Life Cycle Analysis of Greenhouse Gas Emissions from Biosynthetic Base Oil (BBO) compared to Poly-Alpha Olefin (PAO) Base Oil

Prepared for Biosynthetic Technologies

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Summary of Findings

The life cycle greenhouse gas (GHG) emissions from biosynthetic base oil (BBO) are 67.9–79.1% lower than the GHG emissions associated with the poly-alpha olefin (PAO), a product of similar function and use. The variability depends on the combinations of feedstocks used to make short chain fatty acids and oleic acid that make up the eight BBO pathways analyzed in this study. The GHG intensity of PAO was found to be 4.067 kg CO_2e/kg PAO produced. The percent GHG reduction per BBO pathway is listed in Table 1 below.

Table 1 shows the percent reduction eight BBO pathways for short chain fatty acids and oleic acid

BBO Feedstock combination	% GHG reduction
Coconut oil and Palm oil	67.9%
Coconut oil and Canola oil	74.2%
Coconut oil and Tallow oil	67.9%
Coconut oil and Soy oil	73.5%
Palm kernel and Palm oil	72.9%
Palm kernel and Canola oil	79.1%
Palm kernel and Tallow oil	72.9%
Palm kernel and Soy oil	78.5%

Goals and Scope

Biosynthetic Technologies is planning to develop a facility to produce BBO, a biosynthetic base oil derived from vegetable oils, but that has different properties than vegetable base oil (VBO). This is important because VBO may have a shorter use-life time, which necessitates the functional unit being a certain amount of time in use (hours of lubrication). The BBO will compete with high-end synthetic and petroleum-based PAO base oil so the operating lifetime of the fluid is considered to be the same. Biosynthetic Technologies wanted to compare the proposed BBO production facility to the baseline life cycle Greenhouse Gas (GHG) emissions from PAO. To compare GHG emissions the impact category chosen to compare BBO and PAO is Global Warming Potential (GWP) and the final reporting metric of kg CO_2e per kg BBO or PAO respectively.

EcoShift Consulting was retained to conduct a hybrid life cycle analysis (LCA) of GHG emissions associated with the production of BBO and PAO. The LCA was conducted using widely accepted methodologies consistent with ISO 14040 principles and previous research on PAO, biodiesel, and ethyl esters to ensure comparisons are commensurate.

The purpose of this LCA is to compare the GHG savings associated with a renewable lubricant versus one derived from fossil resources. The target audience is the company owner and their design team, who is interested in the GHG impacts of their product compared to a fossil carbon based lubricant base oil (PAO). These findings can be used to make sourcing decisions, understand the impacts of processing, and develop marketing materials noting the benefits and/or tradeoffs with renewable lubricants.

The LCA of BBO relies on forecasts of primary energy data and source mixes from a proposed facility in Texas operated by Biosynthetic Technologies. Since the product is derived from some feedstocks commonly described in other peer-reviewed LCAs, EcoShift drew on the emissions factors used in the GREET model developed at Argonne National Labs for upstream GHG emissions and combined the outputs to estimate the GHG intensity measured as CO_2e (carbon dioxide equivalent, which includes other GHGs such as nitrous oxide and methane corrected for relative global warming impact) normalized by mass (per kg). For emissions factors not found in GREET, EcoShift drew on those found in GaBi, BioGrace, and the peer-reviewed scientific LCA literature.

PAO is a hydrogenated olefin polymer derived from linear alpha olefins. The LCA for the PAO drew upon data available in the scientific LCA literature and LCA databases. Emissions factors were drawn in order of availability from GREET, GaBi, and the peer-reviewed LCA literature.

Previous LCA research on lubricants, biodiesel, and fatty methyl esters has made the following observations. LCAs of bio-based lubricants typically are favorable. For example, Wightman et al. (1999) found the global warming potential (GWP) to be considerably lower for rapeseed oil than mineral base oils. Lucie and Voltebregt (1998) looked at cleaning and degreasing agents used in metal working and compared de-aromatised hydrocarbon and two vegetable based oil (VBO) products (rapeseed methyl ester and ethylhexyl laurate from coconut oil) and found that low volatility and a renewable resource base favored the VBOs. They both found that fertilizer use rates and energy consumption are the two primary drivers of GHG intensities of VBO. We would anticipate similar results for BBO. Fertilizer inputs, land use change, and yields will be important drivers of the variation among different feedstocks for fatty acids and oleic acids. However, the literature suggests that there is much uncertainty associated with the agricultural stage for nearly all biodegradable lubricants, which can affect their relative impacts compared to petroleum and mineral based base oils. This uncertainty is attributed to the complexities of land use change and supply and demand for various crops.

Functional Unit

Since BBO is similar to PAO and other synthetic lubricants, we will use a functional unit based on product mass (kg). There are several ways that the functional unit can be compared. One way to set the functional unit is on the unit of volume of mass of the product. However, if the end use is known, it should be interpreted as its functional equivalent taking into account the life expectancy of lubricants. In some cases an appropriate functional unit might be 20 working hours. These working hours should represent a certain amount of lubricant required to complete that task. If there is a difference in the life expectancy of the compared oil, as is the case when comparing VBO to PAO, these should be represented as the mass needed to do the same functionally equivalent work. However, BBO and PAO are seen as functionally equivalent with similar functional lifetimes. Hence it is appropriate to use volumes or mass as the basis for comparison.

System Boundary

A Cradle to Grave analysis is important for this LCA because the fate of the fossil fuel based synthetic lubricants results in a net increase of GHGs in the atmosphere. A bio-based product, in this case BBO, releases carbon taken from the atmosphere during the growing season. The petroleum-derived PAO takes fossil carbon and adds it to the active carbon cycle, so the fate of all fossil carbon is the atmosphere.

Impact Category

The Impact Category for this project is global warming potential (GWP). The reference substance for this impact category is kg CO_2e.

