining clarified broth is treated in a continuous disk stack centrifuge to recover the organic phase, separating the aqueous phases which contains the trace solids and debris. Reported farmesene recovery can be as high as 97 wt\%^{49} .

Need for review: medium

Need for innovation: medium

4.2.3 Hydrocracking

4.2.3.1 Cracking Fired Heater The cracking reactor feed is heated to the reaction temperature of 332°C by combusting the propane rich waste gases in a fired heater.⁵⁰

Need for review: low

Need for innovation: low

4.2.3.2 Hydroisomerization/Hydrocracking Reactor The straight chain alkanes produced in the hydrodeoxygenation reactor are unsuitable for use as aviation fuel and require further processes. These alkanes need to be cracked and isomerized to generate a suitable product for use as an aviation fuel substitute.⁵⁰ A cracking reactor operating at 332 °C, 5171 kPag, 0.5 hour⁻¹ LHSV, with a specialized UOP catalyst is able to convert around 50 wt% of the feed material into a aviation fuel fraction.⁵⁰ The remainder going to either diesel, naptha, or light gas fractions.

Need for review: medium

Need for innovation: medium

⁴⁸Pray, T. (2010) Amyris Biomass R&D, Technical Advisory Committee: Drop-in Fuels Panel.

⁴⁹P. Tabur and G. Dorin, "Purification Methods for Bio-Organic Compounds," WO Patent 115074, October 7, 2010.

 $^{^{50}{\}rm McCall},$ M.J., Kocal, J.A., Bhattacharyya, A. Kalnes, T.N. & Brandvold, T.A. 'Production of Aviation Fuel from Renewable Feedstocks' US Patent 2009/0283442 A1. November 19, 2009

4.2.4 Product Recovery

4.2.4.1 Hot Flash Vessel High pressure flash vessel to remove light gases prior to product distillation. The temperature and pressure of the flash vessel have been modelled to minimise losses of the key aviation fraction.

Need for review: medium

Need for innovation: low

4.2.4.2 Product Distillation The separation and recovery of the naptha, aviation, and diesel fractions has been modelled in an atmospheric crude distillation unit.⁵¹

Need for review: medium

Need for innovation: low

⁵¹Parkash, S. Refining Processes Handbook: Gulf Professional Publishing (2003)

5 Algae

Algae is grown using flue gas from a coal fired power station as a carbon enriched feed. *Nannochloropsis*, a microalgae with reported high growth and oil content has been used as the basis of the composition and growth data. The harvested algae is recovered using centrifuges. The intracellular oil is extracted through a combination of sonication to disrupt the cells and a solvent extraction process to recover an oil enriched stream. The algae muds are digested to produce biogas which is combusted for electricity and steam recycle. The triacylglyceride oil is degummed (treated to remove phospholipid impurities) prior to being refined into a combination of fuel products. UOPTM refining processes have been modelled, producing hydrocarbon product with a rich aviation fraction. A atmospheric distillation column is used to recover the aviation fuel, along with side-products including naptha and diesel.

Design Basis: 16,000,000 gallons per year of Jet A-1 blend or drop in substitute.

5.1 Algae Ponds

Algae growth in open raceway ponds.

5.1.1 Seawater Feed Pump

The seawater feed pump transfers seawater to the algae ponds. The seawater flow is controlled to maintain the algae ponds salinity. Seawater is assumed to be readily available to the algae ponds site.

Need for review: high Need for innovation: low

5.1.2 Groundwater Feed Pump

The groundwater feed pump provides water to the algae ponds to offset the moisture losses through evaporation. The water could be sourced through the water grid, a water bore, or a combination of both.

Need for review: medium Need for innovation: low

5.1.3 Algae Open Ponds

Open raceway ponds are growing Nannochloropsis microalgae. Growth performance is modelled from reported year-averaged data. An average production rate of $20.0 \text{ g/m}^2/\text{day}^{52}$ has been modelled for an algae culture concentration of 500 mg/L.⁵³ This growth performance was achieved in 0.12 m deep ponds at a salinity of 35 g/L.⁵³ These growth conditions give a residence time of 3 days. Algae pond mixing is achieved through paddle wheels.

