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An Enviro-Economic Assessment of Waste Vegetable Oil to Biodiesel Conversion: An Analysis of Cost and GHG Emissions for the University of Texas at Austin

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An Enviro-Economic Assessment of Waste Vegetable Oil to Biodiesel Conversion: An Analysis of Cost and GHG Emissions for the University of Texas at Austin

by

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Report

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Abstract

An Enviro-Economic Assessment of Waste Vegetable Oil to Biodiesel Conversion: An Analysis of Cost and GHG Emissions for the University of Texas at Austin

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The University of Texas at Austin, 2014

Supervisor: Michael Blackhurst

With its multiple dining halls, close proximity to restaurants, and diesel vehicle fleet, the University of Texas at Austin (UT) has both the supply of raw materials to implement a waste vegetable oil to biodiesel recycling program and the capacity to use it. At face value, implementing a large-scale recycling program provides a source of cheap, low emissions fuel. However, the feasibility of such a program is contingent on its economic cost and environmental impact relative to alternative fuel sources. Thus, this research estimated the greenhouse gas (GHG) inventories and the unit cost associated with 1 megajoule worth of recycled biodiesel derived from three production processes – Alkali Catalyzed, Acid Catalyzed, and Supercritical Methanol–using environmental life cycle assessment and life cycle costing. These GHG inventories and unit costs were then compared to the conventional diesel and oilseed biodiesel sources that make up UT's current fuel portfolio. This analysis suggested that implementing a recycling program using a Supercritical Methanol biodiesel conversion process would have the lowest combined GHG impact and unit cost, although as an emerging technology, it poses a high investment risk. In general, these findings are encouraging to the success and impact of a large-scale recycling program.

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Introduction

As a publicly funded entity, the University of Texas at Austin (UT) is required to purchase alternative fuel vehicles and provide alternative fuel at on-campus fueling stations as determined by the Texas legislature (HB 432, 2009). The purpose of this law is to reduce environmental impact, primarily through the reduction of greenhouse gas (GHG) emissions. As a result, B5 biodiesel fuel, a mixture of 5% oilseed biodiesel with 95% conventional diesel, is available at UT fueling stations along with conventional diesel fuel. From a life cycle standpoint, biodiesel is amongst the most energy efficient and clean burning fuels available, especially in terms of greenhouse gases (Nanaki, 2012). However, biodiesel from raw feedstocks (oilseed biodiesel) has supply chain impacts from activities such as farming and refining that may outweigh its point source benefits (Gerbens-Leenes, 2009). Furthermore, the high percentage of diesel in the B5 blend worsens the potential emissions benefits. Table 1 gives summary characteristics of diesel and B5, which we will frequently refer to as incumbent fuels.

Table 1. Summary characteristics of UT's incumbent fuel mix.

	Diesel	Retail Biodiesel (B5)
Energy Density	39 MJ/L	38 MJ/L
Tailpipe Emissions	2706 g CO_2 e/L	2698 g CO_2 e/L
Current Price	\$1.05/L	\$1.05/L
Value	\$0.027/MJ	\$0.028/MJ

Concurrent to environmental concerns, cost is an issue, as both incumbent fuels are subject to market forces that add uncertainty to future prices. Figure 1 shows a history of retail B5, B20 (20% biodiesel and 80% diesel), and diesel prices over the past decade. Retail biodiesel prices follow the price of diesel closely, but they are consistently more expensive and have a changing price premium. Fluctuations in the price of biodiesel can be attributed to various factors such as expiring tax credits for biofuels and uncertainty about future alternative fuels policy (Schnepf, 2013). A freeze of federal spending on biofuels in 2012 shows a direct increasing impact on the price of retail biodiesel in subsequent months. Diesel is more volatile still, with its price tied to the global price of petroleum. The price of both fuels has generally trended upwards in the last decade. Because of its large fleet of vehicles, relatively small changes in fuel prices have multiplicative budgetary impacts.

Thus, while B5 provides an alternative to conventional diesel, negative upstream impacts, insubstantial tailpipe GHG reduction, and increasing prices should urge decision makers to seek better options.

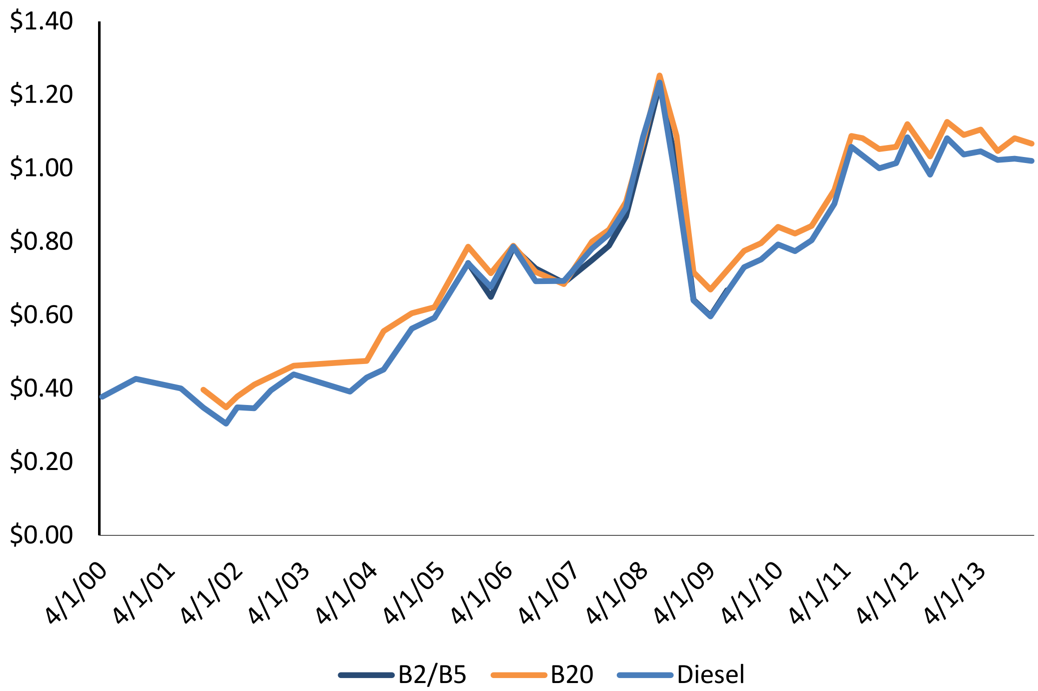

Figure 1. Price volatility in incumbent fuels

The purpose of this study is explore the cost and GHG impact of a program designed to provide UT with biodiesel produced from waste vegetable oil (WVO), the waste product produced from cooking with plant oil or animal fat. As a waste product, WVO has a truncated supply chain in comparison to raw oilseed products and it is often available at little or no cost; thus it is cheaper and avoids the upstream complications of oilseed biodiesel. Additionally, UT has access to a large supply of WVO on campus and from the surrounding metropolitan as well as the financial resources to construct and operate a conversion facility. Furthermore, with its large fleet of diesel vehicles, UT has consistent internal demands for this produced fuel while opportunities might exist to sell off-campus.

At face value, the supply chain differences between biodiesel produced from raw products and WVO would seem to favor the waste-sourced product. However, there are significant differences in the production processes of biodiesel from a waste source versus a raw source that may affect its greenhouse gas abatement potential and its total cost. Additionally, three distinct process technologies for creating biodiesel from WVO exist: Alkali Catalyzed (AlCP), Acid Catalyzed (AcCP), and Supercritical Methanol (ScMP). Each of these processes has differing raw material and energy inputs that alter their supply chain GHG impacts and production costs.

Process based environmental life cycle assessment (LCA) investigates the environmental supply chain impacts of a product through the unit processes that are required to create some unit of output. Figure 2 provides the conceptual framework of the unit processes required to create 1 MJ of energy from WVO, in the form of biodiesel. Unit processes are the elementary steps of a product's creation as well as any subsequent steps in a product's life after production, depending on the scope of the LCA.