Data Quality

The data quality varies across comparisons. Because this is a proposed production facility, actual energy and material inputs are based on expected performance. For data regarding agricultural supply chains, the models used are widely used by the EPA and CARB, so they are very representative of aggregate emissions from various feedstocks. For the PAO model, material and energy inputs are based on emissions factors taken from GREET, GaBi, and the peer reviewed LCA literature. These data were observed from actual PAO production.

Co-product allocation methodology

When a production process produces more than one product, the emissions can be assigned across both products to avoid double counting. The co-product allocation used here was based on the percent of the product by mass. Other options would be by economic value or by energy content. ISO 14000 guidelines suggest that co-product allocation be avoided, and the way this is done in the

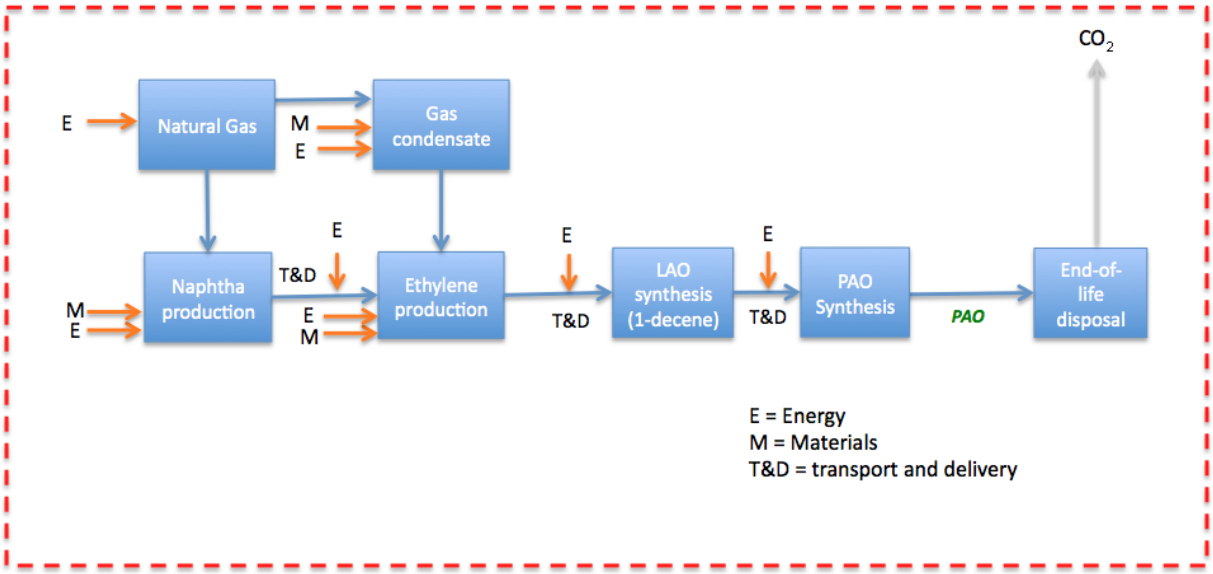
LCA biofuel literature is through system expansion. This means that it is assumed that co-products will displace other sources in the market. For example, soybean meal co-produced with biodiesel is assumed to displace animal feed such as soybean mean and receives a credit for animal feed that does not have to be produced. This approach was used in all the feedstock pathways as well as for the PAO production

Baseline Case: GHG LCA of PAO

PAO is a synthetic lubricant derived from fossil crude oil. The key difference between PAO and the BBO (evaluated in a later section) is that all of the carbon in the PAO is assumed to be of fossil carbon origin. The specific feedstock for PAO production is 1-decene ($C_{10}H_{20}$) monomers, which is derived from ethylene. The ethylene is formed by steam cracking a gas condensate and naphtha (a product of atmospheric condensation). Naphtha is produced by atmospheric distillation, vacuum distillation, and cracking crude oil.

Figure 1 below shows the system boundary set for this LCA of PAO.

PAO System Boundary



Both primary inputs for PAO production—the gas condensate and the naphtha—were assumed to come from North American natural gas production from shale and conventional sources. GREET was used to estimate GHGs from transportation of natural gas and natural gas processing.

Naphtha is produced at a Fischer-Trosch diesel plant and GREET was used to model this as well as Fischer-Trosch naphtha production and ethylene. We used an Intergovernmental Panel on Climate Change (IPCC) emissions factor for naphtha of 3.313 kgCO_2e/kg naphtha, a value confirmed in Benner et al. (2012). The energy used to manufacture Ethylene is estimated to be 4.640 MJ/kg Ethylene for thermal energy based on an energy efficiency of 85% for heat and steam, and 0.503 MJ/kg Ethylene for electricity. Emissions factors for electricity are based on the EPA US average emissions factor electricity, which is used by the EPA for LCAs because a free market in electricity generation means that emissions and electricity move outside of local and regional distribution grids.

Propane is also used in the production of ethylene. GREET was used to model upstream GHGs associated with this process. Ethylene is converted to linear alpha olefins (LAO) via oligomerisation where the yield of 1-decene is about 0.116 kg per kg ethylene, the balance being other LAOs. The 1-decene is converted to PAO via distillation and hydrogenation. Because only 11.6% of the ethylene input by mass becomes PAO, only 11.6% of the emissions associated with that process are assigned to PAO.

Finally, all embodied carbon in PAO was assumed to become CO_2 at the end of the product life. Combining the processing energy and embodied energy in the inputs for PAO production with the embodied fossil carbon in the PAO gives an overall carbon intensity of **4.067 kg CO_2e/kg PAO**.

