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TECHNO-ECONOMIC AND LIFE CYCLE ASSESSMENT OF HYDROTHERMAL PROCESSING OF MICROALGAE FOR BIOFUELS AND CO-PRODUCT GENERATION

by

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Old Dominion University in Partial Fulfillment of the
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May 2018

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ABSTRACT

TECHNO-ECONOMIC AND LIFE CYCLE ASSESSMENT OF HYDROTHERMAL PROCESSING OF MICROALGAE FOR BIOFUELS AND CO-PRODUCT GENERATION

Andrew P. Bessette
Old Dominion University, 2018
Director: Dr. Sandeep Kumar

Traditional processing methods of algae to biofuels require dewatering after harvesting of the algae before the lipids can be extracted. This is typically the most energy intensive and therefore the most expensive step. Old Dominion University (ODU) has successfully utilized a flash hydrolysis (a kind of hydrothermal) process where proteins are solubilized into the liquid phase of product and the remainder lipid-rich, low nitrogen product is separated into a solid phase. The solid phase (lipid-rich) is then an ideal candidate for biofuel feedstock and the liquid phase, or hydrolysate, can be used for coproducts such as a source of nutrients for new batches of algal cultivation or fertilizer production. The importance of this research lies within the energy conservation associated with the flash hydrolysis process, the quality of the co-products that are generated during the flash hydrolysis process, and the subsequent processing methods utilized to recover the nutrients not directly used for biofuel products. Processes which complement each other in the processing of microalgae to biofuel must be utilized for improving life cycle assessment (LCA) and technoeconomic analysis (TEA) results. These LCA and TEA data are critical for investors in both the public and private sectors. A valuable return on investment must be quantified in order for investors to move forward with advanced biofuels production. A combination of resources are utilized in this dissertation to quantify the LCA and TEA of the hydrothermal processes that are utilized in the ODU Biomass Research Laboratory (BRL) which include Argonne National Laboratory GREET, SuperPro Designer, Aspen Plus, and SimaPro's

Ecoinvent databases. This dissertation evaluates the novel processes researched in the BRLfrom the microscopic flash hydrolysis process level to a community level macroscopic evaluation. The clarity of how the flash hydrolysis compares with other hydrothermal processes is studied by conducting a LCA comparison. The flash hydrolysis process is then modeled utilizing two different microalgae species with varying cultivation and nutrient extraction properties. The alternate downstream processing methods for recovering preserved nutrients is then modeled for LCA and TEA results in order to quantify how coproduct generation offsets energy costs associated with algae biofuel processing. The final chapter of this dissertation utilizes the LCA and TEA results captured within the preceding assessments to develop a sustainable community model with algae cultivation and downstream processing at the focus of the sustainable community and an ultimate goal of zero net energy and zero waste system boundaries for the community.

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The Biomass Research Laboratory has been a collective and collaborative organization of which this dissertation would not have been possible. The efforts of which every member puts into researching new and innovative ways to improving environmental sustainability, reducing waste streams, and furthering technology in renewable energy sources is a true testament of the purpose of the team. Thank you to members past, members present, and future members for their pending contributions. I would like to thank Dr. Ben Stuart and Dr. Sandeep Kumar for their guidance and leadership for both the Biomass Research Laboratory and during the duration of my graduate studies and also to my dissertation committee. Thank you to Dr. Eleazer Resurreccion and Montana State University Northern for the amazing collaboration with our research. And to my advisor, Dr. Sandeep Kumar, thank you for believing in me and encouraging me to pursue this great adventure.

NOMENCLATURE

AD	anaerobic digestion
AF	autoflocculation
AP	atmospheric precipitation
APD	algae process description
BI	biofuel intermediate
CAPDET	Computer-Assisted Procedure for Design and Evaluation of Wastewater Treatment Systems
CHG	catalytic hydrothermal gasification
CHP	combined heat and power
CIDI	compressed ignition, direct injection
CSO	clarified slurry oil
DAF	dissolved air flotation
DOE	U.S. Department of Energy
EISA	Energy Independence and Security Act
EMTR	effective marginal tax rate
EROI	energy return on investment
EUI	energy use intensity
FCC	fluidized catalytic cracker
GHG	greenhouse gas
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation
GWP	global warming potential
HAp	Hydroxyapatite
HTL	hydrothermal liquefaction

HTM	hydrothermal mineralization
HRJ	hydroprocessed renewable jet fuel
INL	Idaho National Laboratory
ISO	International Standards Organization
LCA	life cycle assessment
LCI	life cycle inventory analysis
LCIA	life cycle impact assessment
LCO	light-cycle oil
LEA	lipid extracted algae
LHV	lower heating value
LSD	low-sulfur diesel
MC	methane combustion
mmBtu	million Btu
MSW	municipal solid waste
NAABB	National Alliance for Advanced Biofuels and Byproducts
NBB	National Biodiesel Board
NPV	net present value
NREL	National Renewable Energy Laboratory
ORNL	Oakridge National Laboratory
PAR	photosythetically active radiation
PBR	photobioreactor
PI	profitability index
PNNL	Pacific Northwest National Laboratory
PTW	pump to well

PVC	polyvinyl chloride
RA	resource assessment
REU	radiation use efficency
RFG	reformulated gasoline
SI	spark ignition
SLS	solid liquid separation
SMR	steam methane reforming
SNL	Sandia National Laboratory
SPK	synthetic paraffinic kerosene
TEA	techno-economic analysis
VGO	vacuum gas oil
WTP	well to pump
WTW	well to wheels

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CHAPTER 1

INTRODUCTION

1.1 Introduction

The conversion of biomass into liquid fuel products is an area of research that is growing as the world strives to reach the growing demand for petroleum and fossil fuels in order to meet its energy needs. Ethanol production through corn based first generation feedstock production in the United States has reached its limit of 15 billion gallons annually according to the renewable fuel standard set by the Energy Independence and Security Act (EISA) of 2007. EISA requires that by the year 2022, 36 billion gallons of renewable fuel (20% of the United States consumption) must be produced annually. This must come from second generation lignocellulosic biomass and other biofuels. Researchers and industry professionals are developing ways to increase the conversion efficiency of second generation feedstock such as forest residues, agricultural residues, and energy crops that are not used for food production. Thermochemical conversion processes of second generation biomass are not yet efficient enough to ensure a profitable return on investment for most liquid fuel products.

Algae, which is a third-generation biomass, has the potential to fill the gap that exists in our production of renewable fuels and the requirement set forth by EISA. Water based microalgae has several benefits that other lignocellulosic biomass does not. It has a rapid growth rate, grows in wastewater effluent and saltwater streams, does not require arable land (which means it does not compete with food crops), and can utilize CO_2-rich flue emissions. Microalgae also contains a high proportion of lipids. This is important because this is the main component that will yield the bio-oil which is then upgraded to liquid fuels suitable for using in the transportation industry. The oil content of microalgae is typically between 20-50% (Chisti, 2007). Table 1.1 shows how microalgae compares to other lignocellulosic biomass that are used for biofuel production.

Table 1.1 Comparison of Biomass Oil Production Potential

Crop	Oil Yield Gallons/Acre/Year
Soybeans	48
Sunflower	102
Jatropha	202
Oil Palm	635
Algae	1000-6500

The Old Dominion University Biomass Research Laboratory has been conducting experiments in flash hydrolysis (FH) over the last six years. Several journal articles have been published on the experimental results (Barbera, Sforza, Kumar, Morosinotto, & Bertucco, 2016; Barbera, Teymouri, Bertucco, Stuart, & Kumar, 2017; Bessette et al., 2018; Garcia-Moscoso, Obeid, Kumar, & Hatcher, 2013; Garcia-Moscoso, Teymouri, & Kumar, 2015; Talbot, Garcia-Moscoso, Drake, Stuart, & Kumar, 2016; Teymouri et al., 2016; Teymouri, Stuart, & Kumar, 2017, 2018).

The experiments conducted by the BRL utilized a continuous flow reactor at subcritical conditions and short residence times. Temperatures ranged from 240 °C to 320 °C at residence times ranging from 6 seconds to 12 seconds. Pressure was maintained at 3000 psi. The benefit of bringing water to subcritical conditions is that the transport and solvent properties can be tuned for efficiently converting biomass to high energy density fuels and functional materials (Garcia-Moscoso et al., 2013). As reported in *Kinetics of Peptides and Arginine Production from Microalgae (Scenedesmus sp.) by Flash Hydrolysis*, the highest lipid content reported in the solid product analysis was obtained utilizing conditions at 280 °C and 12 seconds. These conditions were used in the mass and energy balance. The properties of water in the subcritical region allow for an increased capacity for dissolving organic compounds and enhances hydrolysis reactions. This allows for the hydrolysis of proteins/peptides into the liquid phase and eliminates the use of corrosive materials.

Microalgae grow in water and therefore require intensive dewatering after harvesting when utilizing traditional biofuel production techniques. The dewatering step is one of the most energy intensive and expensive steps in the biofuel production life cycle. The hydrothermal process of FH eliminates the need for dewatering since a slurry mixture is used in the continuous flow reactor. The slurry concentrations can have a wide range of values, some reports have values up to 37% (Elliott et al., 2013). The value utilized these models was 20% based upon the research conducted by Elliot et al. in 2013 as reported in *Process Development for Hydrothermal Liquefaction of Algae Feedstocks in a Continuous-Flow Reactor* published in Algal Research.

The solid phase product then contains lipids, enriched in carbon and depleted in nitrogen, which is a good feedstock for biofuels production. One of the major benefits of the continuous flow flash hydrolysis process over hydrothermal liquefaction (HTL) batch reactor process is that the coproducts produced in the liquid phase are not degraded. In the HTL process, a longer residence time is required which causes the formation of tar, phenols, oxygenated hydrocarbons, and aromatic compounds (Garcia-Moscoso et al., 2013). The FH process avoids this has a very short residence time so the valuable coproducts can then be used for offsetting the cost of production of the biofuel.