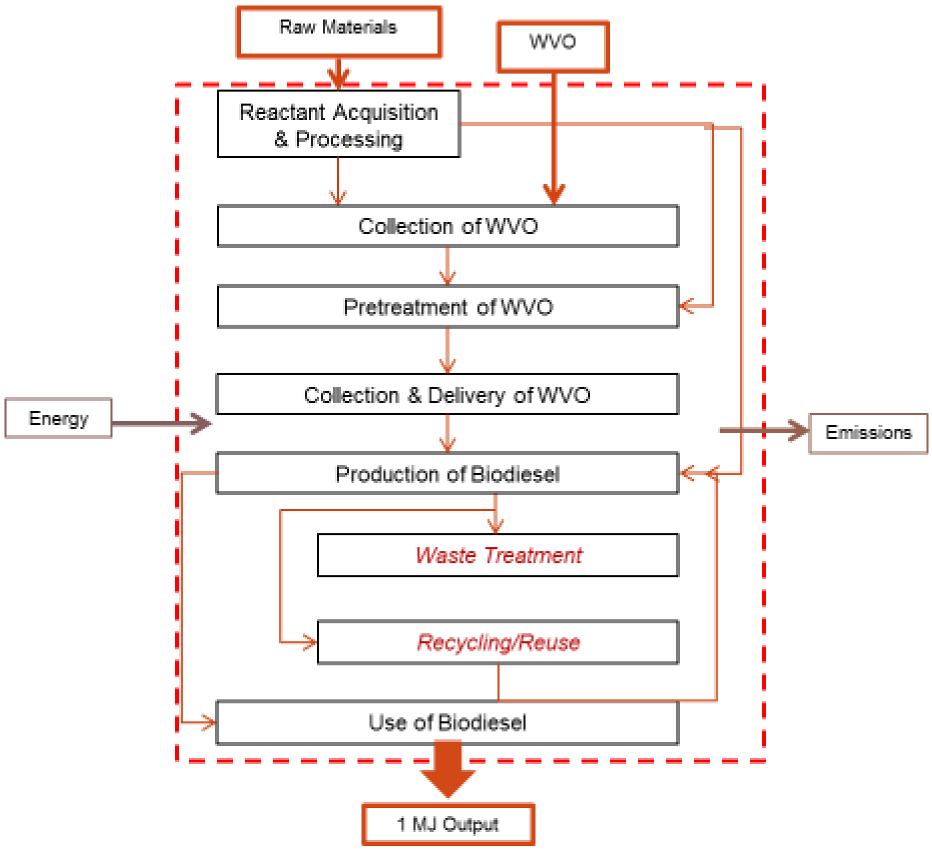

Figure 2. System boundary of recycled biodiesel ELCA. Italicized processes are not included in assessment.

This study uses process-based LCA to compare the life cycle GHG impacts of UT's incumbent fuels with biodiesel produced from WVO using either AlCP, AcCP, or ScMP production technologies on a per MJ basis.

The cost of these production processes are determined using life cycle costing (LCC) to account for the fixed and variable costs of constructing and operating a facility to handle the conversion of waste vegetable oil to biodiesel. In this way, we determine the unit cost per MJ of producing biodiesel during the operable lifespan of a facility, specific to each production technology.

The life cycle GHG and cost information found in this study will further inform decision-makers at UT as to whether implementing a large-scale recycling program would be of environmental and economic benefit to the university. The next section provides background for the study, including details on the scope of the LCA and LCC along with descriptions of the AlCP, AcCP, and ScMP process technologies. Next, we discuss the methods of the study, before presenting the results, and then drawing conclusions and giving recommendations.

Background

Scope

In this LCA, we determine the unit processes needed to deliver the fuel equivalent of 1 MJ of work. Our environmental assessment is bounded from Well-to-Wheel, meaning from acquisition of raw materials to fuel use. Figure 2 is an illustration of the system boundary. Process-based methods (used herein) are subject to truncation errors due to uncertainty upstream in the supply chain (Matthews, 2014). However, the materials in our study have limited upstream supply chains, thus limiting truncation errors. Given our goal of understanding the GHG impacts of our fuels of interest, we focus on the CO_2 equivalent emissions (CO_2e) inventory generated within each unit process.

Our life cycle cost analysis covers only major expenses, e.g., the construction and operation of a production facility, since other expenses, such as the logistics of storage and transportation, are negligible on a unit basis. We calculate the total cost of production in terms of dollar per MJ produced.

Biodiesel Production Process

Biodiesel is a liquid fuel created from lipid materials, such as oils and fats, used mainly for transportation. Oilseed biodiesel fuels, which are produced from raw vegetable oils, can be derived from a variety of feedstocks, although the primary source for US biodiesel is soybeans (EIA).

Biodiesel is composed of fatty acid methyl esters (FAME) derived through a transesterification reaction between triglycerides (vegetable oil) and methanol. Figure 3 gives a basic representation of the reaction. Glycerol is a co-product, as shown (Knothe, 1997). This is a reversible reaction favoring the reactants. Thus, for large-scale production, an excess of methanol and heat is used to drive the reaction forward. The three process technologies of interest, AlCP, AcCP and ScMP, each follow this same basic mechanism, although they differ in regards to the heat, pressure, methanol ratios, and catalytic agents used.

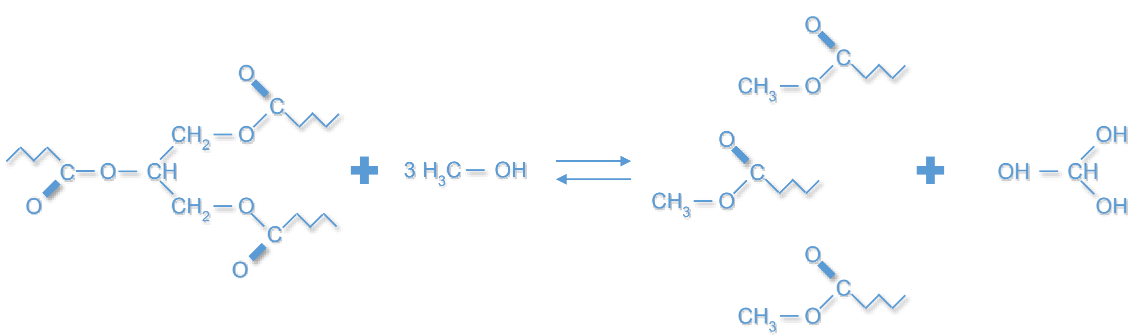

Figure 3. Biodiesel transesterification reaction.

Oilseed biodiesel is produced in mass production plants around the US, primarily using alkali catalyzed processes. There are approximately 20 plants currently operating in Texas (DOE AFDC). Freight and rail are the primary transport infrastructure for biodiesel, which is produced and then blended at distribution points before being delivered to service stations such as the University's Facilities Services fueling station (Ogden, 2011).

WVO to Biodiesel Recycling

Conceptually, a WVO to biodiesel recycling program consists of the steps, logistical and chemical, involved in converting the WVO available to the university into usable biodiesel. These steps are explained in the next several paragraphs.

Collection and Delivery of WVO

WVO is held in specialized receptacles at dining halls and restaurants in the campus area. Trucks then deliver the collected WVO to a processing plant. This study assumes that WVO collection occurs on both the university campus and from the surrounding city. An average collection radius of 8 km is approximated from spatial analysis of restaurants in Austin (Google 2014), assuming the biodiesel plant is located on UT's campus.

Pretreatment of WVO and Production of Biodiesel

Chemically, the composition of WVO is similar to crude oil from oilseed feedstock; however, there are impurities such as food particles and water that are introduced during cooking. These impurities are removed through filtering and washing. Additionally, WVO contains elevated levels of free fatty acids (FFA) that can participate in unwanted side reactions with a basic catalyst, forming soaps and depleting catalyst levels, thereby reducing overall reaction efficiency (Canakci, 2007). To encourage reactions that are more efficient and result in a purer product, several process alterations have been proposed in the literature. Reaction diagrams are shown in Appendix A.

Alkali Catalyzed Process

Similar to the process used for oilseed biodiesel production, an alkali catalyzed process (AlCP) can be used, but to avoid saponification, a pretreatment esterification step is used to convert FFAs into methyl esters. Pretreatment requires a sulfuric acid catalyst (Lepper and Friesenhagen, 1986). AlCP has minimal heat and pressure requirements but long reaction times. Pretreatment adds additional equipment costs.

Acid Catalyzed Process

The acid catalyzed process (AcCP), which avoids the problem of saponification since acids do not react with FFA to form side products, is not prevalent at a large-scale production level, however, theoretical projects have been proposed. The forward reaction is very slow, and thus requires a large excess of methanol and high heat to proceed (Lotero, 2005). Sulfuric acid is primarily used as a catalyst in this process. While no pretreatment is required, AcCP has comparatively high raw material costs.

Supercritical Methanol Process

A third process is the supercritical methanol process (ScMP). This process requires a large excess of methanol, high heat and high pressure. Morias (2010) modeled the process developed by Cao et al. (2005) that uses propane as a co-solvent to decrease the critical point of methanol. Propane is used at a 0.05 to 1 propane to oil molar ratio. It is the most efficient process in terms of energy and material use; furthermore, reactions take place in minutes, rather than hours, as is the case with the other processes.

This process is a fairly new technological development with uncertain large-scale applications and costs; however, it is being increasingly well researched.

Use of Biodiesel

Like oilseed biodiesel, recycled biodiesel is blended with conventional diesel fuel before use. The university can run engines at a B20 mixture, above which adverse effects may occur (Kaligian 2014). Thus, a B20 fuel blend is assumed herein.