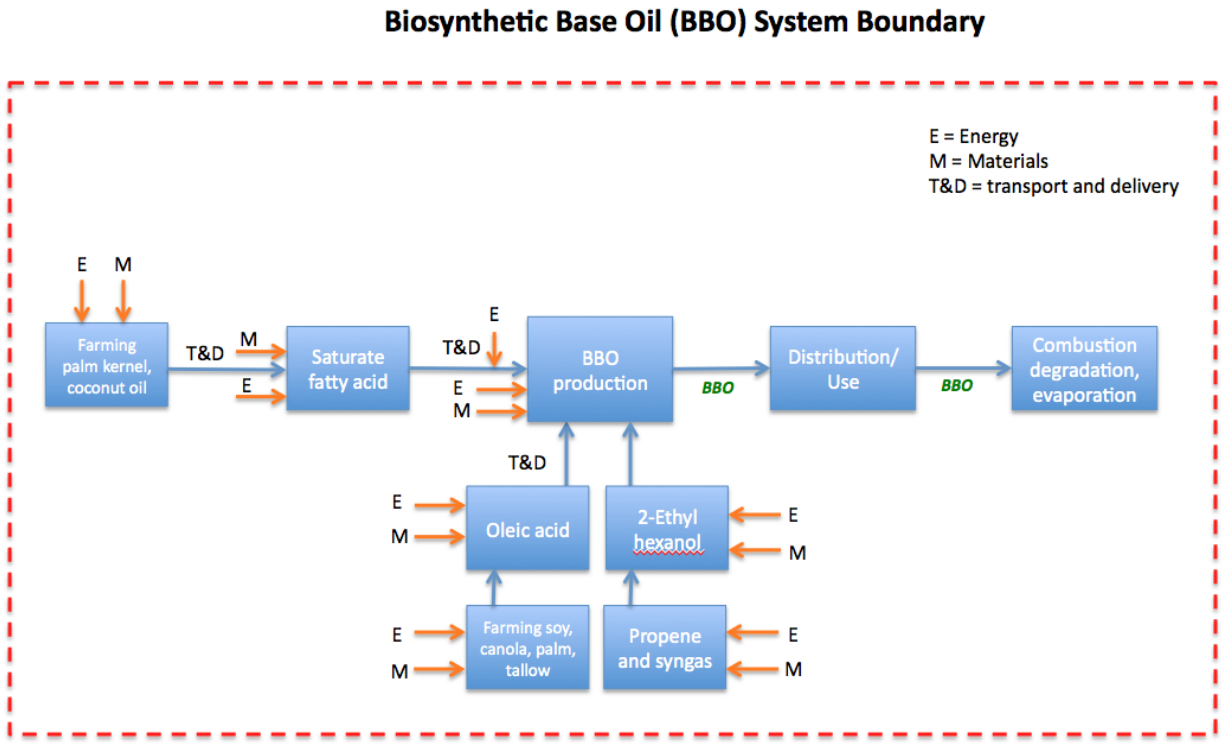
Comparative Case: Renewable Biosynthetic Base Oil Feedstocks

Primary sources for oleic acid include (2A) Palm oil, (2B) Canola oil, (2C) Tallow oil, and (2D) Soy oil. Primary source of fatty acids are (1A) coconut oil and (1B) whole cut palm kernel. This gives a total of eight pathways to compare to the baseline PAO case above. Inventories were compiled from the farming stage through the oil extraction for energy and material inputs across each input life cycle to understand the relative contribution to the overall GHG intensity of the BBO of upstream production activities. For oleic acid production, each crop was assumed to have the same mass-based input, with the exception of soy and canola, which were assumed to have a 1.4 to 1 ratio because the entire acid profile is not used.

Oleic Acid production

Oleic acid is 55% of the mass input for manufacturing BBO. Energy inputs for high oleic soy were not available in the models or literature so it was assumed that similar energy inputs to trans-esterification would be required. It was assumed that 3.131 kg of vegetable oil (tallow, soy, palm, canola) would be required to make 1 kg of oleic acid (Sari et al. 2004). Sari et al. (2004) also estimates that 0.000456 kg of phosphoric acid is required to make 1 kg of oleic acid. Emissions factors from BioGrace and GREET were used.

Figure 2 below shows the system boundary for the BBO case.



Saturate fatty acid production

The vegetable oil extracted from the feedstock must be converted to fatty acids where glycerin is removed. Primary source for short chain fatty acid is coconut oil and palm kernel. Like Oleic Acid above, saturate fatty acid production values were not available. Instead, fatty acid methyl ester production values were used as it is a similar chemical process.

2-Ethyl hexanol production

The 2-EH is produced from n-Butyraldehyde by reacting propene with syngas. The best available information on 2-EH production is from the Canadian government in a report prepared for Alberta in 2004. Transport and distribution emissions were assumed to be zero because it is locally available in the Texas region, and GHG contribution was considered inconsequential.

Life Cycle Impact Assessment of PAO

The baseline case to compare the GHG emissions associated with BBO was PAO as described earlier. The carbon intensities by the various material and energy inputs used to make PAO.

Table 2 shows the carbon intensity of PAO and the contributions from various processes

PAO carbon intensity	4.067	kg CO_2e/kg PAO
Natural gas recovery (naphtha)	0.0442	kg CO_2e/kg PAO
Natural gas transport (naphtha)	0.0002	kg CO_2e/kg PAO
Natural gas processing (naphtha)	0.0588	kg CO_2e/kg PAO
Natural gas transport (naphtha)	0.0002	kg CO_2e/kg PAO
Naphtha production	0.2802	kg CO_2e/kg PAO
Propane	0.0257	kg CO_2e/kg PAO
Naphtha transport	0.0025	kg CO_2e/kg PAO
Natural gas recovery (gas condensate)	0.0184	kg CO_2e/kg PAO
Natural gas transport (gas condensate)	0.0001	kg CO_2e/kg PAO
Natural gas processing (gas condensate)	0.0245	kg CO_2e/kg PAO
Natural gas transport (gas condensate)	0.0001	kg CO_2e/kg PAO
Ethylene production	0.049	kg CO_2e/kg PAO
LAO synthesis, oligomerisation	0.09	kg CO_2e/kg PAO
PAO synthesis, distillation, hydrogenation	0.327	kg CO_2e/kg PAO
Embodied fossil carbon	3.1452	kg CO_2e/kg PAO

Interpretation of PAO results

The results suggest significant GHG reduction when displacing PAO with BBO when compared on a per kg basis The major drivers of the GHG intensity of PAO are (1) the embodied CO_2 in the fossil based feedstock, (2) PAO synthesis, distillation, and hydrogenation, followed by (3) naphtha production. Other processes with relatively smaller GHG impacts include ethylene production and LAO synthesis, but 88.4% of these emissions are assigned to LAOs.