The FH process utilized in the Old Dominion University Biofuels Laboratory has not been evaluated for Life Cycle Assessment (LCA) or Techno-economic Analysis (TEA). Thus far, experiments have proven that the process can utilize subcritical water at low residence times to separate lipids into a solid phase product without traditional thermochemical treatment. The energy consumption during this process should be lower when compared to traditional thermochemical treatment of algae and should be competitive when compared to HTL. The total energy consumption of the FH process must be determined and used as an input parameter in the total LCA of the algae-based transportation fuel.

This dissertation evaluates FH compared to HTL for life cycle comparison using GREET in the production of biodiesel, renewable diesel II, and renewable gasoline. The research is then further expanded to conduct a LCA and TEA of FH and the production of valuable co-products. This research is important to see how the introduction of co-products into the effects the energy and financial returns. Finally, a sustainable community design modelled around algae cultivation is assessed for life cycle and techno-economic implications in an effort to reach a net zero energy and waste rural community in an effort to expand algae cultivation and downstream processing into the macroscopic levels of analysis. A combustion turbine generator is the primary source of electricity for the rural community modeled, fueled off of anaerobic digestion gas produced from digested algae biomass and segregated municipal solid waste.

CHAPTER 2

LIFE CYCLE ASSESSMENT OF ALGAE BASED BIOFUELS USING ARGONNE GREET MODEL

2.1 Background of the Study

The feasibility of converting algae biomass into a liquid transportation fuel product must be fully assessed in order to ensure that the return on investment and environmental impacts are preferable when compared to traditional petroleum transportation fuel products. A LCA is a technique for assessing the environmental aspects and potential impacts associated with a product by compiling an inventory of relevant inputs and outputs of a product system, evaluating the potential impacts associated with those inputs and outputs, and interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study (The International Standard of the International Standardization Organization, 2006a, 2006b). The assessment evaluates all aspects of the product throughout the products life. This is typically called cradle to grave but in this assessment, it will be referred to as well to wheels (WTW). This is from raw material acquisition, to cultivation, biomass processing, conversion to transportation fuel, and final combustion in the mode of transportation. Also included is the transportation processes involved during the products life.

The purpose of this study is to conduct a total LCA of FH compared to HTL in order to determine the preferred method of converting algae biomass into a liquid transportation fuel. This assessment targets analysis of the environmental impact in terms of GHG emissions and total energy usage in terms of energy input and output. This research aims at comparing the two processes using Argonne GREET model. A WTW assessment was conducted which evaluated raw material acquisition, to cultivation, biomass processing, conversion to transportation fuel, and final combustion in the mode of transportation in the system boundary. Biodiesel 20 (BD20), renewable gasoline (RG), and renewable diesel II (RDII) were compared on each model. In addition, the conventional petroleum fuel's petroleum-based reformulated gasoline (RFG) and petroleum-based low sulfur diesel (LSD) were compared.

2.2 Materials and Methods

2.2.1 LCA Methodology

This LCA was conducted in accordance with the International Standards Organization (ISO) 14040 and ISO 14044 (The International Standard of the International Standardization Organization, 2006a, 2006b). These standards were used to develop the various systems to be studied, the system boundaries, the functional unit to be evaluated, and all of the inputs and outputs to be evaluated. The system boundary for this LCA includes a WTW analysis of the fuel production cycle. Activities, which are excluded from this LCA, include human activities such as those associated with the cultivation of the algae and those activities associated with worker transportation to and from work. Infrastructure costs and facility construction costs are also excluded. This includes equipment purchase, replacement, and decommissioning. The unit process data are modeled on an energy basis and the functional unit of this study is based upon 1 million Btu (mmBtu) of the particular fuel produced. No effect from land use change has been taken into consideration in this study.

The systems to be studied can be seen in Table 2.1 below.

Table 2.1 Systems to be Studied in the LCA

Algae-Related Unit Processes	Algae Agriculture
	Algae oil production, transport, storage
	Co-product production, transport, use
	Biodiesel production, storage, use
	Renewable diesel II production, storage, use
	Renewable gasoline production, storage, use
	Vehicle use
Comparisons	ODU algae process biodiesel vs. harmonization biodiesel vs. HTL biodiesel vs. petroleum diesel
	ODU algae process renewable diesel II vs. harmonization renewable diesel II vs. HTL renewable diesel II vs. petroleum diesel
	ODU algae process renewable gasoline vs. harmonization renewable gasoline vs. HTL renewable gasoline vs. petroleum gasoline

2.2.2 Modelling Software

The modeling software used is called Greenhouse gases, Regulatory Emissions, and Energy use in Transportation (GREET) model Argonne National Laboratory, 2016 version. The results of the model simulation were then used to compare the two different algae process products (FH and HTL) with their petroleum counterpart (RFG and LSD). Comparisons include total energy use and total greenhouse gas (GHG) emissions. This study was conducted using the MS Excel based version of GREET. This program is called GREET1. This decision was based upon correspondence with the GREET team at the Argonne National Laboratory (ANL). The reason is that the MS Excel version has been the basis of their algae publications. The ANL team conducted two LCA simulations entitled the Harmonization report and the HTL report. When modeling algae biomass in the production of transportation fuels, GREET1 is used in conjunction with a separate MS Excel based software called the Algae Process Description

(APD). The combined APD-GREET1 system covers all five life cycle stages which consist of feedstock cultivation, feedstock transport, biofuel production, biofuel transport, and biofuel end use in vehicles. The energy consumption of the flash hydrolysis process was determined by conducting an energy and mass balance of the system based upon a 12 second residence time yielding 48 kg/h of slurry at a 20% solids concentration at 3000 psi and 280 °C. These data were then processed using the modeling software provided by ANL.

2.2.3 Algae Agriculture

There are different methods for growing microalgae. The methods range from autotrophic, where CO_2 is used as the primary source of carbon, to heterotrophic, where a more complex carbon substrate is required. Mixotrophic growing processes use a combination of the two carbon substrate types. This study focused on autotrophic growing conditions in an open pond setting and only considered nutrient inputs which are key to that growth mode. Alternate photobioreactor (PBR) scenarios are also available in APD. NREL investigated process and cost trade-offs for cultivation in either open raceway ponds or in tubular PBR systems and found that PBR's are expected to cost at least twice as much as open pond cultivation on a per-gallon selling price basis despite several key advantages of the PBR system (Ryan Davis, Biddy, & Jones, 2013).

The production of the ponds was limited to 330 days per year and the annual average production was produced from the ANL Harmonization report which took the average from all sites in the harmonization study and resulted in 13.2 g/m2/d with an annual average evaporative loss minus precipitation of 0.0423 L/g-algae. APD uses the evaporative loss to add the required water to the fresh water demand and to the energy for supplying the fresh water. The model also accounts for circulation power of the pond in which a value of 48 kWh/ha/d was used for a total circulation power of 0.000364 kWh/g. The energy used to pump water to the site and into the culture was set to 0.000123 kWh/L, 0.000025 kWh/L to pump the culture, and a CO_2 supply rate of 2.017 g/g of algae. The algal oil fraction was set at 25%. All of these values were used for all three algal pathway models. It should be noted that future comprehensive studies should utilize site specific data for average productivity and evaporative loss for more complete results. The nutrient source input values were ammonia (0.00954 g/L) and diammonium phosphate (0.00869 g/L). The summary of the growth and first dewatering input values can be seen in Table 2.2.

Table 2.2 Growth and First Dewatering Input Values

Parameter	Model Input
Productive Days/yr	330
Algal Oil fraction	25%
Evaporative Loss L/d	0.00423
Circulation Power kWh/g	0.000364
Carbon Dioxide Loss	18%
Energy to pump water to site and into culture kWh/L	0.000123
Energy to pump culture kWh/L	0.000025
Carbon Dioxide supply rate g/g algae	2.017
Media Water g/dry g algae	5.73
Ammonia g/dry g algae	0.0191
Diammonium Phoshate g/dry g algae	0.0172
Site Electricity kWh/dry g algae	0.000487
Input per Unit Output	2.46

The “Nutrients” worksheet in APD demonstrates nutrient recycling but the ANL argues that APD does not model nutrient recycling well and that nutrient recycling is better modeled with alternative software such as Aspen.

The CO_2 that is used can come from different sources. This study assumes that the CO_2 is generated by flue gas which is treated as atmospheric carbon. This creates a carbon credit for the original CO_2 that the algae use for its autotrophic growth. Figure 2.1 (Frank, Han, Palou-Rivera, Elgowainy, & Wang, 2011) displays the carbon flows in the pathway.