Phosphorus	
Nitrogen	
Diammonium Phosphate	
Nitrogen	
Nitrate Salt	
Sulfur	
Sulphate (groundwater)	
Carbon	
Flue Gas	

Table 47: Nutrients

It was assumed 10% excess of nutrients (apart from Carbon Dioxide) is needed.

 $^{^{52}}$ Ben-Amotz, A. Biofuel and CO₂ Capture by Algae. Second Algae Biomass Summit (2008) <code>https://newbusiness.grc.nasa.gov/wp-content/uploads/2008/12/ben-amotz-nasa-nov-2008.pdf</code>

⁵³Boussiba, S., Vonshak, A., Cohen, Z., Avissar, Y. & Richmond, A. Lipid and biomass production by the halotolerant microalga Nannochloropsis salina. Biomass 12, 37-47 (1987).

Lipid	20 wt%	53
Biomass	$73 \mathrm{~wt}\%$	53
Ash	7 wt%	54

Table 48: Algae Composition

A detailed breakdown of lipid composition⁵⁵ was simplified to three lipid fractions to model the different lipid and phospholipids.

Neutral Lipid	(TAG)	Triacylglyceride C16:O
Phospholipid	(PC)	Phosphatidylcholine C16:1(n-7)
Non-hydratable Phospholipid	(PG)	Phosphatidylglycerol C16:0 tripalmitin

Table 49: Algae Lipid Composition

Need for review: medium Need for innovation: medium

5.1.4 Flue Gas Cooler

The flue gas needs to be cooled before bubbling through the algae ponds. The flue gas needs to be cooled to 32° C, the maximum temperature for Nannochloropsis growth.⁵³

Need for review: medium Need for innovation: low

5.2 Algae Separation

5.2.1 Algae Concentration

The concentration of the harvested algae stream is achieved through a Phytolutions preconcentration unit specifically engineered to operate with the Evodos centrifuge.

Need for review: High Need for innovation: High

5.2.2 Algae Centrifugation

The concentrated algae stream is centrifuged to further separate algae and water. The modelled centrifuge is based upon the Evodos Centrifuge 2/250. Final algae concentration is a 30 wt% algae paste.²⁶

Need for review: High Need for innovation: High

5.3 Algae Hexane Extraction

The algae cells are disrupted using sonication and the oil components extracted using hexane as solvent.

5.3.1 Hexane Addition

Algal oil extraction has been modelled using a wet biomass extraction technique.⁵⁶ Suitable moisture content and solvent loading data 57 has been adapted for extraction with hexane as an in-

 $^{^{54}}$ Negoro, M. et al. Carbon dioxide fixation by microalgae photosynthesis using actual flue gas discharged from a boiler. Appl Biochem Biotechnol 39-40, 643-653 (1993).

⁵⁵Schneider, J. & Roessler, P. Radiolabeling studies of lipids and fatty acids in Nannochloropsis (Eustigmato-phyceae), An oleaginous marine alga. Journal of Phycology 30, 594-598 (1994).

⁵⁶Converti, A., Casazza, A.A., Ortiz, E.Y., Perego, P. & Del Borghi, M. Effect of temperature and nitrogen concentration on the growth and lipid content of Nannochloropsis oculata and Chlorella vulgaris for biodiesel production. Chemical Engineering and Processing: Process Intensification 48, 1146-1151 (2009).