Life Cycle Impact Assessment of BBO

Eight feedstock scenarios were examined for this LCA. Two different feedstocks for short chain fatty acids were used (1A) coconut oil and (1B) whole cut palm kernel. Four feedstocks for oleic acid were evaluated, including (2A) Palm oil, (2B) Canola oil, (2C) Tallow oil, and (2D) Soy oil. The pathways evaluated in the BBO LCA were:

Table 3 shows the carbon intensity of BBO and the contributions from various processes

	GHG intensity	% GHG reduction
1A + 2A (Coconut oil and Palm oil)	1.305 kg CO_2e/kg BBO	67.9%
1A + 2B (Coconut oil and Canola oil)	1.051 kg CO_2e/kg BBO	74.2%
1A + 2C (Coconut oil and Tallow oil)	1.304 kg CO_2e/kg BBO	67.9%
1A + 2D (Coconut oil and Soy oil)	1.078 kg CO_2e/kg BBO	73.5%
1B + 2A (Palm kernel and Palm oil)	1.104 kg CO_2e/kg BBO	72.9%
1B + 2B (Palm kernel and Canola oil)	0.849 kg CO_2e/kg BBO	79.1%
1B + 2C (Palm kernel and Tallow oil)	1.102 kg CO_2e/kg BBO	72.9%
1B + 2D (Palm kernel and Soy oil)	0.877 kg CO_2e/kg BBO	78.5%

Interpretation of BBO results

Comparing the feedstocks for BBO production shows some variation in GHG intensity, but only marginally so. The best performing feedstocks from a GHG perspective are palm kernel and canola oil, followed by palm kernel and soy oil, while the highest GHG intensities are for coconut oil combined with palm or tallow oil. Further improvements in GHG profiles could be made with more information about the particular farming practices used by actual suppliers to make the various feedstocks.

One half to 1/3rd of the emissions from BBO production result from the embodied carbon in 2-ethyl hexanol, which contributed 0.49 kg CO2e/kg BBO for each of the above feedstock pathways. Another 20-40% of the emissions are associated with the production of 2 ethyl-hexanol, while the balance is primarily from upstream agricultural emissions as has been noted in prior research on biofuels and lubricants. Less than 10% of the emissions are from BBO processing, which is approximately 0.052 kg CO_2e/kg BBO.

Sensitivity to Land Use Change

Because the product investigated here is a land-based resource, the GHGs associated with direct and indirect land use change would be important to include in the analysis. Direct land use change occurs when crops are produced on land that was previously undisturbed. Indirect land use change accounts for the displacement of agricultural production from one site to an undisturbed site (e.g., when soy is grown where corn was previously grown, where did the corn acreage go?).

The addition of land use change adds a great deal of uncertainty to the analysis because it depends on the extent to which land use change is driven by increased feedstock demand as well as the carbon stocks found in various ecosystems which range from tropical forests to grassland prairie. Given these uncertainties, GHG intensities from land use change should be treated as sensitivity in the model. There are different interpretations of whether and how land use change should be treated by regulatory entities. For example, California's Air Resources Board has decided to use the same land use change penalty for all land-based feedstocks, while the US EPA has decided to not assign the GHG intensity of land use change in the absence of evidence that shows actual agricultural expansion into ecosystems. Where the EPA has used FASOM or FAPRI models to predict land use change, they have not backcast models to understand how well they represent real-world land use change that could increase GHGs. Kim and Dale (2011) have argued that biofuel production has not induced any indirect land use change based on historical data from 2002 to 2007, so we have no reason to suspect that BBO, given its very small demand for feedstocks relative to biofuels would warrant a GHG penalty from land use change. It is also important to note that the purchase of feedstocks certified by the Roundtable on Sustainable Biofuels or other *sui generis* certification agencies could minimize these impacts because they attempt to only certify production systems that do not clear new land.

However, if land use change were considered in the LCA, each feedstock would see an increase in GHG intensity as follows.

Table 4 shows the contributions to land use change from various feedstocks

	GHG intensity from land use change
PAO	0.022 kg CO_2e/kg PAO
Coconut oil	0.149 kg CO_2e/kg BBO
Palm kernel	0.093 kg CO_2e/kg BBO
Palm oil	0.766 kg CO_2e/kg BBO
Canola oil	0.202 kg CO_2e/kg BBO
Tallow oil	0.000 kg CO_2e/kg BBO
Soy oil	0.435 kg CO_2e/kg BBO

Since PAO is relying on solar energy stored over millions of years it has the lowest GHG intensity from land use change except for tallow oil which is considered to have no GHGs from land use change. Palm oil has the highest GHGs from land use change mostly because palm expansion occurs in peatlands and tropical forest which sequester significant amount of carbon per unit of land. Soy oil has the second highest GHG intensity because it has a low productivity per unit of land, but usually occurs in areas that contain far less carbon such as grasslands or active agricultural fields. The results show that even considering GHGs from land use change for each of the proposed feedstocks showed significant GHG reductions from PAO.

Future Work

The environmental benefits of BBO extend beyond GHGs. Further work could be done to document the life cycle benefits using impact categories other than global warming potential. These include aquatic and terrestrial toxicity, carcinogenicity, bioaccumulation, eutrophication, acidification, and emissions of criteria air pollutants. Future LCAs could be designed to compare baseline PAO scenarios to the BBO examined in this research.