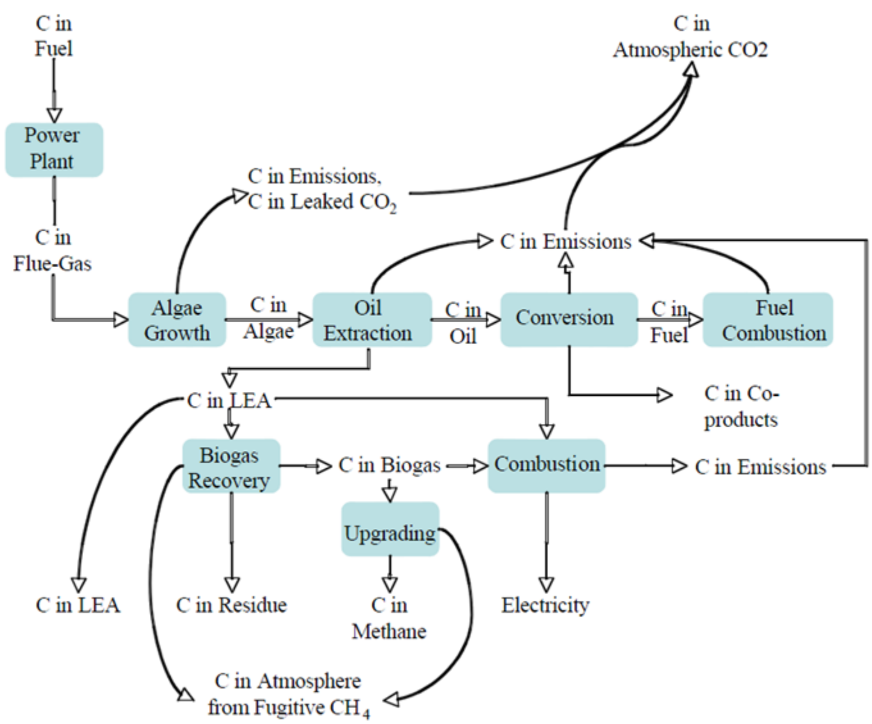

Figure 2.1 Carbon Flows in the Algal WTW Pathway

2.2.4 Algae Oil Production

The dewatering step is one of the most energy intensive and expensive steps in the biofuel production life cycle. The hydrothermal process of FH eliminates the need for dewatering since a slurry mixture is used in the continuous flow reactor. There is however, an initial dewatering step to concentrate the algae biomass. The dissolved air floatation (DAF) process uses a 90% algae recovery efficiency and requires a power consumption of 0.000133 kWh/dry g algae. This value was obtained through the Compute-Assisted Procedure for Design and Evaluation of Wastewater Treatment Systems (CAPDET) (Harris, Cullinane Jr, & Sun, 1982), which is a detailed process and design and cost estimating system for wastewater treatment systems. The models also uses chitosan as a coagulant for DAF and an input value of 0.004 g/dry g algae. The centrifuge process uses a 95% algae recovery efficiency and a required energy input of 1 horsepower per gallon per minute (Harris et al., 1982). This yields a value of 0.00329 kWh/kg influent (0.0000548 kWh/dry g algae).

The slurry concentrations can have a wide range of values, some reports have values up to 37% (Elliott et al., 2013). The value utilized in this experiment was 20% based upon the research conducted by Elliot et al. in 2013 as reported in *Process Development for Hydrothermal Liquefaction of Algae Feedstocks in a Continuous-Flow Reactor* published in Algal Research (Elliott et al., 2013). The experimental setup of the FH process can be seen in Figure 2.2, below:

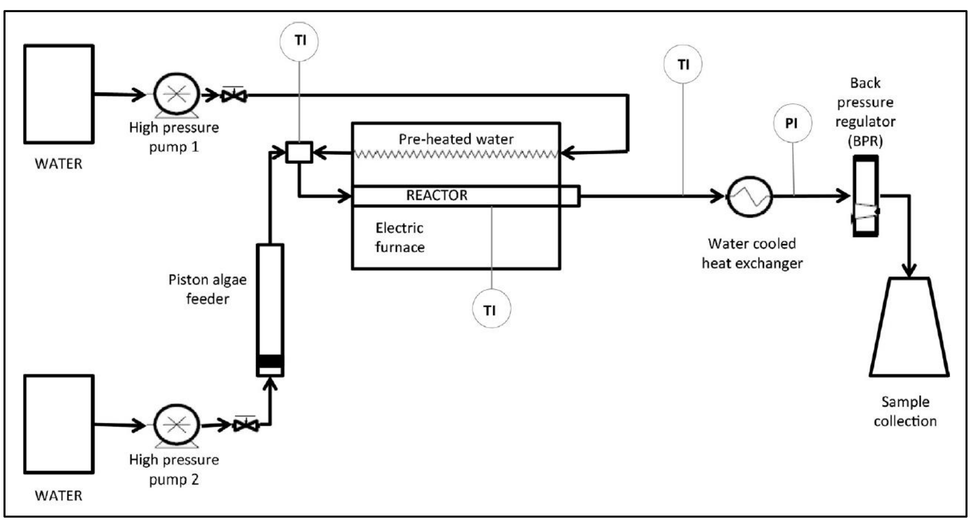

Figure 2.2 Experimental Setup of the Flash Hydrolysis Process

The study used to reproduce the HTL model came from the article *Life cycle comparison of hydrothermal liquefaction and lipid extraction pathways to renewable diesel from algae* which was published in the journal Mitigation and Adaptation Strategies for Global Change in 2013 (Frank, Elgowainy, Han, & Wang, 2013). The HTL model uses a 15% slurry on a dry ash free basis. The slurry is pumped simulating a cement slurry pump at a 50% pump efficiency value. The reactor temperature is 300 °C and maintains a pressure of 1500 psi. The HTL utilizes a heat exchanger (HX) at an 85% efficiency in order to achieve the reactor temperature. The HTL model neglects separation of solids after phase separation. The HTL heat demand for the slurry is 206.31 kJ/kg biocrude. The model then utilizes catalytic hydrothermal gasification (CHG) which requires a 30 °C temperature rise which then equals a 159.31 kJ/kg of biocrude produced. The CHG process produces methane which is then evaluated as a coproduct but requires sulfuric acid as an input requirement. In sum total for the HTL model utilizing the CHG process, each gram of biocrude produced requires 0.001782 kWh site thermal energy, 0.0002443 kWh site electricity, 0.05751 g sulfuric acid, and produces 0.4535 g of methane. The pathway in Figure 2.3 was used for HTL algae production and lipid extraction:

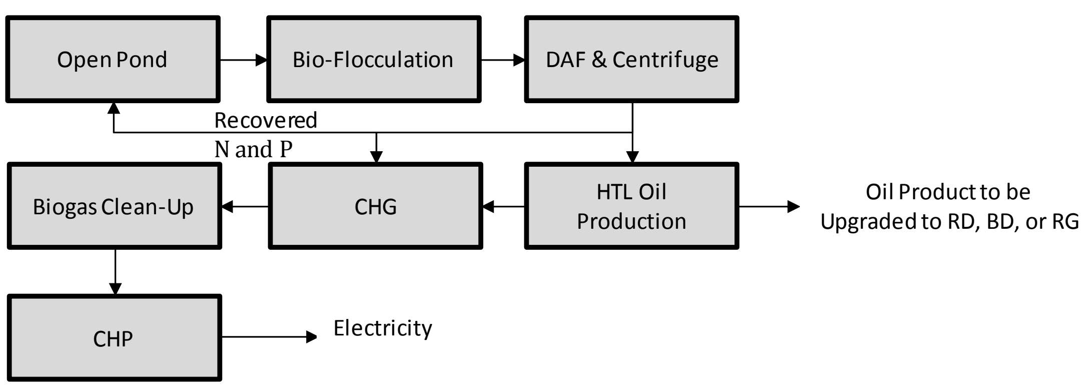

Figure 2.3 HTL Model for Algae Production and Lipid Extraction

The remaining liquid product from the HTL process contains dissolved soluble organics plus ammonia. The C/N ratio of these products is only around 2/1 which is too low for anaerobic digestion because the required C/N ratio is around 20/1 to 30/1 (Frank et al., 2011). For this reason, the HTL model uses the alternative CHG process. CHG is a similar process to HTL that reduces carbon and nitrogen in a wet organic feed stream to biogas and ammonia via catalysts.

The FH model energy and material balance were determined using the experimental results received at Old Dominion University. The elemental composition of the dry algae biomass was determined with a Thermo Finnigan Flash 1112 elemental analyzer. The biomass composition was determined to be 50.5% carbon, 9.4% nitrogen, 7.9% hydrogen, and 32.2% oxygen on a dry weight (dw) basis (Garcia-Moscoso et al., 2015). The experimental results from the flash hydrolysis study determined that a temperature of 280 °C, residence time of 12 seconds, and a pressure of 3000 psi would maximize lipid content in the solid phase of the FH products. The solid phase composition was again determined using a Thermo Finnigan Flash 1112 elemental analyzer. The result was determined to be 65.1% carbon, 7.2% nitrogen, 9.8% hydrogen, and 17.9% oxygen. These conditions produced a lipid content of 74.1%. The liquid phase was determined to be 48.1% carbon, 11.4% nitrogen, 7.1% hydrogen, and 33.4% oxygen.

The specific enthalpy for water at 3000 psi and 280 °C is 1231.13 kJ/kg. The specific enthalpy for water at 14.5 psi and 25 °C is 104.928 kJ/kg. The total change in enthalpy for water is 1126.202 kJ/kg. The heat capacity of algae is 1.80 kJ/kg °K. The flash hydrolyser is assumed to process 20% algae slurry at a rate of 48 kg/h. The algae mass input rate at 20% would be 9.60 kg/h. The water input rate at 80% would be 38.40 kg/hr. The proportion of liquid phase hydrolysate in the flash hydrolysate product is 70% (6.72 kg). The remaining 30% is the solid phase product (2.88 kg). A gaseous product is assumed to be very small and is assumed to be

0% in this model. In order to determine the energy required to process 1 hour of algae biomass through the flash hydrolyzer, the energy flow diagram in Figure 2.4 was utilized.