⁵⁷Belarbi, E.H., Molina, E. & Chisti, Y. A process for high yield and scaleable recovery of high purity eicosapentaenoic acid esters from bicroalgae and fish oil. Enzyme and Microbial Technology 26, 516-529 (1999).

dustrial solvent. Sonication moisture content has been modelled at 82 wt $\%^{57}$, while the extraction moisture content is increased to 92.4 wt $\%^{.57}$

Need for review: medium

Need for review: medium

5.3.2 Sonicator

Sonication has been modelled based upon specific performance data for the Hielsher sonicator. Optimal cell lysis and oil recovery was reported after 60 min sonication at 45° C. ⁵⁸

Need for review: medium

Need for innovation: medium

5.3.3 Hexane Extraction

Improved oil recovery requires additional mixing of the solvent with the algae. 93.8% recovery of algal oil has been reported using a 6 hour residence time.⁵⁶

Need for review: medium

Need for innovation: low

5.3.4 Biomass Centrifuge

A decanting centrifuge is used to separate the aqueous phase and cellular debris from the solvent. The formation of an emulsion is likely and so the centrifuge performance has been modelled similarly to a degumming centrifuge.⁵⁹

Need for review: medium Need for innovation: low

5.3.5 Hexane Evaporator

A three effect evaporator has been modelled for the evaporation and recovery of the hexane solvent for recycle. The evaporation is modelled using performance data for an evaporator in a seed oil extraction plant. 59

Need for review: low Need for innovation: low

5.3.6 Hexane Storage Tank

Make-up hexane flow to cover 1.0 wt% losses to sludge and 120 ppm in the raw oil.⁶⁰ Need for review: low

Need for innovation: low

5.4 Algae Degumming

5.4.1 Feed Heater

Prior to the addition of citric acid addition the raw oil is heated to 70° C.⁶⁰

Need for review: low

Need for innovation: low

5.4.2 Citric Acid Addition

A 50 wt% citric acid solution is added to the oil which reacts with the non-hydratable phospholipids (NHP), transforming them into a hydratable form which can be removed in the centrifuge. A citric acid feed rate of 0.3wt% on raw oil is sufficient to reduce oil phosphorus content to 22 ppm.⁶⁰

Need for review: medium

Need for innovation: low

 $^{^{58}}$ Cravotto, G. et. al. Improved extraction of vegetable oils under high-intensity ultrasound and/or microwaves. Ultrasonics Sonochemistry 15, 898-902 (2008).

⁵⁹Sheehan, J., Camobreco, V., Duffield, J., Graboski, M. & Shapouri, H. Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus: Final Report. 314 (National Renewable Energy Laboratory: 1998).

⁶⁰ H. Ringers and J. Segers, "Degumming Process for Triglyceride Oils," U.S. Patent 4049686, September 20, 1977.

5.4.3 Oil Cooler

The oil-acid mixture needs to be cooled to 32°C before the water wash.⁶⁰

Need for review: low

Need for innovation: low

5.4.4 Water Wash

The cooled oil is mixed with distilled water to hydrate all the phospholipids into a semi-crystalline phase ready for centrifugation. Wash water is added at a rate of 1.0 wt% of the feed oil rate.⁶⁰

Need for review: low

Need for innovation: low

5.4.5 Separation Heater

Prior to centrifugation the oil/aqueous mixture is heated to $85^{\rm o}{\rm C}$ to improve the viscosity for centrifuging. 60

Need for review: low Need for innovation: low

5.4.6 Oil Centrifuge

The oil and aqueous phases are separated in a disk-stack centrifuge. Oil losses in the centrifuge are reported at 3.11 wt%.⁵⁹

Need for review: medium Need for innovation: low

5.5 Algae UOP Refining

5.5.1 Hydrodeoxygenation Heater

The hydrodeoxygenation reactor oil feed is heated to the reaction temperature of 350° C by combusting the propane rich waste gases in a fired heater.⁶¹

Need for review: low Need for innovation: low

5.5.2 Hydrodeoxygenation Reactor

The hydrodeoxygenation reactor is down flow packed reactor divided into three stages, with an equicurent feed of oil and hydrogen. In each stage the triacylglyceride oil is reduced to straight alkanes, corresponding to the lipids, and propane, from the glycerol backbone. The UOP catalyst reduces the oil through both the deoxygenation reaction (60 wt%) and the hydrogenation reaction (40 wt%).⁶² Stage 1 & 2 oil conversion is 90 wt%, while the final finishing stage operates at the higher 98 wt% conversion.⁶¹