Waste Treatment, Recycling, and Reuse

Each process produces water and solids as wastes. Glycerol may be considered a co-product with a market value, and is thus not included as a waste. In the two catalyzed technologies, unreacted catalyst is reclaimed at the end of the reaction to be cleaned and reused in subsequent reactions. In all three processes, unreacted methanol can be recycled. Glycerol can also be harvested for crude WVO washing purposes. We do not consider recycling or reuse within our scope because the ratios of reusable materials are minor. UT waste treatment policy for a project of this type does not exist and so waste treatment is omitted in our model.

Method

LCA

We use environmental life cycle assessment (LCA) to determine the well-to-wheel GHG inventories of producing biodiesel through a large-scale WVO recycling program by using three distinct process technologies: AlCP, AcCP, and ScMP. These inventories are then compared to the equivalent results of LCAs of B5 oilseed biodiesel and diesel fuel.

Well-to-Pump

We use process-based methods to aggregate the impacts of unit processes required for the production and delivery of our target fuels from Well-to-Pump, that is, from raw material acquisition to the service station where university vehicles are fueled. The process data we use are from a number of databases. The US Life Cycle Inventory (USLCI) Database, created by the National Renewable Energy Laboratory, provides unit process data for diesel fuel, which we use to model conventional diesel as well as the diesel base in the oilseed B5 and recycled B20 biodiesel blends. Other raw materials are also modeled using the USLCI database, although those not catalogued therein are derived from the Ecoinvent database. The Ecoinvent database is Swiss based and includes Europe-centric unit processes, which we modify to reflect conditions on UT campus. See Appendix B for example modifications.

Table 2 shows the reactant and energy inventory associated with the three considered processes. Materials lists for a base-catalyzed, acid-catalyzed, and supercritical methanol processes are derived from Morias (2010).

Table 2. Materials list for three process technologies.

Unit Inputs (kg input/kg produced fuel)	AlCP	AcCP	ScMP
Raw Materials			
Waste Vegetable Oil	1.04	1.04	1.00
Methanol	0.13	0.21	0.11
NaOH	0.01	0.00	0.00
H2SO4	0.00	0.15	0.00
H3PO4	0.01	0.00	0.00
CaO	1.00E-04	0.09	0.00
Glycerol	5.00E-05	0.00	0.00
Propane	0.00	0.00	2.00E-05
Utilities			
Electricity (kwh)	1.01E-03	9.50E-04	4.01E-03
High pressure steam (300 C)	0.00	0.00	0.20
Medium pressure steam (250 C)	0.94	0.93	0.24
Low pressure steam (100 C)	1.75	3.37	0.00
Water (Process)	0.05	0.04	0.00
Water (Cooling)	3.14	5.03	0.51
Outputs (kg/kg)			
Glycerol	0.11	0.11	0.11
Biodiesel	1.00	1.00	1.00

Use Phase (Wheels)

Stationary combustion emissions factors provided by EPA are used to determine use phase emissions for the fuels we consider (2014). Table 3 gives the tailpipe emissions of diesel, biodiesel, and the various blend rates. Biodiesel is chemically the same whether it is produced using an AlCP, AcCP, or ScM process so it has the same emissions profile for the three technologies.

Table 3. EPA Stationary Combustion Emissions Factors

	g CO_2 e/MJ Stationary Combustion
Diesel	70.7
B5 Biodiesel	70.9
B20 Biodiesel	71.6

LCC

We model the fixed and variable costs required to construct and operate a plant capable of producing biodiesel from waste vegetable oil using life cycle costing in order to estimate the economic impact of biodiesel production. These fixed and variable costs vary based on decision variables such as capacity, service life, and operating hours. Furthermore, the future valuations of different project components change based on an assumed discount rate. Table 4 lists the assumptions for these decision variables.

Table 4. Decision Variables

Parameter	Value	Unit
Discount Rate	5	%
Service Life	15	yr
Operating Hours	1880	hr
Capacity (UT Plant)	2100	tonne/yr

1880 operating hours corresponds to a standard work year. Capacity is in terms of biodiesel produced, and roughly corresponds to the amount of waste vegetable oil available from Austin area restaurants, which produce an average of 3000 gallons per year (EPA). These assumptions are further discussed in the uncertainty section; however, it should be noted that economies of scale play a major part in determining costs due to equipment and raw material costs, among others.

We calculate the net present value (NPV) of a project constructed using AlCP, AcCP, or ScMP technology and divide the NPV by the MJ equivalent of fuel produced over the lifespan of the project to determine the break-even price, or the price per MJ of fuel to cover all costs incurred in building and operating the facility. The NPV of a project is determined by summing the fixed costs–onetime costs associated with capital goods (such as equipment and facilities in our case)–and variable costs–periodic costs associated with operation (such as raw material and labor costs)–discounted across the service life of the project. We then compare the break-even price of the three technologies with current prices for incumbent fuels.

Fixed Costs

Each production technology has unique equipment requirements due to various factors such as operating pressure, temperature, and acidity. Thus, equipment costs vary across technologies. Table 5 provides the equipment costs used in this study, which have been readjusted to 2014 dollars and scaled to the model plant operating capacity. These costs are extracted from various published sources.

Table 5. Equipment Costs of Various Production Technologies

Technology	Reference Year	Original Capacity	Original Cost ($)	Source
AlCP	2003	31,800 tonne/yr	3,616,000	Haas
AlCP	2000	8,000 tonne/yr	1,640,000	Zhang
AcCP	2000	8,000 tonne/yr	1,570,000	Zhang
ScMP	2007	36,000 tonne/yr	$1,377,000	Marchetti
ScMP	2005	8000 tonne/yr	$332,954	Kasteren

Available studies on the costs and benefits of biodiesel production focus on industrial scale production and thus, in most cases, this study scales costs significantly.

Other fixed cost investments, both direct and indirect, are estimated using methods adapted from Plant Design and Economics for Chemical Engineers to determine a total Fixed Capital Investment (FCI) using the equation $FCI = I_{IE} * (1 + \sum_{i=1}^{n} f_i)$, where I_{IE}= initial equipment investment f_i= the ratio factor for direct and indirect investments. Table 6 shows the ratios used for f_i.

Table 6. Direct and Indirect Fixed Cost Ratios

Direct investments	%
Investment for installed equipment	100
Instrumentation and controls	24
Piping	46
Electrical systems	8
Buildings	12
Yard improvements	7
Service facilities	48
Total direct investment	245
Indirect investments	%
Engineering and supervision	22
Construction expenses	28
Legal expenses	3
Contractor's fee	15
Contingency	30
Total indirect investment	98
Fixed Capital Investment (FCI)	343

Variable Costs

A number of recurring costs are required for biodiesel production, most notably raw materials and utilities, which vary depending on technology as shown in Table 2. Other indirect costs, shown in Table 7, are also accounted for in our model. Those costs not empirically available are estimated using methods from Plant Design for Chemical Engineers. Similarly, working capital, or cash on hand, is determined as 5% of FCI (Peters, 2003).

Table 7. Variable Costs.

Cost Category		Unit	Source (if assumed)
Indirect Costs			
Plant operating labor	79	$/hr	
Maintenance labor	74	$/hr	
Supervision	130	$/hr	
Total Labor	280	$/hr	
Labor fringe benefits	110	$/hr	40% of Total Labor
Operating supplies	16	$/hr	20% of Operating Labor
Maintenance Supplies Cost		$/yr	1% of capital costs, annually
General and Administrative Cost		$/yr	.5% of capital costs
Taxes-property		$/yr	Assumed as zero
Insurance		$/yr	.5% of capital costs, annually
Working Capital		$/yr	5% of FCI

All UT specific costs, plant operator salary for example, are empirically determined when possible. Furthermore, current or spot prices of raw materials are used when available. If we could not find such information, historic prices are adjusted to 2014 dollars. Costs based on capital costs vary across technologies. Sources for raw material costs can be found in Appendix C.

Glycerol Credit

Glycerol, a waste product in the conversion reaction, has a market value. Market rates are used to refund a credit in conjunction with produced biodiesel.

Results and Discussion

LCA

Cradle-to-use impacts of alkali catalyzed, acid catalyzed, and supercritical methanol processes along with B5 oilseed biodiesel and diesel fuel are shown in Figure 4. CO_2e inventories are broken into five categories, CO_2e Uptake, Land Transform CO_2e, Fossil CO_2e, Biogenic CO_2e, and Stationary Combustion Emissions. These inventories are aggregated as Net Well-to-Wheels Emissions.