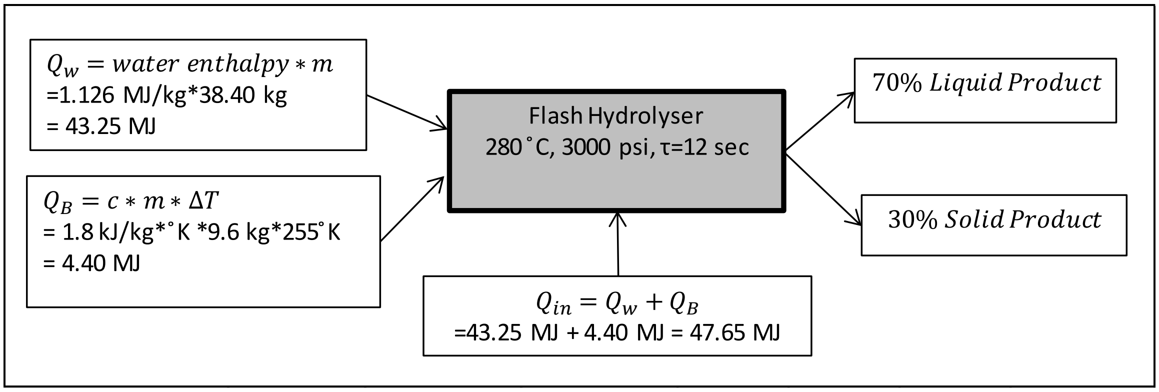

Figure 2.4 Energy Balance of Flash Hydrolysis Process

The energy required for conversion of 9.71 kg of dry algae biomass to 2.88 kg (30% of dry algae biomass) of solid phase, lipid rich product is theoretically 47.65 MJ. Of that 30% solid product, 74.1% was determined to be lipids (Garcia-Moscoso et al., 2015). Using settling and gravity filtration during the product recovery process, it is assumed that this lipid will be separated as biocrude and will be further upgraded to a biofuel at a later process in the LCA. This yields 2.13 kg of biocrude. In the thermal heating of the biomass slurry, it is assumed that the subcritical water used in the flash hydrolysis can be recovered and cooled. The depressurizing and flashing of the water will generate heat. This heat will be recovered in a heat exchanger and used in a thermal heat recycling loop. This flashing will occur from 280 °C to 99 °C. The enthalpy of water at 14.5 psi and 99 °C is 414.88 kJ/kg. In order to calculate the available energy that can be recovered from the heated water, the Equation 2.1 was used:

Equation 2.1 Recycle Water Heat Release

$Q_{recycle\ water} = m * \Delta enthalpy$ = 38.40kg*(1231.13 kJ/kg-414.88 kJ/kg) = 31.34 MJ

The efficiency of the heat exchanger is assumed to be 85%. 85% of 31.34 MJ yields 26.64 MJ. The total heat requirement for the flash hydrolysis process is therefore 47.65 MJ – 26.64 MJ for a yield of 21.01 MJ at a 20% slurry.

The GREET model APD spreadsheet requires the remaining process input to be in the form of kWh/g solid product. At a 20% algae slurry, the input mass is 9.6 kg. The FH process yields 30% solid product of which 74.1% is lipids, which yields 2.13 kg. The following conversion was made for the FH process:

Equation 2.2 FH process MJ/kg to kWh/g conversion

$$\frac{21.01\ MJ}{2.13\ kg} * \frac{1\ kg}{1000\ g} * \frac{.278\ kWh}{1\ MJ} = \frac{.00274\ kWh}{g\ solid\ product}$$

It is assumed that the remaining liquid solid separation after the FH process will be completed by setting and gravity filtration therefore no additional energy requirement was calculated for this phase of the processing.

A sensitivity analysis was conducted for the energy requirement at a low level of 15% slurry and a high level of 25% slurry. The change in slurry concentration effects various parameters in the energy balance. Table 2.3 provides the input values received from changing the slurry concentration for the sensitivity analysis.

Table 2.3 Sensitivity Analysis Adjustments for Change in Slurry Concentration

Parameter	Slurry Solids Concentration (%)		
	15%	20%	25%
Input Solid Mass, (kg)	7.20	9.20	12.00
Input Liquid Mass, (kg)	40.80	38.40	40.80
30% Solid Product, (kg)	2.16	2.88	3.60
74.1% Lipids from Solid Product (kg)	1.60	2.13	2.68
70% Liquid Product, (kg)	5.04	6.72	8.40
Energy for Algae, (MJ/kg)	3.30	4.40	5.51
Energy for Water, (MJ/kg)	45.95	43.25	40.54
Total Energy Input Before Recycling, (MJ/kg)	49.25	47.65	46.05
Recycle Water Energy, (MJ/kg)	33.30	31.34	29.39
Recycle Water Energy (85% HX), (MJ/kg)	26.64	28.31	24.98
Total Energy Input After Recycling, (MJ/kg)	20.95	21.01	21.07
kWh/g of Lipid Product	0.00364	0.00274	0.00220

The solid product from the FH process will ultimately need to have the 74.1% lipids extracted in order to get the biocrude. A solvent extraction is the best method but experimental data does not exist for this type of solid product extraction. Hexane extraction is typically conducted on whole algae biomass which must be processed. Hexane was chosen due to the lower boiling point which makes for less heat demand for solvent stripping and recovery, lower cost, and lower miscibility which leads to less solvent loss into the water phase during separation (Davis et al., 2012). A solvent to biomass ratio of 5:1 is used. A hexane loss of 0.055 g/g extracted oil is used in accordance with Landon et al. (2009). Hexane extraction is largely experimental but the results of the harmonization yielded a site electricity input of 0.0000689 kWh/g extracted oil and a site thermal heat requirement of 0.00309 kWh/g extracted oil at a hexane extraction efficiency of 95%. The wet extraction process carries a relatively high degree of uncertainty in terms of overall process performance and efficiency assumptions primarily due to the fact that pertinent data are scarce and the majority of data that are available are based on bench-scale experiments that dry the material to very low moisture levels (<5 wt% moisture) and use solvent combinations that are commercially infeasible (Davis et al., 2013).

2.2.5 Co-product Production

There are various methods for dealing with coproducts when modeling with GREET. The displacement method uses the new product to displace a conventional product. The total energy and emissions that would have been produced by the coproduct generated are subtracted from the total energy and emissions of the life cycle being evaluated. The equivalent products to be displaced can be seen in Table 2.4.

Table 2.4 Coproduct Displacement Equivalent Products

Coproduct	Product to be Displaced
Propane fuel mix	Liquefied petroleum gas
Product gas	Natural gas
LCO	Diesel fuel
CSO	Residual oil

An alternative method for dealing with coproducts is based on an allocation approach. This approach is further separated into an energy-based allocation and a market value-based allocation. These two approaches use the energy value and market value of different coproducts to offset the cost of the primary transportation fuel product. Energy content value is established and steady state. Market values can fluctuate based upon demand and region. Generally, the market value approach is used for coproducts such as animal feed and dry meal. Glycerin should also use this approach because it is heavily supplied worldwide and the price is not expected to rise in the near future (Huo, Wang, Bloyd, & Putsche, 2008). Typical energy coproducts use the energy-based allocation. The various energy and market values of coproducts can be seen in Table 2.5.

Table 2.5   Energy and Market Values of Coproducts

Product	**Energy Content (Btu/lb)**	**Market Value ($/lb)**
Glycerin	7,979	0.250
Propane Fuel Mix	18,568	0.301
Product Gas	18,316	0.114
LCO	19,305	0.248
CSO	18,738	0.177

This LCA uses the same type of coproduct treatment for both of the models evaluated. The treatments are based on a process level allocation. The biodiesel production uses a market value-based allocation because of the glycerin coproduct. The renewable gasoline and renewable diesel II both use an energy value-based allocation because their coproducts are energy products.

2.2.6 Biodiesel Production

Biodiesel is produced through the transesterification process where bio-oil is combined with a type of alcohol (usually ethanol or methanol). A catalyst is added which forms ethyl of methyl ester. The catalyst used could be sodium hydroxide or some other catalyst depending upon the production plant technology being utilized. Steam and electricity are added as energy inputs and produces both biodiesel and a coproduct of glycerin. The specific energy and material inputs for the transesterification process are unique to each private company’s biodiesel production process. These are often secretive due to the highly competitive market of the biofuel industry. The material and energy input data used in the GREET transesterification model came from a survey conducted by the National Biodiesel Board (NBB) in 2008 in which 230 biodiesel producing companies were surveyed. The NBB reported good participation in the survey and that these data are considered of excellent quality considering the representation and cross section of biodiesel plant size, biodiesel production technologies, and biodiesel feedstocks. The data represent the industry-weighted average of energy and material inputs and products and other outputs (United Soybean Board, 2013) and can be seen in Table 2.6, below:

Table 2.6 Biodiesel Input and Output Parameters

Biodiesel Inputs and Outputs (quantity per 1 gal Biodiesel)	
Inputs	*Quantity*
Soy oil (lb)	7.3285
Electricity (kWh)	0.12
Natural Gas (Btu)	2,763
Methanol (lb)	0.6735
Sodium Methylate (lb)	0.1712
Sodium Hydroxide (lb)	0.0072
Hydrochloric Acid (lb)	0.3214
Phosphoric Acid (lb)	0.0047
Citric Acid (lb)	0.0054
Water (gal)	0.3
Outputs	
Biodiesel (gal)	1
Glycerine (lb)	0.8881

2.2.7 Renewable Diesel II Production

RDII, also referred to as green diesel, can be produced by a process called hydrogenation. This process was developed by the Honeywell International Company UOP (formerly known as Universal Oil Products). In the hydrogenation process, the bio-oil is fed into a diesel hydrotreater. The energy and material inputs are electricity, steam, and hydrogen. The outputs are RDII and also a coproduct of a propane fuel mix. UOP reports that the RDII product has a cetane value of 75-90, excellent cold flow properties, excellent oxidative stability, and similar energy content to petrol-diesel, which allows the product to be used interchangeably in traditional petrol-diesel trucks and automobiles without vehicle technology changes. UOP also reports that RDII has lower emissions than petrol-diesel, up to 80% lower. The values in the table below are the GREET values for the production of soy-oil based RDII. The values were produced from the study conducted by ANL in 2008 (Huo et al., 2008). The thermal energy is assumed to generated from natural gas in the GREET model and uses a conversion efficiency of 80% and that the hydrogen is produced from natural gas using steam methane reforming process (SMR). This study assumes that the production of algae oil based renewable diesel II requires the same material and energy inputs as soy-oil based RDII and can be seen in Table 2.7, below:

Table 2.7 Renewable Diesel II Input and Output Parameters

Renewable Diesel II Inputs and Outputs (lb or Btu per lb renewable diesel II)	
Inputs	*Quantity*
Soy oil (lb)	1.174
Hydrogen (lb)	0.032
Natural gas (Btu)	84.05
Electricity (Btu)	93.83
Outputs	
Renewable Diesel II	1
Propane fuel mix (Btu)	1095.5

2.2.8 Renewable Gasoline Production

RG, also referred to as green gasoline, can be produced by a process called catalytic cracking. This process uses a fluidized catalytic cracker (FCC). The bio-oil is fed into the FCC with inputs of vacuum gas oil (VGO), steam, and electricity. The outputs are RG and coproducts of product gas, light cycle oil (LCO), and clarified slurry oil (CSO). A significant portion of the energy content are in the coproducts so it is important that the GREET model takes into consideration credits for the coproducts generated. The values were produced from the study conducted by ANL in 2008 (Huo et al., 2008). This study assumes that the production of algae oil based RG requires the same material and energy inputs as soy-oil based renewable gasoline and can be seen in Table 2.8, below:

Table 2.8 Renewable Gasoline Input and Output Parameters

Renewable Gasoline Inputs and Outputs (lb or Btu per lb renewable gasoline)	
Inputs	*Quantity*
Soy oil (lb)	2.231
Electricity (Btu)	185.6
Outputs	
Renewable Gasoline	1
Product gas (Btu)	6313.5
LCO (Btu)	4737.4
CSO (Btu)	5460.3

2.2.9 Vehicle Usage

Both of the algae-oil derived diesel fuels, biodiesel, and RDII, produced using the HTL model, and the FH model were utilized in compress-ignition, direct injection (CIDI) engine vehicles. The RG produced using the three models is used in spark ignition (SI) vehicles. The emissions and the fuel economy for the CIDI engines, regardless of diesel type utilized, is assumed to be the same due to lack of available data. Similarly, the emissions and the fuel economy for the SI engines, regardless of gasoline type utilized, is assumed to be the same due to lack of available data.

2.2.10 Fuel Transportation

The default method of transportation of the biocrude to the biofuel plant is set to 100% railway. The energy and emissions for this portion of the life cycle are then calculated using a distance of 600 miles for an energy intensity of 370 Btu/ton mi. The fuel transportation to the terminal uses a combination of barge (8%, 520 miles, 403 Btu/ton mi), rail (29%, 800 miles, 370 Btu/ton mi), and heavy-duty truck (63%, 50 miles, 1028 Btu/ton mi). The fuel is then transported to the pumping station which utilizes a heavy-duty truck at a 100% rate over a distance of 30 miles for an energy intensity of 1,028 Btu/ton mi (ABL/ESD/11-5, 2011a). In addition to these input and output values which were used on both models, RDII also has input values which can be adjusted for the hydrogen demand and the yield of RDII. The default value from the APD worksheet is used for both of these values (1,673 Btu/lb. RDII for hydrogen demand and 1.17 lb. algae oil/lb. RDII). The HTL study uses alternate values for both and are set at 3,545 Btu/lb. RDII for hydrogen demand and 1.25 lb. algae oil/lb. RDII.

2.3 Results and Conclusions

The WTW results represent all of the energy required and the emissions generated in the production of the fuel from cultivation through end use in the vehicle including upstream material energy and emissions. The data are normalized to represent 1 mmBtu of fuel production and use. The following results are separated into three categories in each chart. These are vehicle operation, fuel, and feedstock. The fuel category represents the individual biodiesel, RDII, and RG processes which take place in order to upgrade the biocrude to a transportation fuel and transport that fuel to the filling station. The feedstock represents all of the processes from cultivation through biocrude production and transportation of the biocrude to the fuel production facility. The vehicle operation stage represents the energy and emissions associated with the combustion of the fuel in the vehicle. The combination of the feedstock and fuel categories represents the WTP results and the vehicle categories represents the PTW results. Together, these represent the WTW life cycle.

2.3.1 Energy Usage

The data in Figure 2.5 represent the total energy use in the WTW production of biodiesel of both models and compares those results to its conventional fuel counterpart, LSD. It can be seen that when compared to LSD, the HTL process is 12.4% greater, and the FH process is 3.2% greater.

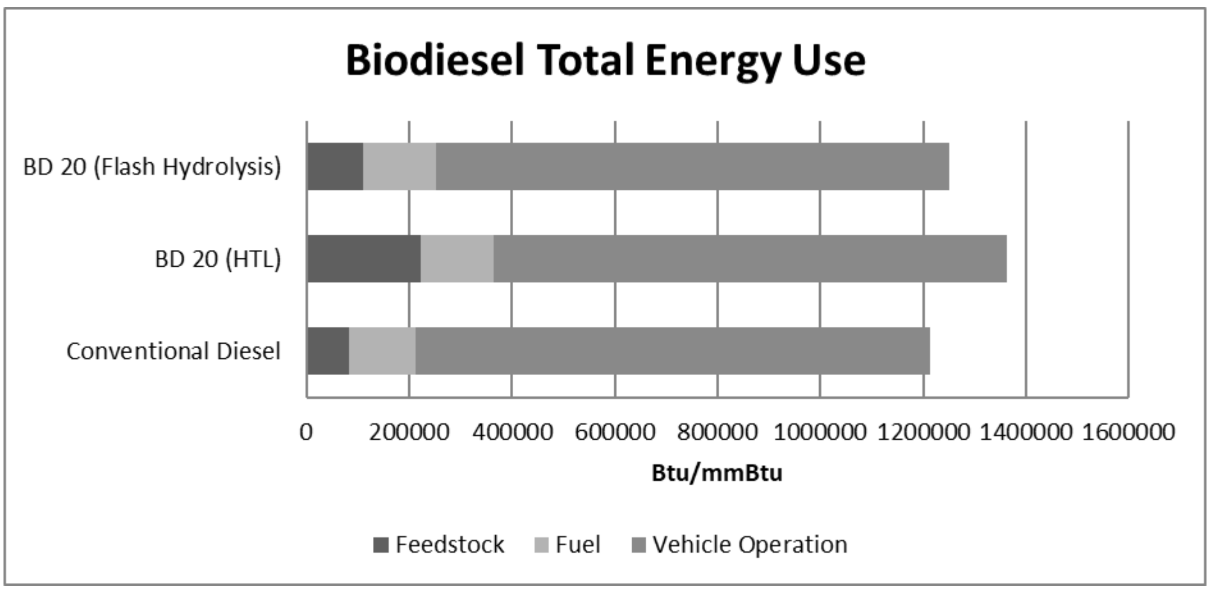

Figure 2.5 Total Energy Use for WTW Biodiesel

The data in Figure 2.6 represent the total energy use in the WTW production of RDII of both models and compares those results to its conventional fuel counterpart, LSD. It can be seen that when compared to LSD, the HTL process is 71.9% greater and the FH process is 8.6% greater.

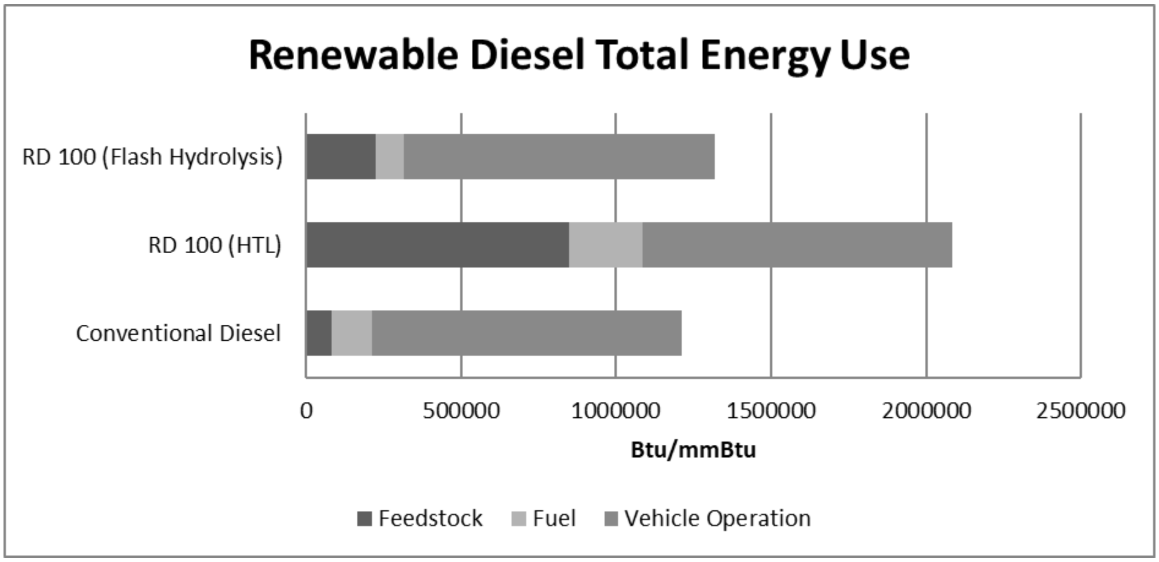

Figure 2.6 Total Energy Use for WTW Renewable Diesel II

The data in Figure 2.7 represent the total energy use in the WTW production of RG of both models and compares those results to its conventional fuel counterpart, RFG. It can be seen that when compared to RFG, the HTL process is 47.1% greater and the FH process is 0.6% less.