Deoxygenation Reaction: 1 Glycerol Trioleate $(C_{57}H_{104}O_6) + 6$ Hydrogen $(H_2) \rightarrow 3$ Heptadecane $(C_{17}H_{36}) + 1$ Propane $(C_3H_8) + 3$ Carbon Dioxide (CO_2)

Hydrogenation Reaction: 1 Glycerol Trioleate $(C_{57}H_{104}O_6) + 15$ Hydrogen $(H_2) -> 3$ Octadecane $(C_{18}H_{38}) + 1$ Propane $(C_3H_8) + 6$ Water (H_2O)

Need for review: low

Need for innovation: low

5.5.3 Intermediate Gas Flash

Before the final finishing stage of the hydrodeoxy genation reactor all the waste gases (CO₂, H₂, H₂O, and short hydrocarbons - particularly propane) are flashed off. Model conditions of 100 °C and 35 bar were optimised for hydrocarbon recovery.

Need for review: medium

⁶¹Kokayeff, P., Marker, T.L. & Petri, J.A. "Production of Fuel from Renewable Feedstocks using a Finishing Reactor" US Patent 2010/0133144 A1. June 3, 2010

⁶²Perego, C., Sabatino, L., Baldiraghi, F. & Faraci, G. "Process for Producing Hydrocarbon Fractions from Mixtures of a Biological Origin" US Patent 2009/0300970 A1. December 10, 2009

Need for innovation: low

5.5.4 Hot Hydrogen Stripper

A countercurrent stripper removes the waste light gases by using the dry hydrogen feed. This is particularly to reduce the water concentration (catalyst poison for the hydrocracking catalyst) to $100 \text{ pm}.^{63}$

Need for review: low Need for innovation: low

5.6 Algae Hydrocracking

5.6.1 Cracking Fired Heater

The cracking reactor feed is heated to the reaction temperature of 332° C by combusting the propane rich waste gases in a fired heater.⁵⁰

Need for review: low

Need for innovation: low

5.6.2 Hydroisomerization/Hydrocracking Reactor

The straight chain alkanes produced in the hydrodeoxygenation reactor are unsuitable for use as aviation fuel and require further processes. These alkanes need to be cracked and isomerized to generate a suitable product for use as an aviation fuel substitute.⁵⁰ A cracking reactor operating at 332 °C, 5171 kPag, 0.5 hour⁻¹ LHSV, with a specialized UOP catalyst is able to convert around 50 wt% of the feed material into a aviation fuel fraction.⁵⁰ The remainder going to either diesel, naptha, or light gas fractions.

Need for review: medium Need for innovation: medium

5.7 Algae Product Recovery

5.7.1 Hot Flash Vessel

High pressure flash vessel to remove light gases prior to product distillation. The temperature and pressure of the flash vessel have been modelled to minimise losses of the key aviation fraction.

Need for review: medium

Need for innovation: low

5.7.2 Product Distillation

The separation and recovery of the naptha, aviation, and diesel fractions has been modelled in an atmospheric crude distillation unit.⁵¹

Need for review: medium Need for innovation: low

5.8 Algae Amine Scrubber

5.8.1 Amine Scrubber

The waste gas from the hydrodeoxygenation is treated to remove impurities, particularly carbon dioxide and water. An amine scrubber, a counter current gas-liquid contactor, with a 10 wt% MDEA (Methyl diethanol amine) absorbent. At the high pressure conditions used in this process a carbon dioxide removal efficiency of 71 wt%⁴² has been reported. The hydrogen rich scrubbed gas is recycled as hydrogen feed to the hydrodexygenation reactor.