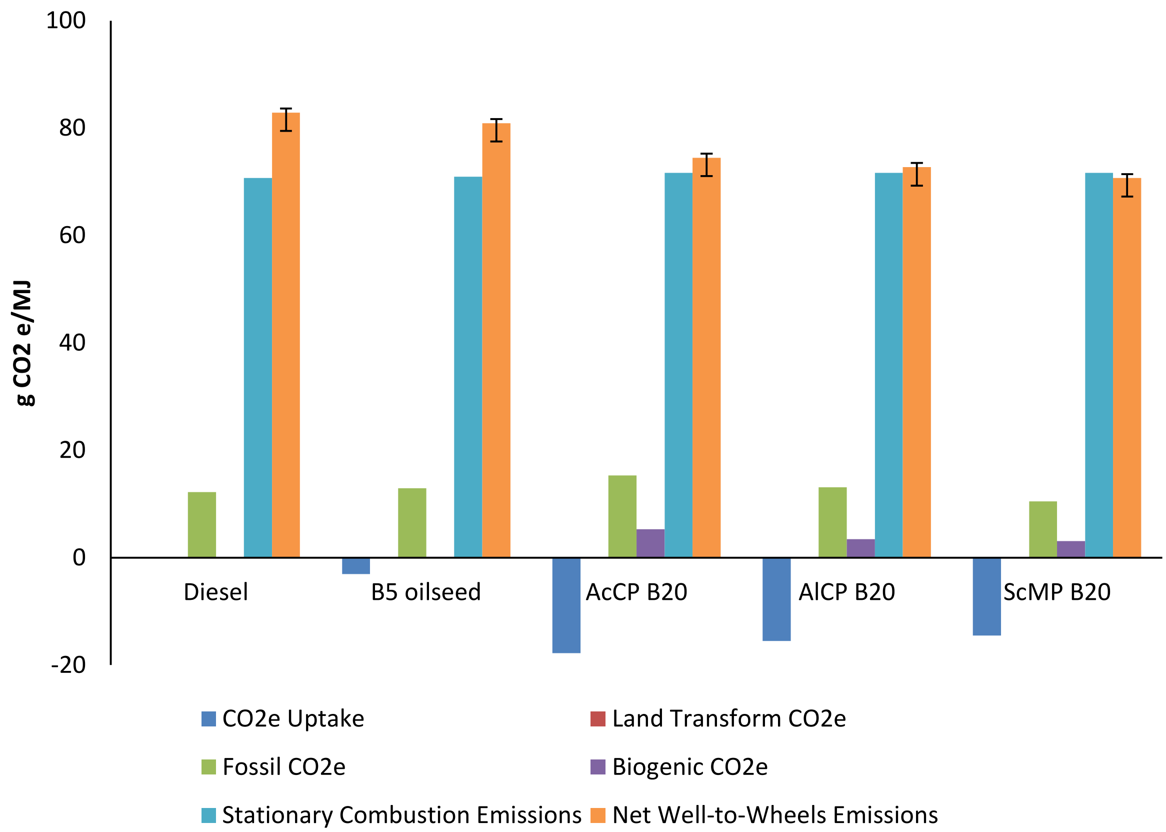

Figure 4. Breakdown of well-to-wheels GHG emissions.

GHG impacts across each fuel type differ in their source. A credit (negative GHG inventory) is assigned for each of the production technologies (here called "CO_2e Uptake") because carbon is sequestered in the growth of agricultural products in the supply chain of biodiesel. Accordingly, each unit process that contains an organic material balances the carbon sequestered in the production of that material against the carbon released in its combustion.

Fossil CO_2e is carbon released in the supply chain from fossil fuel sources. Predominantly, this impact can be attributed to the fuel mix for energy generation and steam production needed for different unit processes. Table 2 shows that the three production technologies have differing energy and fuel needs that result in slightly different fossil emissions. Surprisingly, diesel fuel and retail biodiesel, which have international and national scale infrastructures associated with their distribution and production, have fossil emissions comparable to UT based biodiesel production.

Biogenic CO_2e accounts for GHGs released during the production of crops; the large percentage visible for the three WVO processes come from the large percentage of biodiesel in the fuel mix, although there is a minimal amount also accredited to the B5 oilseed.

Stationary combustion emissions are the tailpipe emissions across the five fuels. The use phase contributes the greatest portion of CO_2e for all five fuel types considered. This is largely due to the high carbon content of both biodiesel and diesel fuel.

Land transform CO_2e accounts for GHG impacts from changing land uses. A number of processes along the supply chain might have land use impacts, such as the construction of a building that has some marginal impact on GHG emissions in an area.

Figure 4 also shows the net emissions across the fuel types. The GHG impact of all three recycled fuel types fall below the fuels in the university's current fuel mix.

Given the nature of environmental life cycle analysis, there will always be some variability and uncertainty in the results. This uncertainty is primarily driven by limitations in empirical data used in LCA modeling. The simplest uncertainty to identify is the truncation error inherent in process-based ELCA. Supply chains involve an indefinite number of steps that are oftentimes interconnected. Precisely modeling the full extent of a supply chain through process-based methods is therefore a futile endeavor, which is why system boundaries are established (Matthews, 2014).

Furthermore, modeling choices at the unit process level also contribute to the uncertainty of results. We identified emissions factors for electricity production, steam generation, and transportation distances and methods as the main drivers of GHG emissions at the unit process level. Emissions factors are estimates of the total GHG emissions produced by using a certain type of fuel mix for electricity production (Siler, 2012). Electricity generation technologies vary regionally but this spatial distribution is not well represented in the USLCI database. Similarly, steam is generated at various temperatures and using certain fuels, both of which affect its GHG impact. However, the exact specifications of steam that might be used in a UT-based project are unclear. Tailpipe emissions are major GHG contributors; thus both transportation distance and transportation type, e.g., fuel mix, truck weight, and other vehicle specifications, impact total GHG emissions over a fuel's life cycle.

To account for errors in emissions factors, permutations of the LCA model where run with varying electricity, steam, and transportation emission factors. The error ranges shown for net emissions on Figure 4 are the result of this sensitivity analysis on total GHG emissions for the recycled fuel production technologies. High and low parameters for each major GHG contributor are chosen to show the range between extreme assumptions. Our sensitivity analysis demonstrates that our baseline assumptions are relatively conservative. Additional information on the parameters included in the analysis can be found in Appendix D.

LCC

The net present value of the total cost to produce B100 from waste vegetable oil from the three production technologies is shown in Figure 6. These costs are then readjusted with current diesel prices to determine the B20 break-even price.

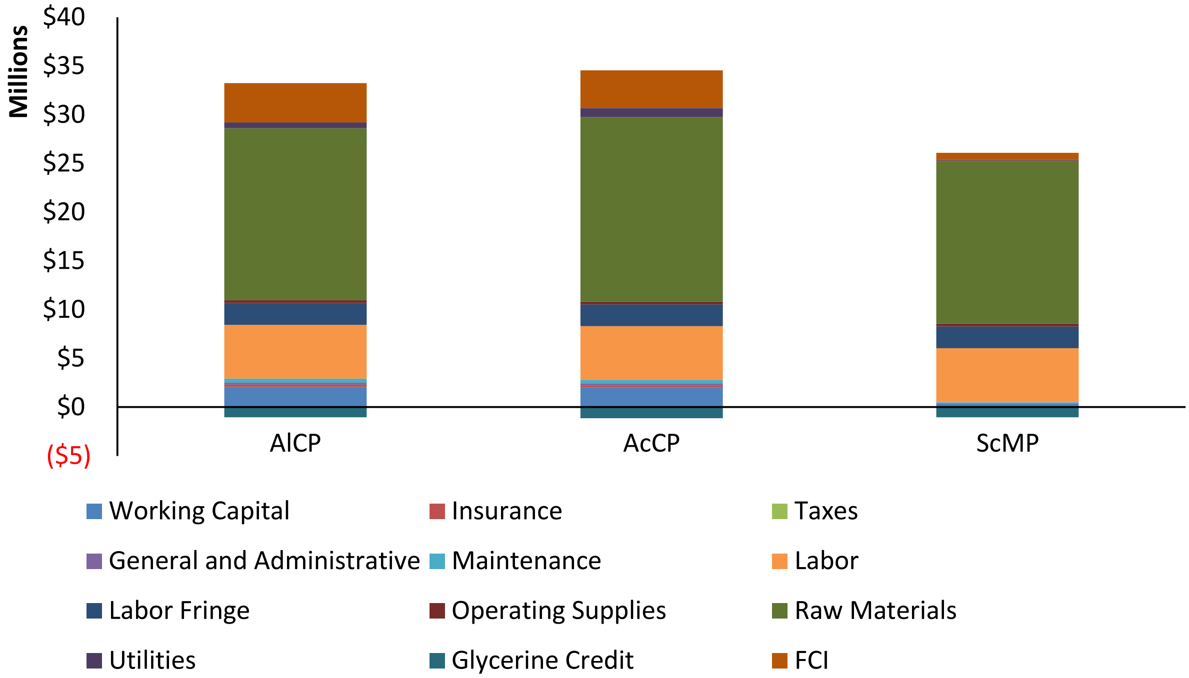

Figure 5. Net Present Value of Process Technologies

Variable costs, especially those associated with raw materials and labor, account for the majority of costs. The specific chemical demands of each technology drive the cost differences between the equipment and material needs of the technologies, as can be seen by the major differences in FCI and raw material requirements.