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Appendix A: LCA Inventory for BBO

STATIONARY PROCESS 1A: Coconut Oil for SCFA			**Source**
Emissions factor	0.760	kg CO_2e/kg coconut oil	Tan et al. 2004
Energy density	35.7	MJ/liter coconut oil	
Energy density	135.1	MJ/gal coconut oil	
Heating value	38.0	MJ/kg	Vega 2011
Allocation coconut oil	0.313	%	Oil content of coconut
Yield	2400	kg oil/ha	Dumelin 2009
Yield	0.700	t/ha	Dumelin 2009
N	62.0	kg/t oil	Dumelin 2009
P_2O_5	62.0	kg/t oil	Dumelin 2009
K_2O	104.0	kg/t oil	Dumelin 2009
Pesticide	0.0	kg/t oil	Dumelin 2009
Carbon intensity LUC	0.149	kg CO_2e/kg BBO	
Carbon intensity	0.205	kg CO_2e/kg BBO	

TRANSPORTATION PROCESS for 1A: coconut oil transportation from farm to extraction site to SCFA production

	Distance (mi)	Share (%)
Heavy duty truck	10.0	100%
Carbon intensity	0.0038	kg CO_2e/kg coconut oil
Carbon intensity	0.001	kg CO_2e/kg BBO

STATIONARY PROCESS 1B: Palm kernel (whole cut) farming for SCFA			
Palm FFB Farming	0.087	kg CO_2e/kg palm FFB	GREET
Palm FFB Farming allocation to kernel	0.015	kg CO_2e/kg palm kernel	
Energy input	11.0	GJ/ton	Reijnders and Huijbregts
Co-product allocation to kernel	0.167		Pleanjai, 2009
energy density	17.0	MJ/kg	
Palm oil yield	2800	kg oil/ha	
Palm oil + kernel yield (fruit)	5.5	t/ha	Dumelin 2009
N	19	kg/t oil	Dumelin 2009
N	7.79	kg/t FFB	
P_2O_5	3.0	kg/t oil	Dumelin 2009
P_2O_5	0.05	kg/t FFB	
K_2O	29.0	kg/t oil	Dumelin 2009
K_2O	14.41	kg/t FFB	
Pesticide	0.010	kg/t oil + kernel	Dumelin 2009
Land Use Change	2.060	kgCO_2e/kg palm FFB	Croezen et al. 2010
LUC allocation kernel	0.344	kg CO_2e/kg palm kernel	
Carbon intensity LUC	0.093	kg CO_2e/kg BBO	
Carbon intensity	0.004	kg CO_2e/kg BBO	

TRANSPORTATION PROCESS for 1B: palm kernel transportation from farm to extraction site to SCFA production

	Distance (mi)	Share (%)
Heavy duty truck	10.000	100%
Carbon intensity	0.004	kg CO_2e/kg palm kernel
Carbon intensity	0.001	kg CO_2e/kg BBO

STATIONARY PROCESS 2A: Palm oil farming & extraction for Oleic acid

Palm FFB Farming	0.087	kg CO_2e/kg palm FFB		GREET
Diesel for nonroad engines	15.441	g CO_2e/kg palm FFB		GREET
Nitrogen	70.262	g CO_2e/kg palm FFB		GREET
Herbicides	0.35	g CO_2e/kg palm FFB		GREET
Insecticides	0.011	g CO_2e/kg palm FFB		GREET
Co-product allocation to oil	0.676			Pleanjai, 2009
Carbon intensity palm oil	0.185	kg CO_2e/kg palm oil		GREET
PKS and fibre	0.164		220	kg
EFB	0.141		190	kg
POME	0.498		670	kg
Kernels	0.037		50	kg
Oil	0.160		215	kg
Palm oil density	890.1	kg/m^3		ChemPro
Palm oil density	3.369	kg/gal		
Palm oil extraction	0.240	MJ/kg PME		Pleanjai, 2009
Palm oil refining	2.070	MJ/kg PME		Pleanjai, 2009
Land Use Change	2.060	kg CO_2e/kg palm oil		Croezen et al. 2010
Land Use Change	6.941	kgCO_2e/gal oil		
Carbon intensity LUC	0.766	kg CO_2e/kg BBO		
Carbon intensity	0.185	kg CO_2e/kg palm oil		
Carbon intensity	0.319	kg CO_2e/kg BBO		

TRANSPORTATION PROCESS for 2A: palm oil transportation from farm to extraction site to transesterification

	Distance (mi)	Share (%)
Heavy duty truck	10.0	100%
Carbon intensity	0.012	kg CO_2e/kg palm oil
Carbon intensity	0.007	kg CO_2e/kg BBO

STATIONARY PROCESS 2B: Rapeseed Oil Farming and Extraction for Oleic acid

Diesel input	916115	btu	GREET
Emissions factor	0.022	kg CO_2e/kg rapeseed	GREET
Co-product allocation to canola oil	0.428	%	CARB GREET
Co-product allocation to canola meal	0.572	%	CARB GREET
Yield	1.400	t/ha	Dumelin 2009

N	183.000	kg/t oil	Dumelin 2009
N	0.007	kg CO_2e/kg rapeseed	GREET
P_2O_5	65.0	kg/t oil	Dumelin 2009
P_2O_5	0.014	kg CO_2e/kg rapeseed	GREET
K_2O	260	kg/t oil	Dumelin 2009
K_2O	0.013	kg CO_2e/kg rapeseed	GREET
Pesticide	35.0	kg/t oil	Dumelin 2009
Herbicides	0.001	kg CO_2e/kg rapeseed	GREET
Land Use Change	0.368	kg CO_2e/kg rapeseed	Lange 2011
Carbon intensity LUC	0.202	kg CO_2e/kg BBO	
Carbon intensity	0.009	kg CO_2e/kg canola oil	GREET
Carbon intensity	0.030	kg CO_2e/kg BBO	