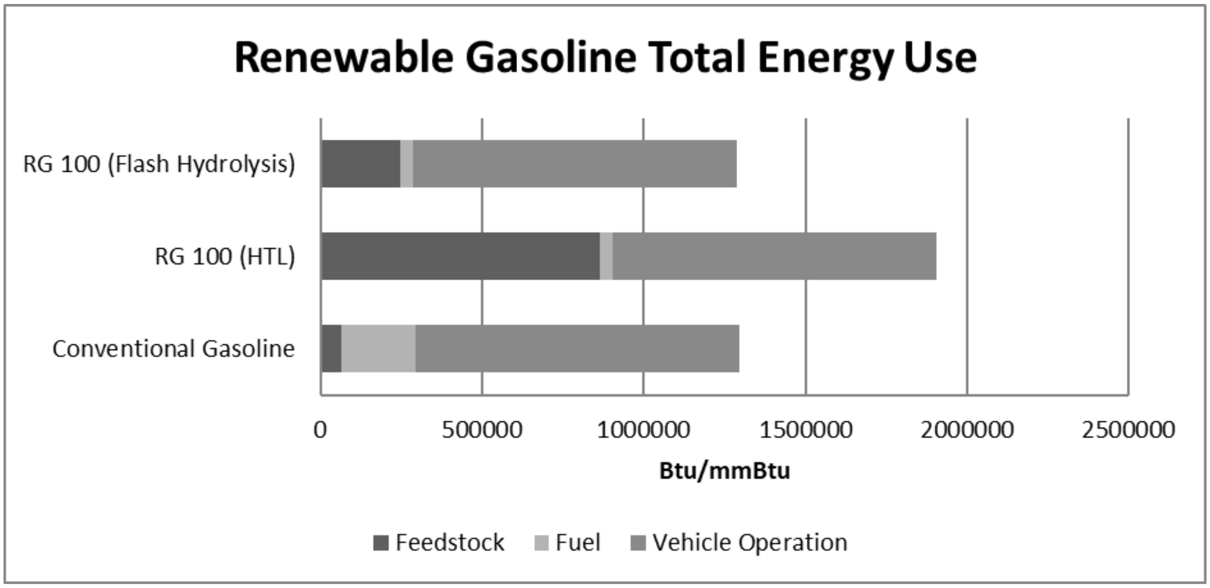

Figure 2.7 Total Energy Use for WTW Renewable Gasoline

2.3.2 GHG Emissions

The following GHG comparisons represents 1 mmBtu of fuel production and compares with grams of GHG equivalent compounds released. Each fuel type has two charts, one in which GHG emissions are broken down into the feedstock, fuel, and vehicle categories similar to the total energy usage. The feedstock portion results in credits for GHG emissions therefore a second chart is used to represent the total overall GHG emissions after the credit for the feedstock portion is received.

Figures 2.8 and 2.9 represent the GHG emissions in the WTW production of biodiesel of both models and compares those results to its conventional fuel counterpart, LSD. It can be seen that when compared to LSD, the HTL process is 86.8% the rate of LSD and the FH process is 90.8% the rate of LSD.

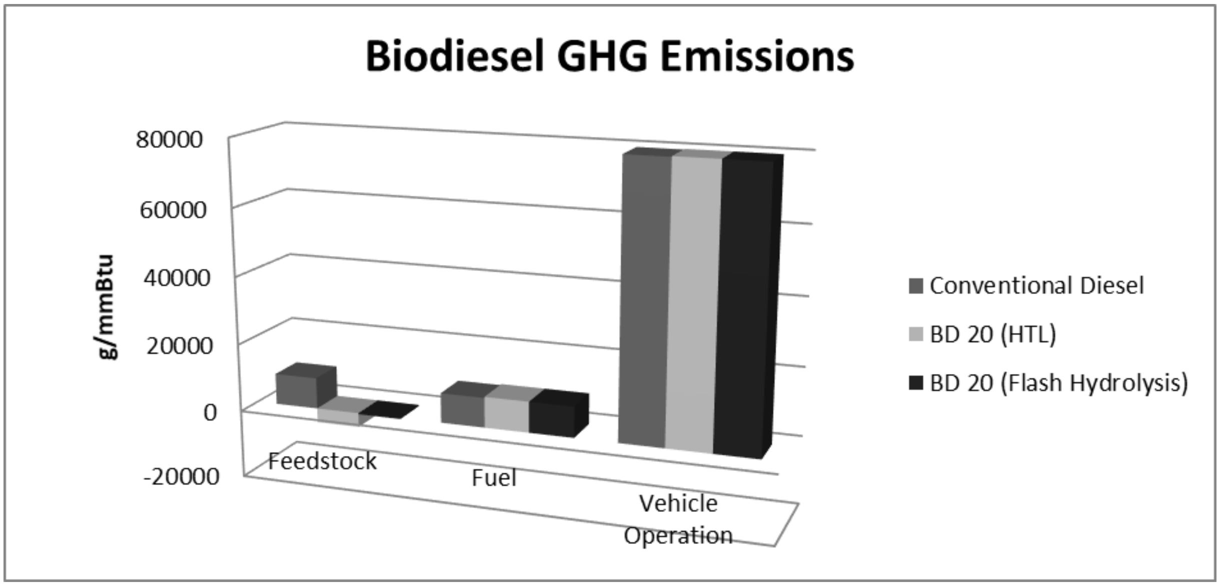

Figure 2.8 GHG Emissions for WTW Biodiesel

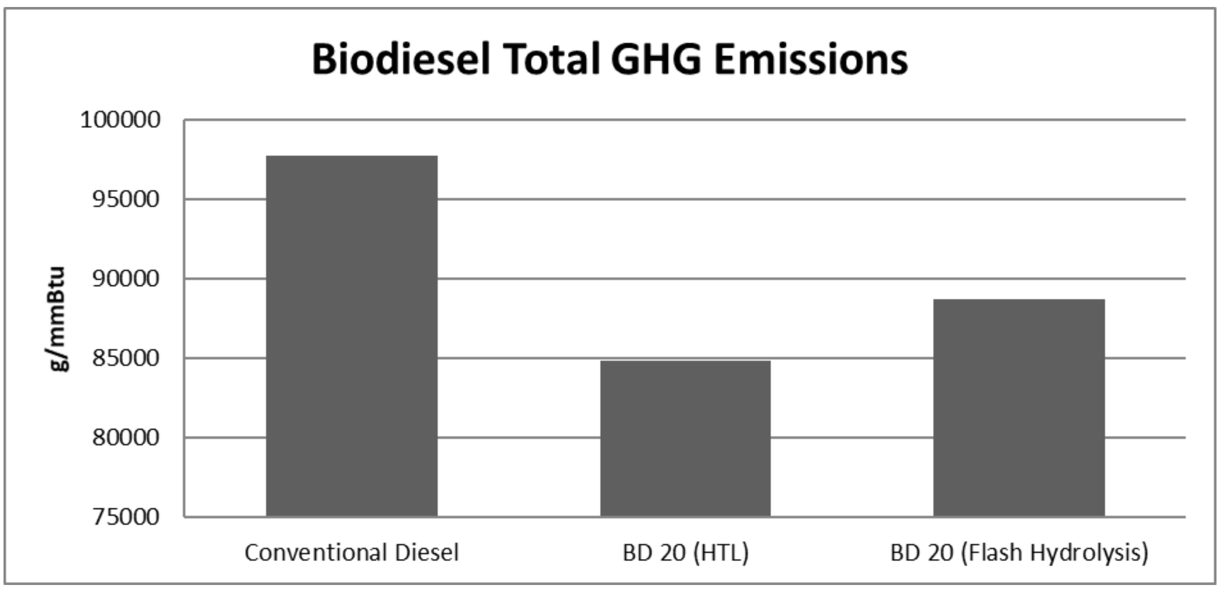

Figure 2.9 Total GHG Emissions for WTW Biodiesel

Figures 2.10 and 2.11 represent the GHG emissions in the WTW production of RDII of both models and compares those results to its conventional fuel counterpart, LSD. It can be seen that when compared to LSD, the HTL process is 39.0% the rate of LSD and the FH process is 48.6% the rate of LSD.