Break-even prices take into account the diesel fuel that is mixed into the produced biodiesel to create a B20 blend. Table 8 shows the breakdown of these costs for the three technologies. Because diesel is slightly more expensive than the produced B100 fuel, the unit price is raised above the B100 cost for all three fuels, but because of the high energy density of diesel, the change in price per MJ is slight.

Table 8. Unit Cost of Fuel Options

	Baseline ($/MJ)	Low	High
Diesel	0.0204	0.0143	0.0266
B5 oilseed	0.0210	0.0163	0.0257
AcCP B20	0.0203	0.0187	0.0226
AlCP B20	0.0202	0.0188	0.0225
ScMP B20	0.0191	0.0179	0.0213

For diesel and B5 fuel, the baseline price represents average $/MJ price in May 2014. High and low ranges for diesel fuel are a standard deviation above and below the baseline price over a period between 2000 and 2013. High and low ranges for the B5 price are a standard deviation above and below the baseline price taken from a period between 2005 and 2009. These data are provided by the Energy Information Agency.

With the many individual factors that contribute to the overall price of recycled biodiesel production, there is ample opportunity for variability and uncertainty in the results. Variable costs change dependent on market prices, while the fixed costs used in this study, especially equipment costs, are estimated and scaled from larger projects. The high and low ranges for the break-even price of the three biodiesel production technologies in Table 8 are averages across the high and low costs found from the sensitivity analysis performed below.

Tornado diagrams, such as the one for the supercritical methanol process shown in Figure 6, provide a range of possible break-even prices. The diagram shows the change in break-even price depending on the variations of fixed costs, variable costs, and decision variables in our model. The high and low extremes of each model parameter indicate the amount of swing that they introduce to the model. Only variables that resulted in a significant price swing are shown below. Appendix D provides tornado diagrams for the other two production technologies.

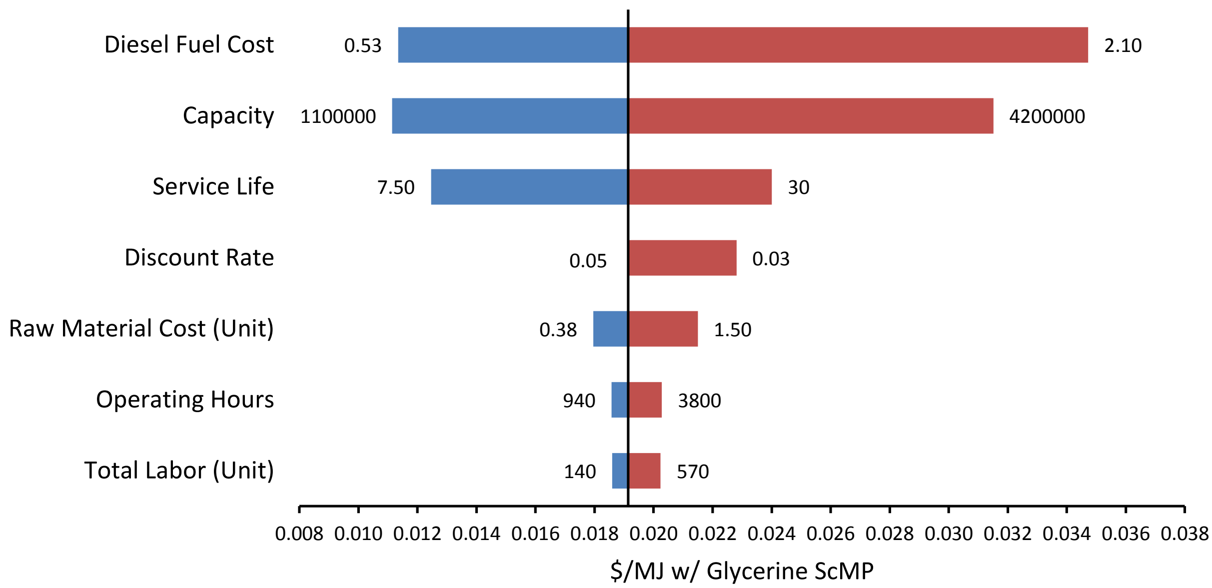

Figure 6. Cost variability for ScMP

We found the break-even price ranges found in Figure 6 by varying each fixed cost and variable cost to its extremes, while holding all other variables constant. For fixed and variable costs, high and low values were found empirically using historical prices or assumed to be either twice the baseline price on the high end or half the baseline cost on the low end. Decision variables and diesel cost are also included in this analysis. We used historical price ranges for diesel, while decision variables were given ranges of twice the baseline on the high end and half the baseline on the low end. Figure 6 shows that the decision variables assumed for the model play a major role in determining break-even price. This suggests that planning logistics such as plant size and equipment service life should be carefully accounted for in any future analysis. Additionally, the cost of diesel fuel is very deterministic in break-even price, which unfortunately is a factor outside of UT's control. Of the fixed and variable costs, our analysis shows that only raw material cost and total labor have a significant impact on break-even price.

Cost-Effectiveness

In order to compare our environmental and economic assessments, we calculate the emissions-effectiveness and cost-effectiveness of each fuel type, B20 AlCP, AcCP, ScMP, diesel, and B5 oilseed biodiesel on a per MJ basis. Figure 7 combines these two measures to give a graphical representation of each fuel type within a field of increasing impact and increasing cost. The closer a fuel is to the origin, the less impactful and cheaper it is. ScMP is clearly a superior choice from this perspective.

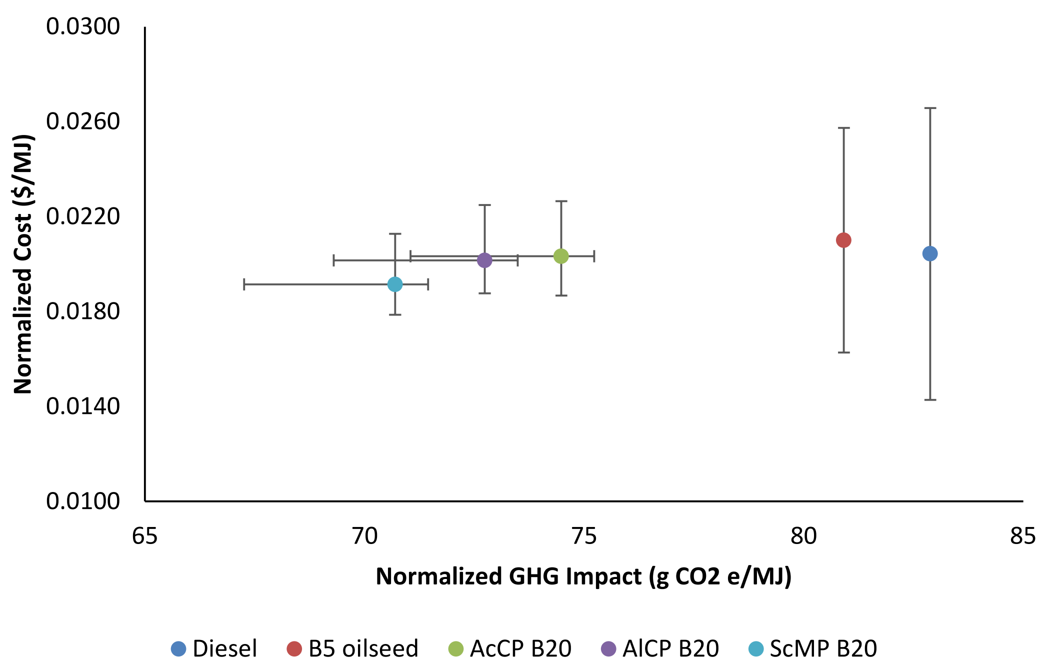

Figure 7. Cost and Emissions Effectiveness of Fuel Options

The other two production technologies are also an improvement in cost and emissions over the two incumbent technologies. However, it should be noted that the UT produced fuels are cheaper only at current prices. The volatile price history of diesel and B5 suggest that they may be a less expensive option in the future.

Furthermore, implementing any of the three biodiesel conversion technologies with the aim of reducing GHG emissions is cost competitive with many other clean energy and energy efficiency technologies that decision makers at UT may consider. Figure 8, created by McKinsey & Company, displays the marginal cost per associated ton CO_2e abatement for various technologies available to decision makers. It also shows each technology's potential for abatement per year.