TRANSPORTATION PROCESS for 2B: Rapeseed oil transportation from farm to stacks to transesterification

	Distance (mi)	Share (%)
Medium heavy duty truck farm to stack	10.000	100%
GHGs	0.004	kg CO_2e/kg canola oil
Heavy duty truck stack to plant	40.000	100%
GHGs	0.037	kg CO_2e/kg canola oil
Oil profile yield	1.400	
Carbon intensity	0.043	kg CO_2e/kg BBO

STATIONARY PROCESS 2C: Tallow Oil Feedstock production for Oleic acid

Tallow using lower energy use	19.650	gCO_2e/MJ	LCFS lookup table
Tallow energy minus transport	17.190	gCO_2e/MJ	LCFS report
Energy density	35.700	MJ/gallon	
Emissions factor	0.614	kg CO_2e/gallon tallow	
Emissions factor	0.184	kg CO_2e/kg tallow	
Density	7.500	lbs/gal	
Thermal energy	28813.000	btu/gal	
Electrical energy	0.930	btu/gal	
Natural gas	82.500	%	
Electricity	10.900	%	US average
Tallow as fuel	6.600	%	
Density	3.331	kg/gal	
Carbon intensity	0.317	kg CO_2e/kg BBO	

TRANSPORTATION PROCESS for 2C: tallow oil transportation from collection to production site to transesterification

	Distance (mi)	Share (%)
Medium heavy duty truck farm to stack	10.0	100%
GHGs	0.004	kg CO_2e/kg tallow oil
Heavy duty truck stack to plant	40.0	100%

GHGs	0.012	kg CO_2e/kg tallow oil	
Carbon intensity	0.007	kg CO_2e/kg BBO	

STATIONARY PROCESS 2D: Soy oil farming for Oleic acid

Soybean in	2.411	kg soybean	GREET
Soy oil out	0.454	Kg	GREET
Soybean per kg soy oil	5.316	kg soybean/kg soy oil	GREET
Soybean oil farming and production	21.250	gCO_2e/MJ	LCFS lookup table/GREET
Soybean farming	0.011	kg CO_2e/kg soybean	GREET
Land Use Change	62.0	gCO_2e/MJ	LCFS lookup table
Land Use Change	2.030	kgCO_2e/kg soybean oil	Croezen et al. 2010
Land Use Change trop rainforest	737.0	t CO_2e/ha	Dumelin 2009
Land Use Change cerrado	85.0	t CO_2e/ha	Dumelin 2009
Allocation to oil	0.390		Dumelin 2009
Carbon intensity	83.250	g CO_2e/MJ	GREET
Carbon intensity land use change	0.435	kg CO_2e/kg BBO	
Natural Gas	57.570	%	GREET
Coal	28.343	%	GREET
Electricity	12.450	%	
LPG	1.635	%	GREET
Yield	0.6	t/ha	Dumelin 2009
N	0.0	kg/t oil	Dumelin 2009
P_2O_5	136	kg/t oil	Dumelin 2009
K_2O	136	kg/t oil	Dumelin 2009
Pesticide	21	kg/t oil	Dumelin 2009
Oil profile yield	1.40		Biosythentic personal communication
Carbon intensity	0.160	kg CO_2e/kg soybean	Kim and Dale 2004
Carbon intensity	0.058	kg CO_2e/kg soy oil	GREET
Carbon intensity	0.045	kg CO_2e/kg BBO	

TRANSPORTATION PROCESS for 2D: Soyoil transportation from field to stacks to mill to transesterification plant

Field to stack	Distance (mi)	Share (%)		
Med Heavy duty truck	10.0		100	GREET
Carbon intensity	0.004	kg CO_2e/kg soybean		GREET
Carbon intensity	0.023	kg CO_2e/kg soy oil		GREET
Stack to mill	Distance (mi)	Share (%)		GREET
Heavy duty truck	40.000		1	GREET
Carbon intensity	0.014	kg CO_2e/kg soybean		GREET
Carbon intensity	0.073	kg CO_2e/kg soy oil		GREET
Mill to plant	Distance (mi)	Share (%)		GREET
Barge	520.0		0.4	GREET
Carbon intensity	0.014	kg CO_2e/kg soy oil		GREET
Rail	700.0		0.2	GREET
Carbon intensity	0.004	kg CO_2e/kg soy oil		GREET
Heavy duty truck	80.0		0.2	GREET
Carbon intensity	0.006	kg CO_2e/kg soy oil		GREET
Carbon intensity	0.092	kg CO_2e/kg BBO		GREET

STATIONARY PROCESS: 2-Ethyl hexanol production

Emissions factor	1.250	kg CO_2e/kg 2EH	Alberta Environment 2004
Carbon intensity	0.225	kg CO_2e/kg BBO	

STATIONARY PROCESS: fatty acid production

Carbon intensity electricity	0.024	kg CO_2e/kg BBO	CARB/GREET
Carbon intensity thermal energy	0.011	kg CO_2e/kg BBO	CARB/GREET
Carbon intensity	0.009	kg CO_2e/kg BBO	