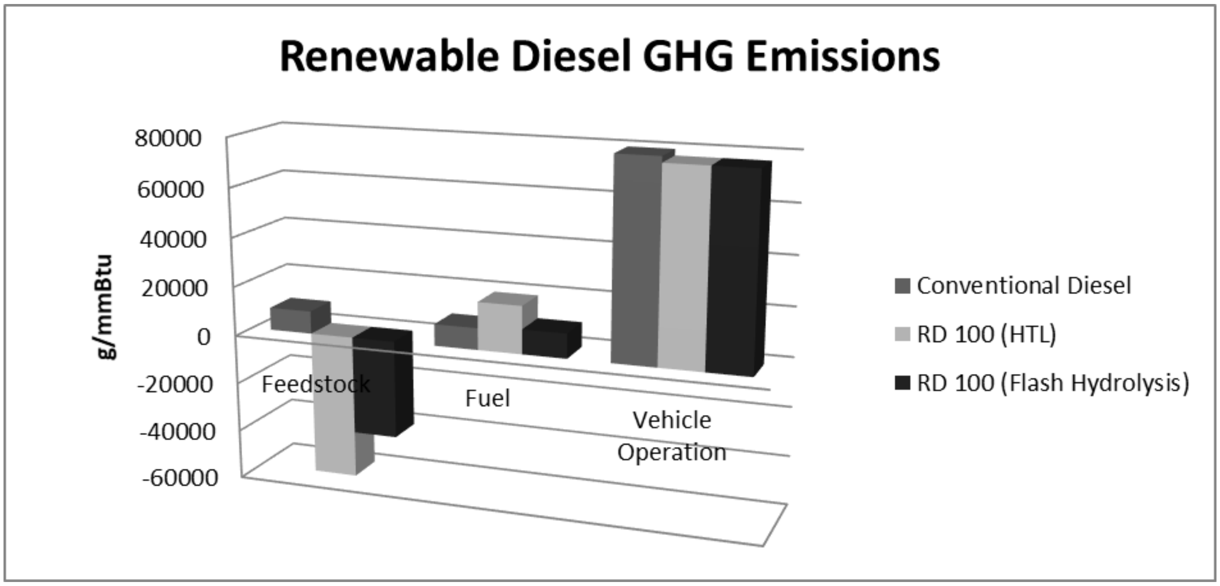

Figure 2.10 GHG Emissions for WTW Renewable Diesel II

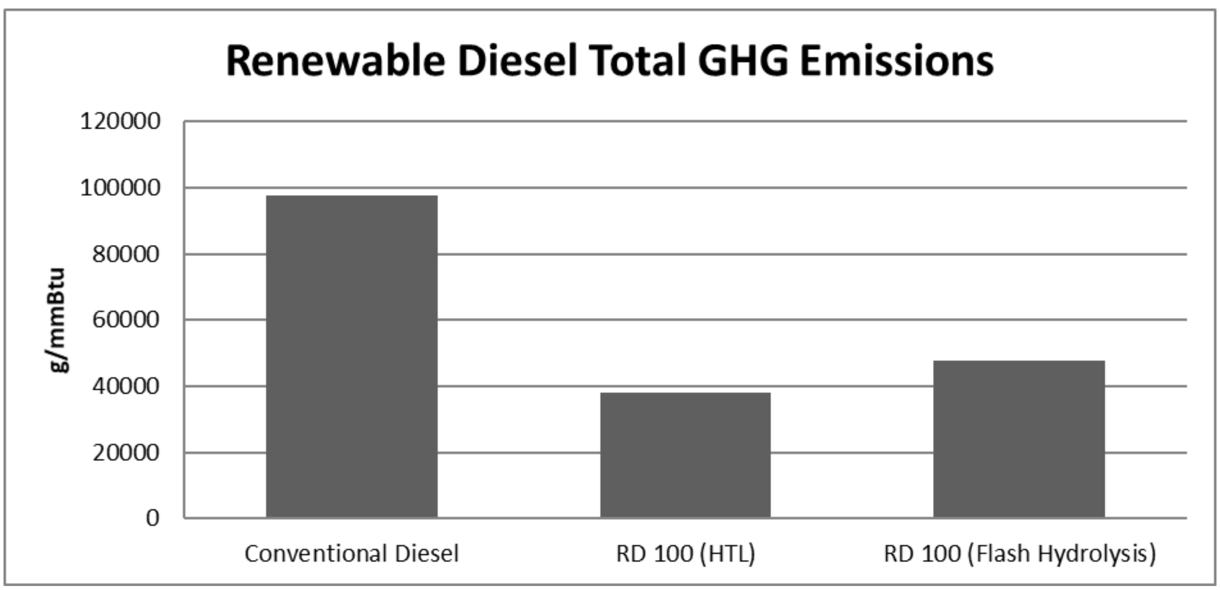

Figure 2.11 Total GHG Emissions for WTW Renewable Diesel II

Figures 2.12 and 2.13 represent the GHG emissions in the WTW production of RG of both models and compares those results to its conventional fuel counterpart, RFG. It can be seen that when compared to RFG, the HTL process is 22.0% the rate of RFG and the FH process is 44.1% the rate of RFG.

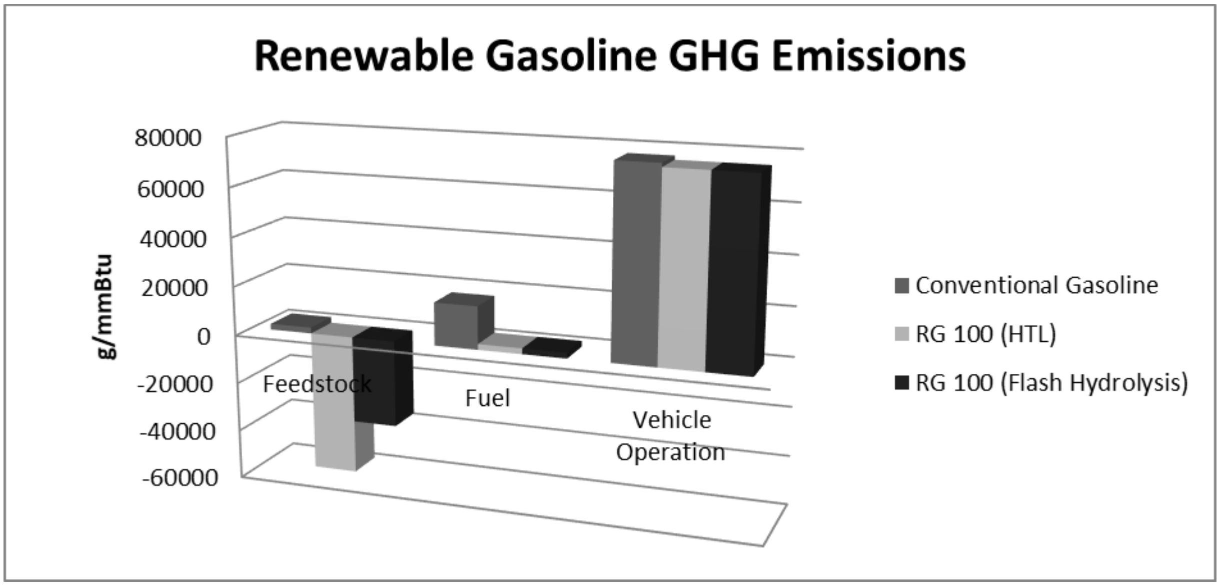

Figure 2.12 GHG Emissions for WTW Renewable Gasoline

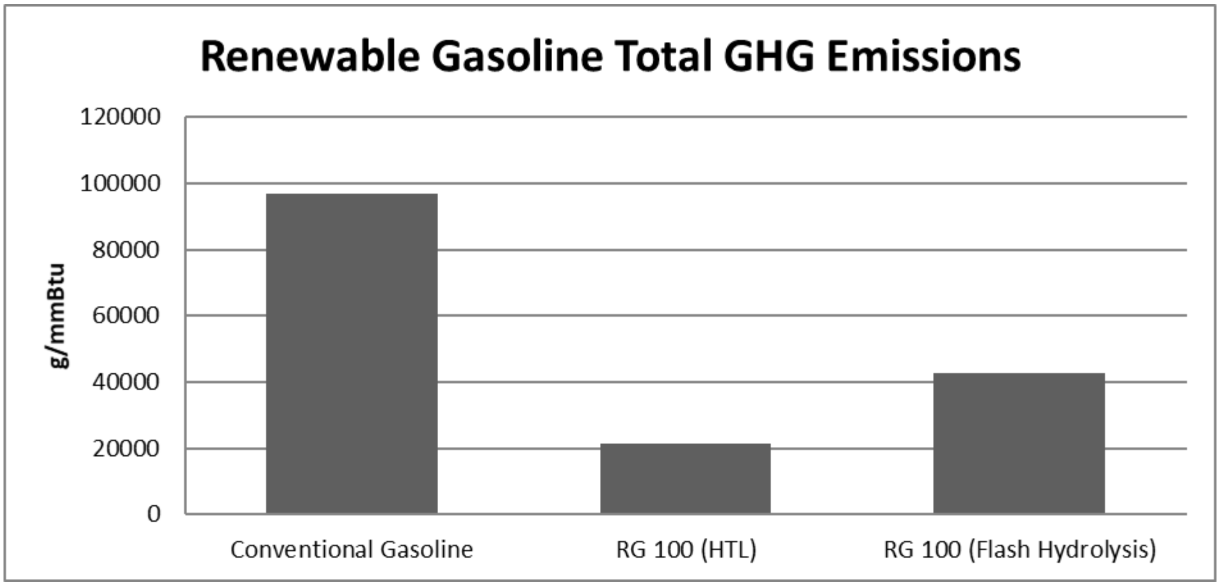

Figure 2.13 Total GHG Emissions for WTW Renewable Gasoline

2.3.3 Flash Hydrolysis Conclusions

The algal slurry concentration sensitivity analysis of the FH process performed as expected. With increasing slurry concentration up to 25%, energy use and GHG emissions were reduced. They were not reduced as much as expected however. The total energy demand for the biodiesel was only reduced by 1.1%, the RDII by 6.2%, and the RG by 6.7%. The reason is that there is a tradeoff when the slurry concentration is increased. Increasing the throughput of the algae biomass will make more oil per hour but with less water being heated to subcritical conditions, less heat is available for recovery through the heat exchanger. This all effects the energy balance. In addition, increasing the slurry concentration over 20% algae biomass would likely require increased pumping power due to the viscous nature. It is recommended that the concentration not be increased over 20%.

The FH process also has the potential to produce coproducts which can be valuable on the market or for nutrient recycling. Neither of these options were investigated in order to maintain the clarity of the results. Nutrient recycling is available in GREET but may be better modeled in other software such as Aspen. This will be an important factor for a large-scale operation. Microalgae is estimated to be capable of producing 10–20 times more biodiesel than rapeseed, a second-generation biofuel feedstock, but they need 55–111 times more nitrogen fertilizer – 8 to16 tons/ha/year (Demirbas, 2011). If a product that could be sold on the market is deemed to be more beneficial than nutrient recycling, then this coproduct could easily be added with a market-based allocation. A product made from the peptide arginine which is solubilized in the liquid phase of the FH product would be ideal.