Need for review: low

Need for innovation: low

 $^{^{63}}$ Perego, C., Sabatino, L., Baldiraghi, F. & Faraci, G. "Process for Producing Hydrocarbon Fractions from Mixtures of a Biological Origin" US Patent 2009/0300970 A1. December 10, 2009

5.8.2 Degasifier

The rich MDEA solution from the amine scrubber is treated in a degasifier to remove the absorbed carbon dioxide.

Need for review: medium Need for innovation: low

5.8.3 Carbon Dioxide Flash

The degasified carbon dioxide is flashed to recover trace water. Need for review: low Need for innovation: low

5.9 Algae Anaerobic Digestion

5.9.1 Anaerobic Digester

The biomass sludge from the biomass centrifuge is digested anaerobically. A 31 hour residence time digestor has been reported to give a 24% biomass reduction of algae sludge.⁶⁴ 90% of the digester muds is recycled to algae ponds to allow undigested nutrients to be recycled.

Need for review: medium

Need for innovation: medium

5.10 Algae Cogeneration

5.10.1 Methane Boiler

The digester biogas is combusted in a methane boiler to generate high pressure (80 bar) steam for use in covering process electricity and steam requirements.

Need for review: low Need for innovation: low

5.10.2 Turbogenerator

A multi-stage turbogenerator is used to generate electricity and generate the processes requirement for process steam.

Need for review: low

Need for innovation: low

⁶⁴Samson, R. & Leduy, A. Biogas production from an aerobic digestion of Spirulina maxima algal biomass. Biotechnology and Bioengineering 24, 1919-1924 (1982)

6 Pongamia

Pongamia pinnata is a legume tree which produces a seed rich in oil. These seeds are harvested, dried, cracked, dehulled, and flaked in preparation for extraction of the oil. Industrial hexane is used to extract the seed oil in a continuous belt extractor. The remainder of the seed biomass is digested to produce biogas which is combusted for electricity and steam recycle. The triacylglyceride oil is degummed (treated to remove phospholipid impurities) prior to being refined into a combination of fuel products. UOPTM refining processes have been modelled, producing hydrocarbon product with a rich aviation fraction. A atmospheric distillation column is used to recover the aviation fuel, along with side-products including naptha and diesel.

Design Basis: 16,000,000 gallons per year of Jet A-1 blend or drop in substitute.

6.1 Seed Processing

6.1.1 Prestorage Dryer

Prior to storage the raw kernels are dried to a moisture content of 14.0 wt $\%^{65}$ in a fluidized bed dryer. Drying conditions and energy consumption were modelled based upon soybean drying performance.⁶⁶

Need for review: medium Need for innovation: low

6.1.2 Kernel Silo

The pongamia kernels are stored to compensate for the seasonal production of seeds. 240 days worth of material are stored, allowing for a 90 day seed harvesting season.⁶⁶

Need for review: low

Need for innovation: low

6.1.3 Kernel Dryer

The moisture content of the kernels needs to be reduced to 10.0 wt% to allow efficient cracking and separation of the hulls⁶⁵. Drying conditions and energy consumption were modelled based upon soybean drying performance.⁶⁶

Need for review: medium Need for innovation: low

6.1.4 Cracking Mill

The dried kernels are broken into particles one-fourth to one-sixth the size of the kernel.⁶⁵ Need for review: medium

Need for innovation: low

6.1.5 Aspirator

An aspirator removes the hulls from the cracked kernels, removing the hulls for anaerobic digestion with the extracted meal.

Need for review: low

Need for innovation: low

6.1.6 Flaking Mill

The kernels are rolled into flakes 0.25-0.37mm prior to hexane extraction.⁶⁵

Need for review: medium

Need for innovation: low

 65 Moore, N.H. Oilseed handling and preparation prior to solvent extraction. J Am Oil Chem Soc 60, 189-192 (1983).

⁶⁶Soponronnarit, S., Swasdisevi, T., Wetchacama, S. & Wutiwiwatchai, W. Fluidised bed drying of soybeans. Journal of Stored Products Research 37, 133-151 (2001).