STATIONARY PROCESS: Oleic acid production

Vegetable oil in/Oleic acid out	3.131	kg vegetable oil/kg oleic acid	Sari et al 2004
Phosphoric acid	0.000	kg phosphoric acid/kg oleic acid	
Phosphoric acid emissions factor	3.010	kg CO_2e/kg phosphoric acid	Sari et al 2004
Carbon intensity phosphoric acid	0.001	kg CO_2e/kg BBO	CARB/GREET
Glycerol production	0.243	kg glycerol/kg oleic acid	CARB/GREET
Electricity emissions factor	1.477	lbs CO_2e/kWh	EPA eGRID, US average
Carbon intensity electricity	0.024	kg CO_2e/kg BBO	CARB/GREET
Electricity for transesterification	121.800	btu/kg BBO	CARB/GREET
Electricity for transesterification	0.036	kWh/kg BBO	CARB/GREET
Thermal energy for transesterification	822.090	btu/kg BBO	CARB/GREET
Thermal energy for transesterification	0.241	kWh/kg BBO	CARB/GREET
Thermal energy emissions factor	0.070	kg CO_2e/MJ natural gas	CARB/GREET
Thermal energy emissions factor	0.252	kg CO_2e/kWh natural gas	CARB/GREET
Carbon intensity thermal energy	0.061	lbs CO_2e/kg BBO	CARB/GREET
Carbon intensity thermal energy	0.028	kg CO_2e/kg BBO	CARB/GREET
Carbon intensity	0.052	kg CO_2e/kg BBO	

STATIONARY PROCESS: Biosynthetic Base Oil (BBO) production

Biosynthetic Production	20,000,000	gallons of biosynthetic/year	Biosynthetic PFDs
Specific Gravity (biosynthetic product)	0.90		
Density	3.405	kg/gal	Biosynthetic PFDs
Product Production	150,120,000	lbs/yr	
BBO production	68,093,231	kg/yr	
Coproduct Production	4,503,600	lbs/yr	
Yield	99%	% of feed converted into product	Biosynthetic PFDs
Total Feed Input	156,185,455	lbs/yr	Biosynthetic PFDs
Oleic acid	55%	% of total product weight	
	85,902,000	lbs/yr	Biosynthetic PFDs
	1.948	kg/gal of biosynthetic	
saturate fatty acid	0.170	% of total product weight	
	26,551,527	lbs/yr	Biosynthetic PFDs
	0.602	kg/gal of biosynthetic	
alcohol (2-EH)	0.180	% of total product weight	
	28,113,382	lbs/yr	Biosynthetic PFDs
	12,752,005	kg/y	
	0.638	kg/gal BBO	
50% NaOH	40452	kg/yr	CARB/GREET

50% NaOH	0.235	kg CO_2e/kg NaOH	CARB/GREET
50% NaOH	0.001	kg NaOH/kg BBO	
carbon intensity NaOH	0.00014	kg CO_2e/kg BBO	
Electricity for estolide	0.201	kWh/kg BBO	
Electricity emissions factor	1.477	lbs CO_2e/kWh	EPA eGRID, US average
carbon intensity electricity	0.297	lbs CO_2e/kg BBO	
carbon intensity electricity	0.135	kg CO_2e/kg BBO	
Thermal energy for estolide (natural gas)	0.005	MSCF/kg BBO	Biosynthetic PFDs
Thermal energy for estolide (natural gas)	4600	btu/kg BBO	
Thermal energy for estolide (natural gas)	1.348	kWh/kg BBO	
Thermal energy for steam (natural gas)	0.00040	Mlb/kg BBO	Biosynthetic PFDs
Thermal energy for steam (natural gas)	0.40	lb steam/BBO	
Thermal energy for steam (natural gas)	400	btu steam/BBO	
Thermal energy for steam (natural gas)	0.117	kWh steam/BBO	
Thermal energy emissions factor	0.070	kg CO_2e/MJ natural gas	CARB/GREET
Thermal energy emissions factor	0.252	kg CO_2e/kWh natural gas	CARB/GREET
carbon intensity thermal energy	0.061	lbs CO_2e/kg BBO	
carbon intensity thermal energy	0.028	kg CO_2e/kg BBO	
manufacturing yield	0.980		Hansen et al. 2005
modern NG power plant	400	g CO_2e/kWh	
Carbon intensity	0.052	kg CO_2e/kg BBO	NaOH + energy inputs

STATIONARY PROCESS 6: BBO EoL

% fossil carbon by weight 2-ethyl hexanol	0.738	$C_8H_{18}O$	
% fossil carbon by weight BBO	0.133	%	
Carbon intensity	0.488	kg CO_2e/kg BBO	

Appendix B: LCA Inventory for PAO

STATIONARY PROCESS: North American Natural Gas from Shale and Regular Recovery

Naphtha ouput	1	kg	
Shale	22.8	%	
Regular	77.2	%	
Land Use Change	0.8	kg CO_2e/MWh	US DOE NETL 2010
Land Use Change	0.000222	kg CO_2e/MJ	
LHV	50	MJ/kg natural gas	
Land Use Change	0.0111	kg CO_2e/kg natural gas	
GHGs	0.523015	kg CO_2e/kg naptha	
carbon intensity	**0.04423**	**kg CO_2e/kg PAO**	

TRANSPORTATION PROCESS: Natural gas to gas processing plant

Pipeline	100	%
Distance	50	Miles
natural gas	1	Kg
GHGs	0.00206	kg CO_2e/kg NG
carbon intensity	**0.0002390**	**kg CO_2e/kg PAO**

STATIONARY PROCESS: North American Natural Gas Processing

NG	1	kg	
Natural gas	1	mmbtu	
Diesel nonroad engines	1	%	
Natural gas	96	%	50% large gas turbine, 50% utility boiler
Electricity	3	%	Transported electricity
GHGs	0.69537	kg CO_2e/kg NG	
carbon intensity	**0.05880**	**kg CO_2e/kg PAO**	

TRANSPORTATION PROCESS: Natural gas to Fischer-Trosch Diesel Plant (naphtha)

Pipeline	100	%
Distance	50	Miles
natural gas	1	Kg
GHGs	0.00206	kg CO_2e/kg NG
carbon intensity	**0.0002390**	**kg CO_2e/kg PAO**

STATIONARY PROCESS: FT
Naphtha Production

Naphtha	1	Kg
Efficiency	63%	%
Natural gas	99.7	%
N-butane	0.3	%
carbon intensity	3.313	kg CO_2e/kg naptha
carbon intensity	**0.2802**	**kg CO_2e/kg PAO**