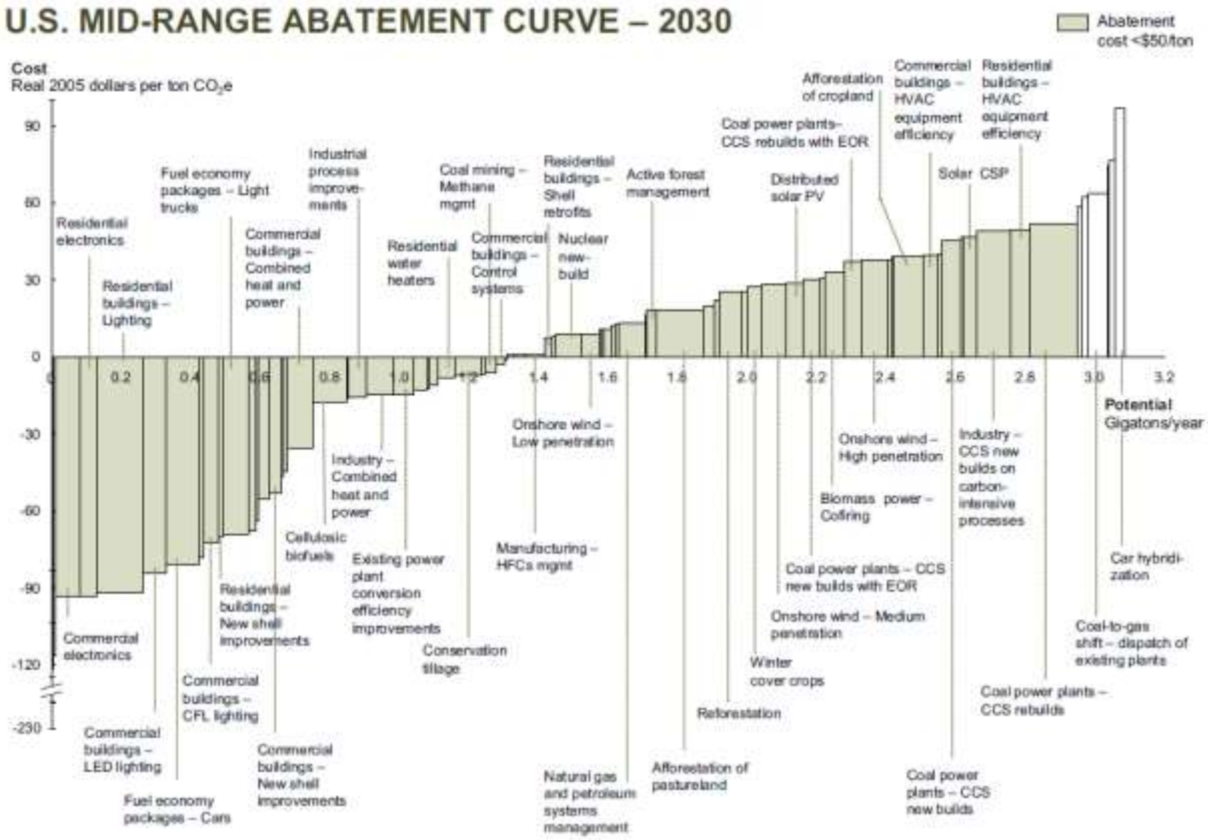

Figure 8. US Mid-Range Abatement Curve – 2030 (McKinsey Analysis)

McKinsey & Company calculated abatement costs and potentials in reference to prices and greenhouse gas impacts included in reports primarily from the US Energy Information Agency, among other federal and international data sources. For comparison, we have calculated GHG abatement costs and potentials for the three technologies in reference to current diesel fuel costs (Table 1) and the GHG impacts included in this report. Prices are discounted to 2005 dollars. The marginal cost of abatement and the potential for abatement are shown in Table 9. The low and high cases that are shown take into account the GHG reduction and price ranges determined in our sensitivity analysis. The baseline and low cases have a negative marginal cost because of the dollar savings per MJ in fuel cost that each of the technologies have relative to diesel fuel.

Table 9. GHG Abatement Potential and Marginal Cost of WVO Biodiesel Conversion.

	Marginal Well-to-Wheels $\frac{USD\ (2005)}{ton\ CO_2e}$			**Abatement Potential (Mton CO_2e)**
	Baseline	*Low*	*High*	
AcCP B20	-$8.55	-$263.00	$181.00	0.0117
AlCP B20	-$19.90	-$184.00	$140.00	0.0141
ScMP B20	-$78.30	-$218.00	$49.00	0.0169

In comparison to the many technologies available to the University to decrease GHG emissions, such as HVAC equipment efficiency, distributed solar, building retrofits, etc., both the AcCP and AlCP technologies are highly competitive from a cost standpoint, while ScMP is cost competitive with almost every technology included in the McKinsey study.

We calculated abatement potential assuming every MJ of B20 produced would replace a MJ of diesel fuel. Comparison to abatements in Figure 8 are less valuable since the McKinsey study was done on a national scale; however, if the UT could produce abatement numbers for other savings technologies these figures might become more relevant.

Conclusions and Recommendations

From the perspective of GHG emissions reduction, the University of Texas at Austin would be well served to implement a WVO to biodiesel recycling program. B20 fuels produced using AlCP, AcCP, and ScMP each show offer 2 CO_2e/MJ reductions compared to diesel of 10.1, 8.4, and 12.2, respectively. B5 biodiesel only offers a reduction of 2.0 2 CO_2e/MJ. Among these three technologies, ScMP offers the least GHG impact.

Additionally, from an economic standpoint, a WVO to biodiesel recycling program would lower the price of fuel on a MJ basis regardless of the production technology used. The university could save $0.05/L diesel equivalent ($0.19/gal) by running vehicles on ScMP B20, while it is currently spending $0.02/L diesel equivalent ($0.08/gal) more on B5. Furthermore, WVO to biodiesel is cost competitive in comparison to other GHG mitigation technologies, including some that the University may already be considering.

Considering the financial and environmental benefits of implementing a WVO to biodiesel recycling program, our recommendation would be to encourage the development of a recycling program based on ScMP technology.

ScMP is a nascent technology, so opportunities exist for UT to become a leader in promoting ScMP as an efficient method for producing recycled biodiesel at a large scale. Both the design and operation of a plant would provide the opportunity for professors and students to perform cutting-edge renewable fuels research. However, with no large-scale industrial plants currently in operation, there are risks from the technology's functionality at the large-scale. Thus we recommend further research into the logistics of plant construction and operation prior to making a final decision.

Appendix A: Reaction Mechanisms

AlCP Reaction:

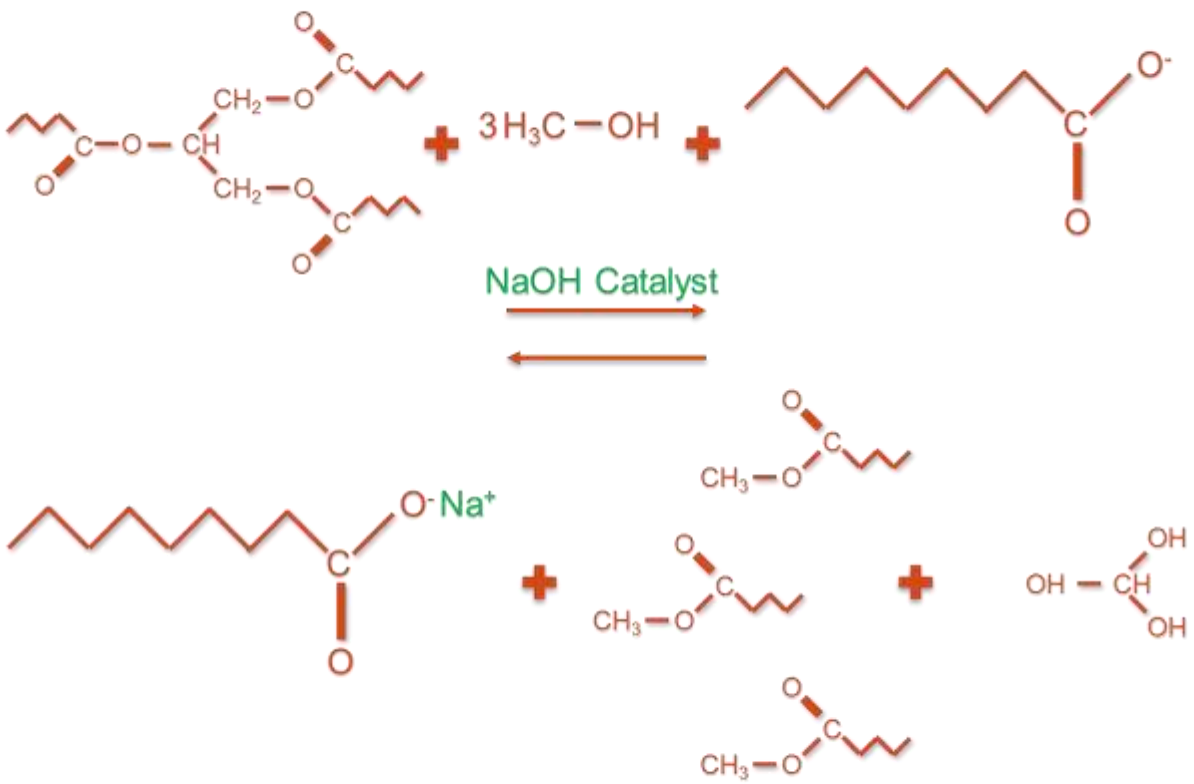

Figure 9. The AlCP reaction uses a base catalyst to encourage the forward reaction towards biodiesel. A waste product of soap is created through side reactions between free fatty acids and the base catalyst.