6.2 Pongamia Hexane Extraction

6.2.1 Hexane Extraction

The oil is extracted from the flaked pongamia seeds using industrial hexane in a counter-current belt extractor, assumed to operate with similar conditions and performance as when processing soybeans. Oil extraction performance, extractor mass balance, and energy requirements where based on reported soybean data⁵⁹. An extraction residence time of 0.57 hours⁶⁷ and operating temperature of 60 °C⁶⁸ are modelled.

Need for review: medium Need for innovation: low

6.2.2 Desolventiser

The desolventiser (meal desolventiser-toaster) using hexane vapour to recover hexane solvent retained in the meal for recycling.⁶⁸

Need for review: medium Need for innovation: low

6.2.3 Meal Cyclone

The desolventised pongamia flakes are cycloned to separate the hexane vapour from the flakes. Need for review: medium

Need for innovation: low

6.2.4 Hexane Evaporator

A three effect evaporator has been modelled for the evaporation and recovery of the hexane solvent for recycle. The evaporation is modelled using performance available for soybean oil. ⁵⁹

Need for review: low

Need for innovation: low

6.2.5 Hexane Storage Tank

Make-up hexane flow of 0.0024 kg/kg flaked seed to cover losses in the hexane extraction to the pongamia meal.⁵⁹

Need for review: low Need for innovation: low

6.3 Pongamia Degumming

6.3.1 Feed Heater

Prior to the addition of citric acid addition the raw oil is heated to 70°C.⁶⁰ Need for review: low Need for innovation: low

6.3.2 Citric Acid Addition

A 50 wt% citric acid solution is added to the oil which reacts with the non-hydratable phospholipids (NHP), transforming them into a hydratable form which can be removed in the centrifuge. A citric acid feed rate of 0.3wt% on raw oil is sufficient to reduce oil phosphorus content to 22 ppm.⁶⁰

Need for review: medium

Need for innovation: low

⁶⁷Faner, S.A., Durand, G.A., Crapiste, G.H. & Bandoni, J.A. A Model for Optimal Operation in a Soy Oil and Flour Plant. 2nd Mercosur Congress on Chemical Engineering 1-10 (2005).

⁶⁸Shahidi, F. Bailey's Industrial Oil and Fat Products. 1, (Wiley-Interscience: Hoboken, New Jersey, 2005).

6.3.3 Oil Cooler

The oil-acid mixture needs to be cooled to 32°C before the water wash.⁶⁰

Need for review: low

Need for innovation: low

6.3.4 Water Wash

The cooled oil is mixed with distilled water to hydrate all the phospholipids into a semi-crystalline phase ready for centrifugation. Wash water is added at a rate of 1.0 wt% of the feed oil rate.⁶⁰

Need for review: low

Need for innovation: low

6.3.5 Separation Heater

Prior to centrifugation the oil/aqueous mixture is heated to $85^{\rm o}{\rm C}$ to improve the viscosity for centrifuging. 60

Need for review: low Need for innovation: low

6.3.6 Oil Centrifuge

The oil and aqueous phases are separated in a disk-stack centrifuge. Oil losses in the centrifuge are reported at 3.11 wt%.⁵⁹

Need for review: medium Need for innovation: low

6.4 Pongamia UOP Refining

6.4.1 Hydrodeoxygenation Heater

The hydrodeoxygenation reactor oil feed is heated to the reaction temperature of 350° C by combusting the propane rich waste gases in a fired heater.⁶¹

Need for review: low Need for innovation: low

6.4.2 Hydrodeoxygenation Reactor

The hydrodeoxygenation reactor is down flow packed reactor divided into three stages, with an equicurent feed of oil and hydrogen. In each stage the triacylglyceride oil is reduced to straight alkanes, corresponding to the lipids, and propane, from the glycerol backbone. The UOP catalyst reduces the oil through both the deoxygenation reaction (60 wt%) and the hydrogenation reaction (40 wt%).⁶² Stage 1 & 2 oil conversion is 90 wt%, while the final finishing stage operates at the higher 98 wt% conversion.⁶¹

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Need for review: low

Need for innovation: low

6.4.3 Intermediate Gas Flash

Before the final finishing stage of the hydrodeoxygenation reactor all the waste gases (CO₂, H_2 , H_2O , and short hydrocarbons - particularly propane) are flashed off. Model conditions of 100 °C and 35 bar were optimised for hydrocarbon recovery.