STATIONARY PROCESS: Propane Production			
GHGs	3.04	kg CO_2e/kg propane	
Carbon intensity	**0.0257**	**kg CO_2e/kg PAO**	
TRANSPORTATION PROCESS: FT Naphtha plant to Bulk terminal to ethylene plant			
Pipeline	60	%	
Distance	400	Miles	
GHGs	0.006695	kg CO_2e/kg naptha	
Rail	7	%	
Distance	800	Miles	
GHGs	0.002244	kg CO_2e/kg naptha	
Barge	33%	%	
Distance	520	Miles	
GHGs	0.013181	kg CO_2e/kg naptha	
bulk terminal to ethylene plant			
heavy duty truck	100	%	
GHGs	0.007617	kg CO_2e/kg naptha	
GHGs total	0.029737	kg CO_2e/kg naptha	
Carbon intensity	**0.00251468**	**kg CO_2e/kg PAO**	
STATIONARY PROCESS: North American Natural Gas from Shale and Regular Recovery			
Gas condensate ouput	1	kg	
Shale	22.8	%	
Regular	77.2	%	
Land Use Change	0.8	kg CO_2e/MWh	US DOE NETL 2010
Land Use Change	0.000222	kg CO_2e/MJ	
LHV	50	MJ/kg natural gas	
Land Use Change	0.0111	kg CO_2e/kg natural gas	
GHGs	0.523015	kg CO_2e/kg gas condensate	
Carbon intensity	**0.01844**	**kg CO_2e/kg PAO**	
TRANSPORTATION PROCESS: Natural gas to gas processing plant			
Distance	50	miles	
Pipeline	100	%	
natural gas	1	kg	
GHGs	0.00206	kg CO_2e/kg NG	
carbon intensity	**0.0000726**	**kg CO_2e/kg PAO**	

STATIONARY PROCESS: North American Natural Gas Processing				
NG			1	kg
Natural gas	1	Mmbtu		
Diesel nonroad engines	1	%		
Natural gas	96	%	50% large gas turbine, 50% utility boiler	
Electricity	3	%	Transported electricity	
GHGs	0.69537	kg CO_2e/kg NG		
Carbon intensity	**0.02452**	**kg CO_2e/kg PAO**		
TRANSPORTATION PROCESS: Natural gas to gas condensate processing plant				
Pipeline				100
Distance	50	miles		
Natural gas	1	kg		
GHGs	0.00206	kg CO_2e/kg NG		
Carbon intensity	**0.0000726**	**kg CO_2e/kg PAO**		
STATIONARY PROCESS: Ethylene production via steam cracking				
Ethylene output	1	Kg		
Propane	0.1	Kg		
Gas condensate	0.304	Kg		
Naptha	0.729	Kg		
Thermal energy input	4.64	MJ/kg ethylene	APME 2003	
Thermal emissions factor	0.07	kg CO2e/MJ natural gas	CARB/GREET	
Thermal carbon intensity	0.32	kg CO2e/kg ethylene		
Electrical energy input	0.503	MJ/kg ethylene	APME 2003	
Electricity emissions factor	1.477	lbs CO_2e/kWh	EPA eGRID, US average	
Electricity emissions factor	0.186	kg CO_2e/MJ		
Carbon intensity electric	0.094	kg CO_2e/kg ethylene		
Carbon intensity e + th	**0.418**	**kg CO_2e/kg ethylene**		
Ethylene production	2.18	kg CO_2e/kg ethylene	czaplicka-kolarz 2010	
Iron Ore	0.0002	mg/kg ethylene		
Limestone	0.0001	mg/kg ethylene		
Bauxite	0.0003	mg/kg ethylene		
Clay	20	mg/kg ethylene		
Ferromanganese	1	mg/kg ethylene		
Carbon intensity	**0.049**	**kg CO_2e/kg PAO**		

STATIONARY PROCESS: LAO synthesis, Oligomerisation			
1-decene yield	0.116	kg/kg ethylene	Nieschalk 2003
Other LAO yield	0.884	kg/kg ethylene	
Ethylene input	1	Kg	
Thermal energy input	7.66	MJ/kg ethylene	Nieschalk 2003
Thermal emissions factor	0.07	kg CO_2e/MJ natural gas	CARB/GREET
Thermal carbon intensity	0.54	kg CO_2e/kg ethylene	
Electrical energy input	1.34	MJ/kg ethylene	Nieschalk 2003
Electricity emissions factor	1.477	lbs CO_2e/kWh	EPA eGRID, US average
Electricity emissions factor	0.186	kg CO_2e/MJ	
Carbon intensity electric	0.249	kg CO_2e/kg ethylene	
Carbon intensity e + th	**0.786**	**kg CO_2e/kg ethylene**	
Carbon intensity e + th	**0.09**	**kg CO_2e/kg PAO**	

STATIONARY PROCESS: PAO synthesis, distillation, hydrogenation			
PAO yield	1	Kg	
1-decene input	1	Kg	
Thermal energy input	1.94	MJ/kg ethylene	Nieschalk 2003
Thermal emissions factor	0.07	kg CO_2e/MJ natural gas	CARB/GREET
Thermal carbon intensity	0.14	kg CO_2e/kg ethylene	
Electrical energy input	1.03	MJ/kg PAO	Nieschalk 2003
Electricity emissions factor	1.477	lbs CO_2e/kWh	EPA eGRID, US average
Electricity emissions factor	0.186	kg CO_2e/MJ	
Carbon intensity electric	0.192	kg CO_2e/kg PAO	
Carbon intensity e + th	**0.327**	**kg CO_2e/kg PAO**	

STATIONARY PROCESS: PAO decomposition end-of-life disposal			
% carbon by weight	0.857		Exxon Mobil
Carbon intensity	**3.1452**	**kg CO_2e/kg PAO**	