AcCP Reaction:

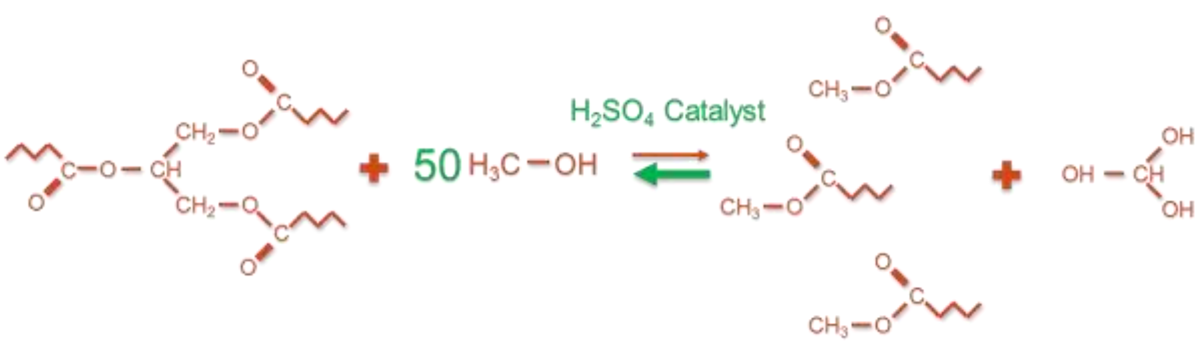

Figure 10. The AcCP reaction is catalyzed by an acid. It requires a large excess of methanol to proceed forward.

ScMP Reaction:

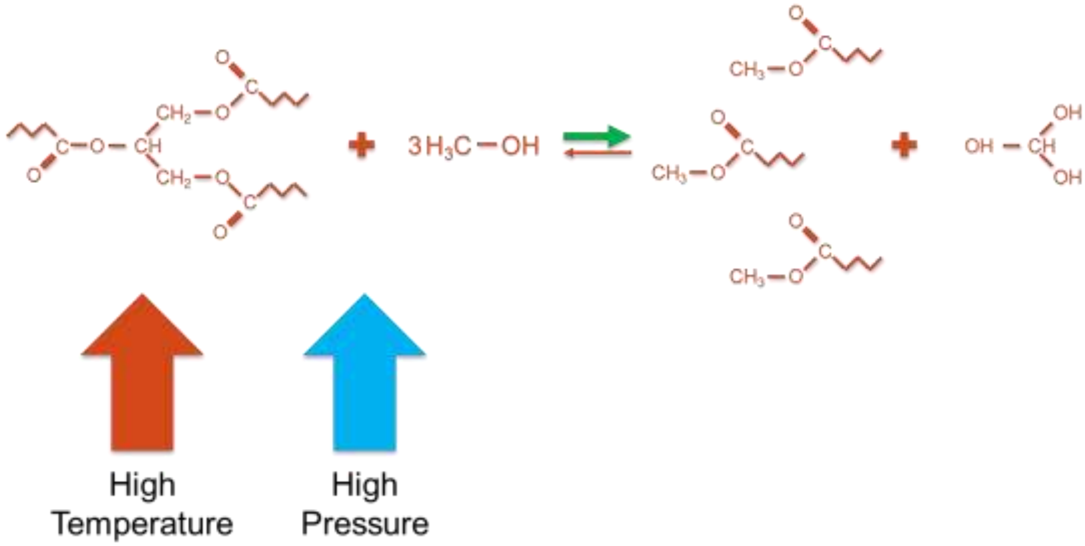

Figure 11. The ScMP reaction requires high temperature and pressure to allow methanol to enter a supercritical state, at which time it has a density approaching a liquid but viscocity and transport qualities closer to a gas (De Boer, 2011). The exact reaction mechanism is still debated. No catalyst is needed.

Appendix B: Example unit process modification

Table 10. Comparison between an original unit process and one modified to reflect conditions at UT. Primary changes are transportation modes and distances.

Ecoinvent					**Modified**				Comments
Products					*Products*				
Vegetable oil, from waste cooking oil, at plant/CH U		1	kg		Vegetable oil, from waste cooking oil, at plant/UT U		1	kg	
Resources					Resources				
Carbon dioxide, in air	in air	2.8435	kg		Carbon dioxide, in air	in air	2.8435	kg	
Materials/fuels					*Materials/fuels*				
Electricity, medium voltage, at grid/CH U		0.0508	kWh		Heat, natural gas, at industrial furnace >100kW/RER U		0.77304	MJ	
Heat, natural gas, at industrial furnace >100kW/RER U		0.77304	MJ		Transport, single unit truck, diesel powered/US		0.00805	tkm	Average distance to UT campus
Transport, freight, rail/CH U		0.08076	tkm		Vegetable oil esterification plant/CH/I U		9.1E-10	p	
Transport, lorry 20-28t, fleet average/CH U		0.00673	tkm						
Transport, lorry 3.5-20t, fleet average/CH U		0.10082	tkm						
Vegetable oil esterification plant/CH/I U		9.1E-10	p						
Methanol, at regional storage/CH U		0.0269	kg						
Glycerine, from rape oil, at esterification plant/CH U		0.1056	kg						
Sulphuric acid, liquid, at plant/RER U		0.0021	kg						

Electricity/heat					*Electricity/heat*				
Emissions to air					*Emissions to air*				
Heat, waste	high. pop.	2.6217	MJ		Heat, waste	high. pop.	2.6217	MJ	
Carbon dioxide, biogenic	high. pop.	0.16657	kg		Carbon dioxide, biogenic	high. pop.	0.16657	kg	
Emissions to water					*Emissions to water*				
BOD5, Biological Oxygen Demand	river	0.0035	kg		BOD5, Biological Oxygen Demand	river	0.0035	kg	
COD, Chemical Oxygen Demand	river	0.0035	kg		COD, Chemical Oxygen Demand	river	0.0035	kg	
DOC, Dissolved Organic Carbon	river	0.00043	kg		DOC, Dissolved Organic Carbon	river	0.00043	kg	
TOC, Total Organic Carbon	river	0.00043	kg		TOC, Total Organic Carbon	river	0.00043	kg	
Emissions to soil					*Emissions to soil*				
Oils, biogenic	industrial	0.0005	kg		Oils, biogenic	industrial	0.0005	kg	

Appendix C: Empirical Variable Prices

Table 11. Variable Prices used and source.

Variable Costs				
Inputs	baseline (4/6/2014)	units	Corrected ($/kg)	**baseline**
Raw Materials				
Used Cooking Oil	0.315	$/lb	0.694455	http://www.ams.usda.gov/mnreports/lswagenergy.pdf
Methanol	1.8	$/gal	0.600543	http://www.methanex.com/products/methanolprice.html
NaOH	309.5	$/tonne	0.3095	http://www.indexmundi.com/commodities/?commodity=potassium-chloride
K2SO4	309.5	$/tonne	0.3095	http://ycharts.com/indicators/potassium_chloride_muriate_of_potash_spot_price
H2SO4	95	$/tonne	0.095	http://fw.crugroup.com/fertilizer/dashboards/sulphuric-acid/reports/weekly-preview-reports/2012/9/192388/192391
H3PO4			0.458766	Zhang
CaO				
Glycerol	0.202397	$/lb	0.446208	http://www.oleoline.com/wp-content/uploads/products/reports/Jun2013_966055.pdf
Propane	1.061	$/gal	0.568533	
Utilities				
Electricity (kwh)	0.073	$/kWh	0.073	University cost
Steam (from natural gas)	11.33421	$/tonne	0.011334	
High pressure steam (300 C)	13.4931	$/tonne	0.013493	Zhang
Medium pressure steam (250 C)	11.33421	$/tonne	0.011334	linear interpolation
Low pressure steam (100 C)	9.17531	$/tonne	0.009175	Zhang
Water (Process)	5.12148	$/Mgal	1.35E-06	University cost
Water (Cooling)	0	$/m3	0.000007	University cost

Appendix D: Sensitivity Analysis

Table 12. Parameters changed in ELCA sensitivity analysis.