Need for review: medium

Need for innovation: low

6.4.4 Hot Hydrogen Stripper

A countercurrent stripper removes the waste light gases by using the dry hydrogen feed. This is particularly to reduce the water concentration (catalyst poison for the hydrocracking catalyst) to $100 \text{ pm}.^{62}$

Need for review: low Need for innovation: low

6.5 Pongamia Hydrocracking

6.5.1 Cracking Fired Heater

The cracking reactor feed is heated to the reaction temperature of 332° C by combusting the propane rich waste gases in a fired heater.⁵⁰

Need for review: low

Need for innovation: low

6.5.2 Hydroisomerization/Hydrocracking Reactor

The straight chain alkanes produced in the hydrodeoxygenation reactor are unsuitable for use as aviation fuel and require further processes. These alkanes need to be cracked and isomerized to generate a suitable product for use as an aviation fuel substitute.⁵⁰ A cracking reactor operating at 332 °C, 5171 kPag, 0.5 hour⁻¹ LHSV, with a specialized UOP catalyst is able to convert around 50 wt% of the feed material into a aviation fuel fraction.⁵⁰ The remainder going to either diesel, naptha, or light gas fractions.

Need for review: medium Need for innovation: medium

6.6 Pongamia Product Recovery

6.6.1 Hot Flash Vessel

High pressure flash vessel to remove light gases prior to product distillation. The temperature and pressure of the flash vessel have been modelled to minimise losses of the key aviation fraction.

Need for review: medium

Need for innovation: low

6.6.2 Product Distillation

The separation and recovery of the naptha, aviation, and diesel fractions has been modelled in an atmospheric crude distillation unit.⁵¹

Need for review: medium

Need for innovation: low

6.7 Pongamia Amine Scrubber

6.7.1 Amine Scrubber

The waste gas from the hydrodeoxygenation is treated to remove impurities, particularly carbon dioxide and water. An amine scrubber, a counter current gas-liquid contactor, with a 10 wt% MDEA (Methyl diethanol amine) absorbent. At the high pressure conditions used in this process a carbon dioxide removal efficiency of 71 wt%⁴² has been reported. The hydrogen rich scrubbed gas is recycled as hydrogen feed to the hydrodexygenation reactor.

Need for review: low

Need for innovation: low

6.7.2 Degasifier

The rich MDEA solution from the amine scrubber is treated in a degasifier to remove the absorbed carbon dioxide.

Need for review: medium Need for innovation: low

6.7.3 Carbon Dioxide Flash

The degasified carbon dioxide is flashed to recover trace water. Need for review: low Need for innovation: low

6.8 Pongamia Anaerobic Digestion

6.8.1 Anaerobic Digester

The extracted meal from the meal cyclone and hulls from the aspirator are digested anaerobically. A 31 hour residence time digestor has been reported to give a 24% biomass reduction of algae sludge.⁶⁴ 90% of the digester muds is recycled to algae ponds to allow undigested nutrients to be recycled.

Need for review: medium Need for innovation: medium

6.9 Pongamia Cogeneration

6.9.1 Methane Boiler

The digester biogas is combusted in a methane boiler to generate high pressure (80 bar) steam for use in covering process electricity and steam requirements.

Need for review: low Need for innovation: low

6.9.2 Turbogenerator

A multi-stage turbogenerator is used to generate electricity and generate the processes requirement for process steam.

Need for review: low Need for innovation: low