Parameter	Base Case	Min	Max	Units	Unit Process	Description
Transport, single unit truck, diesel powered/US	0.00805	0.001	0.014	tkm	Vegetable oil, from waste cooking oil, at plant low/UT U	Distance traveled to transport waste oil in a radius around UT
Stream Variable	On-site steam average E	Steam from direct oxidation of n-butane, at plant/RER S	On-site steam average E	-	Recycled Biodiesel, at plant, Morias AcCP/UT U	steam emissions factor
Electricity Variable	Electricity, medium voltage, at grid/US U	Electricity, low voltage, at grid/US U	Electricity, high voltage, at grid/US U	-	Recycled Biodiesel, at plant, Morias AcCP/UT U	electricity emissions factor

Only parameters with >0% swing are shown.

Acid Catalyzed Process

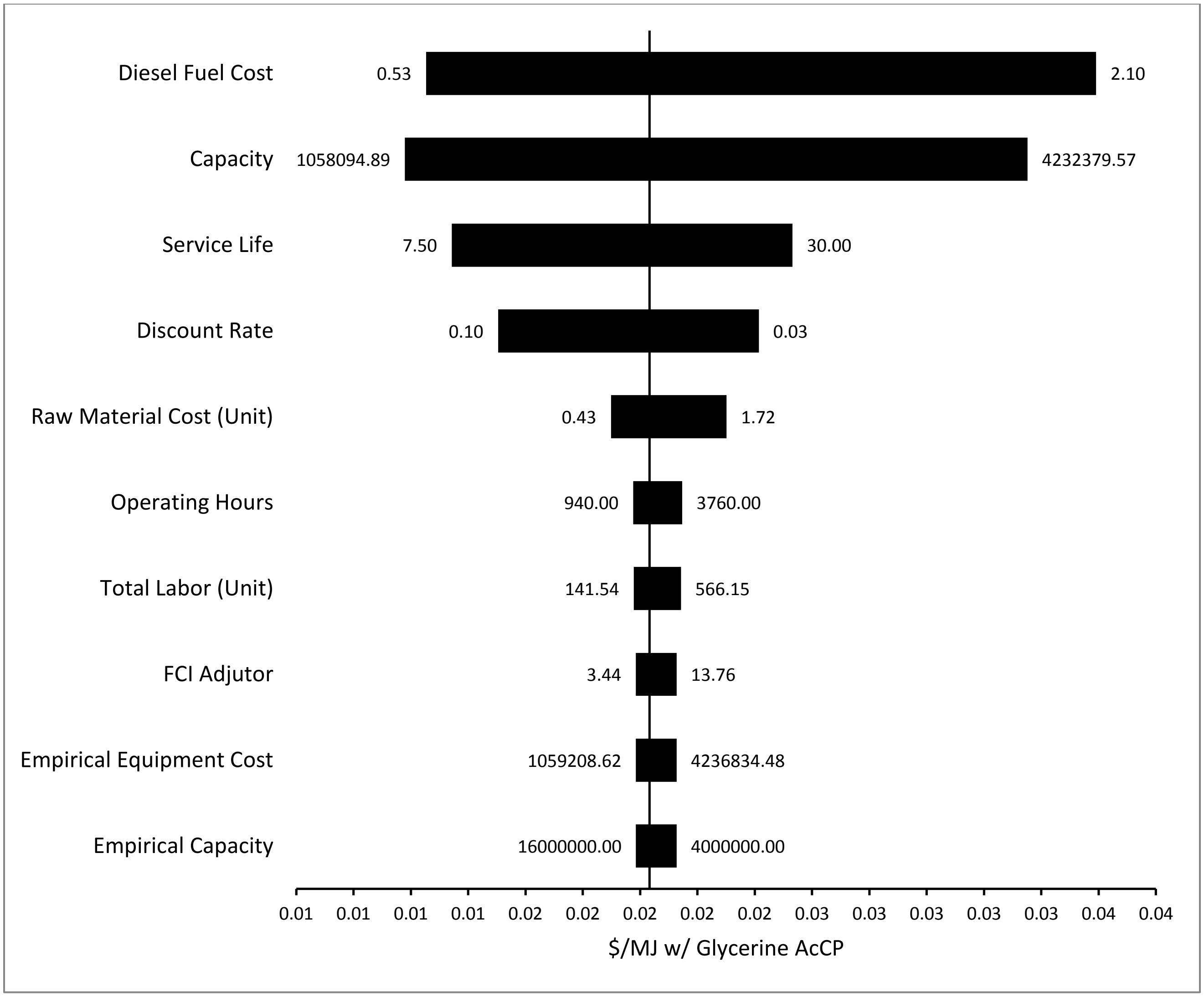

Figure 12. Acid Catalyzed Process Tornado Diagram

Alkali Catalyzed Process

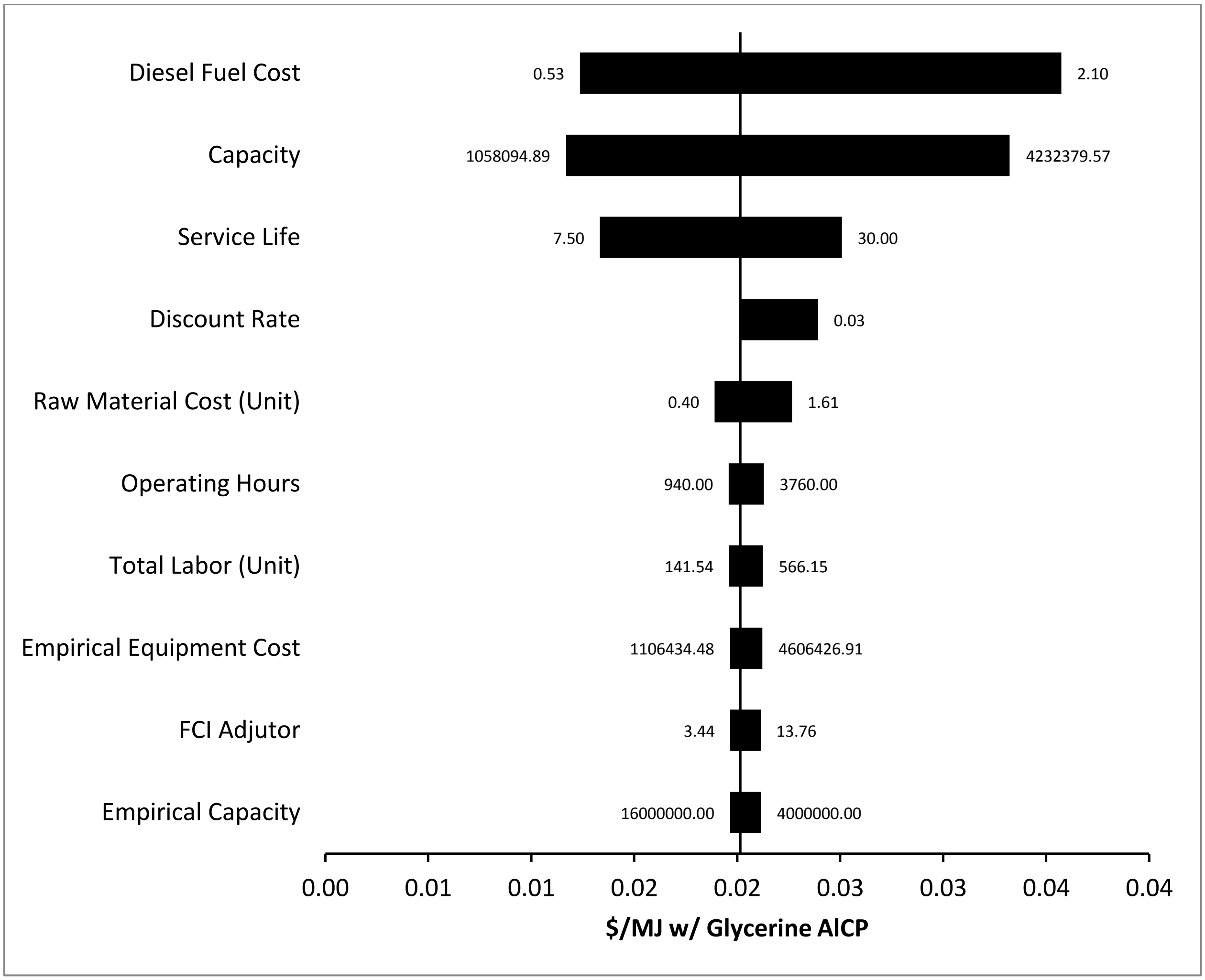

Figure 13. Alkali Catalyzed Process Tornado Diagram

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