This LCA does not specifically address spatiotemporal conditions which may factor greatly into different processes. The models utilize cultivation data from the harmonization study that take conditions from widely varying regional conditions and attempt to yield best estimated average inputs. Economic and sustainability objectives can conflict and therefore a unified analysis of economics and sustainability driven by spatiotemporal RA is required and is suggested as the proper methodology for research, policy, and financial communities to use when making algal biofuel development decisions (Davis et al., 2014). In *Microalgae for Biofuels and Animal Feeds* (Benemann, 2013) it is suggested that water resources will ultimately limit algal feed and fuel production. Seawater has been a promising water resource for algae but these are restricted to coastal areas of modest elevation. Humid areas generally have more fresh water available but these areas are typically subject to cloud cover and subject to higher pond temperature due to limited evaporative cooling. Factors such as annual days of cultivation, access to railways for transportation, average daily productivity, access to carbon dioxide produced by flue gas, and evaporative loss in ponds all have spaciotemporal characteristics that need to be considered at a local level before investment decisions are made.

The energy and emissions associated with infrastructure was also omitted from this LCA. Canter and colleagues found that infrastructure-cycle related emissions were non negligible compared to fuel-cycle emissions (Canter, Davis, Urgun-Demirtas, & Frank, 2014). Their work studied renewable diesel fuel product specifically and found that pond related infrastructure was the most prevalent GHG producer. The plastic liners accounted for much of the emissions. Their results showed that the algae baseline result of 64 gCO2e/MJ RD for fuel-cycle emissions increases to 72 gCO2e/MJ RD when infrastructure-cycle emissions are added. Companies interested in investing in large scale production of algal biofuels at site specific locations should take into consideration infrastructure related energy and emissions in their LCA's.

CHAPTER 3

LIFE CYCLE IMPACTS AND TECHNO-ECONOMIC IMPLICATIONS OF FLASH HYDROLYSIS IN ALGAE PROCESSING

3.1 Background of the Study

There has been an abundance of research published over the last few years that show that microalgae have the potential to be a feedstock contender in biofuels technology. Microalgae has several properties that are purported by researchers to produce advanced biofuels with low overall production cost and better environmental performance (Clarens, Resurreccion, White, & Colosi, 2010; Singh, Nigam, & Murphy, 2011). In the past, most biofuel production in the United States has been associated with corn ethanol and over time, other biofuel feedstocks such as microalgae have been studied. EISA requires that by the year 2022, 36 BGY of renewable fuels (20% of the U.S. consumption) must be produced annually ("Energy Independence and Security Act of 2007", 2007). Feedstock for the renewable fuel must come from lignocellulosic biomass (oxygenated hydrocarbons), energy crops, and other biomass sources. Researchers and industry professionals are developing ways to increase the conversion efficiency of non-food feedstocks such as forest residues, agricultural residues, and energy crops that are not used for food production (Naik, Goud, Rout, & Dalai, 2010; Sims, Mabee, Saddler, & Taylor, 2010). Currently, thermochemical conversion processes of non-food biomass are still inefficient. Algae has the potential to fill the gap that exists in our renewable fuels technology and to address critical LC-GHG requirements set forth by EISA. Water-based microalgae has several advantages over other lignocellulosic biomass. It has a rapid growth rate, grows well in wastewater effluent and saltwater streams (Ahmad, Yasin, Derek, & Lim, 2011; Mutanda et al., 2011), does not require arable land making it non-competitive with food crops (Chisti, 2007), and can utilize CO2-rich flue gas emissions (Maeda, Owada, Kimura, Omata, & Karube, 1995). Microalgae also contains a high proportion of lipids. This is important because lipid is the main component that will yield the bio-oil which is subsequently upgraded to liquid fuels suitable for use in ground and air transportation. Microalgae is typically between 20-50% lipid content (Chisti, 2007).

Recycling and recovery of nutrients during microalgae cultivation and processing is the motivation for numerous LCA's and TEA's performed on microalgae (Clarens, Nassau, Resurreccion, White, & Colosi, 2011; Clarens et al., 2010; Davis, Aden, & Pienkos, 2011; Davis et al., 2014; M.-O. P. Fortier, Roberts, Stagg-Williams, & Sturm, 2014; Mu et al., 2017; Quinn & Davis, 2015; Resurreccion, Colosi, White, & Clarens, 2012). These studies seek to evaluate algal biofuels sustainability. Most of these modeling efforts utilize some form of dewatering process to concentrate microalgae slurry and HTL to convert wet microalgae slurry into biocrude. This work offers an alternative conversion pathway via FH. It differs from traditional HTL in that it requires very short residence time (9 s) at 280 °C in a continuous flow reactor20-21, 23-24. FH partitions microalgae in an aqueous protein-rich peptides and arginine (low-value bioproducts) and a solid lipid-rich 'biofuels' intermediates phase (Garcia-Moscoso et al., 2015). The aqueous phase undergoes hydrothermal mineralization (HTM) or atmospheric precipitation (AP) because these processes recover/store the maximum macronutrients as valuable co-products. The struvite and hydroxyapatite obtained from HTM and AP, respectively, offer more economic value as opposed to peptides and arginine, with an estimated market value of $200/Mg for struvite and $500/Mg for hydroxyapatite and because they are in a stable form with market demand. The solid phase is transferred to HTL via a rotary vacuum drum filter to produce biocrude.

The nutrient demands for industrial-scale algae production are extremely large therefore it is critical that nutrients are incorporated into co-products and/or recycled back into cultivation to minimize impacts on terrestrial food production (Venteris, Skaggs, Wigmosta, & Coleman, 2014). In addition, studies have shown that phosphorus, which is in limited supply, could be depleted in the 21st century (Lougheed, 2011). Biomass-based sources of renewable fuels such as microalgae are expected to exacerbate this situation (Neset & Cordell, 2012). Research conducted at Old Dominion University over the past several years (Barbera et al., 2016; Barbera et al., 2017; Garcia-Moscoso et al., 2013; Garcia-Moscoso et al., 2015; Talbot et al., 2016; Teymouri et al., 2016; Teymouri et al., 2017, 2018) has shown that the FH process has the potential to produce biocrude while preserving macronutrients as valuable co-products. However, a comprehensive LCA or TEA has not been conducted to quantify environmental impacts and assess economic profitability.

It is imperative that assessments are made on the combined FH-HTL-HTM/FH-HTL-AP systems to determine if the energy-return-on-investment (EROI) and profitability are measurably beneficial. While it is apparent that the HTM process requires more energy compared to AP because of the required hydrothermal conditions, it is still unknown by how much this increase in energy is if the overall "well-to-pump" production of drop-in transportation (ground and air) fuel is evaluated. We know that the production of hydroxyapatite via HTM creates a more valuable co-product when compared to the production of struvite/dittmarite via AP but we do not know by how much this affects the overall TEA when assessed in combination with the drop-in fuel production and varying yields of co-product generation.

The main objective of this study is to provide an overall LCA and TEA for the FH process in conjunction with HTM/AP using a "well-to-pump" system boundary. This study is the first of its kind to compare the production of three fuel products (RDII, RG, and hydroprocessed renewable jet fuel (HRJ)) using FH as the central thermochemical process in the production of intermediates, HTM/AP as co-product generation processes in the recovery of macronutrients, and HTL as a method of producing biocrude, the raw material for drop-in transportation fuel. The results determined the environmental performance of FH/co-product generation for drop-in renewable transportation fuels. Finally, this study evaluated how the combined FH-HTL-HTM/FH-HTL-AP processes compare to a standalone HTL.

3.2 Materials and Methods

3.2.1 Model Overview

The LCA models for this study were built in spreadsheet format using Microsoft Excel in conjunction with the Crystal Ball predictive modeling suite. This add-in for Microsoft Excel facilitates Monte Carlo analyses for complex systems by defining statistical distributions for input parameters. The program automatically samples from each input distribution and generates distributions of selected output parameters (i.e., ‘forecasts’). The Monte Carlo analysis was conducted using 10,000 trials. From earlier work conducted by Clarens et al. (2011), increasing the number of trials to 100,000 model ‘runs’ does not significantly change model results. All material, energy, and heat inputs were determined using literature values and first-principles engineering calculations. Environmental burdens associated with these inputs were calculated using impact factors obtained from the Ecoinvent® LCA database, as accessed using SimaPro v. 8. Our model outputs include three environmental impacts: net energy use (in MJ), and global warming potential (GWP) (in kg carbon dioxide equivalents, “kg CO2 eq”).

The LCA and TEA of FH with HTM/AP as co-product generation pathway and HTL as biofuel production method was accomplished through the creation of six models which were subsequently compared with each other: (1) RDII-AP, (2) RDII-HTM, (3) RG-AP, (4) RG-HTM, (5) HRJ-AP, and (6) HRJ-HTM. Impact factors for the LCA were obtained from either EcoInvent™ or Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) databases contained in SimaPro v8, a LCA modeling software; GREET database developed by ANL; and other open source LCA databases. The functional unit (FU) for this LCA study was 1 MJ of usable energy. This LCA is conducted on a "well-to-pump" basis. Figure S1 describes the overall process of converting algae biomass into usable transportation energy (i.e., renewable diesel II (RDII), renewable gasoline (RG), or hydroprocessed renewable jet (HRJ) fuel). So-called "well-to-pump" system boundaries encompass the following processes: upstream manufacture of material and energy inputs, cultivation of algal biomass, pre-processing and concentration of algal biomass, lipid extraction of algal biomass, and conversion of algae biomass into usable energy product and usable co-products. Process inputs include freshwater culture medium, energy, heat, catalysts, mineralizers, and hydrogen for various conversion unit operations. Process outputs include both energy (as either algae renewable transportation fuel or energy co-products) and algae biomass mineralized co-products. The overall model scheme can be seen in Figure 3.1. Solid purple arrows denote mass flows while red dashed arrows denote energy/heat flows. The system boundary is "well-to-pump".

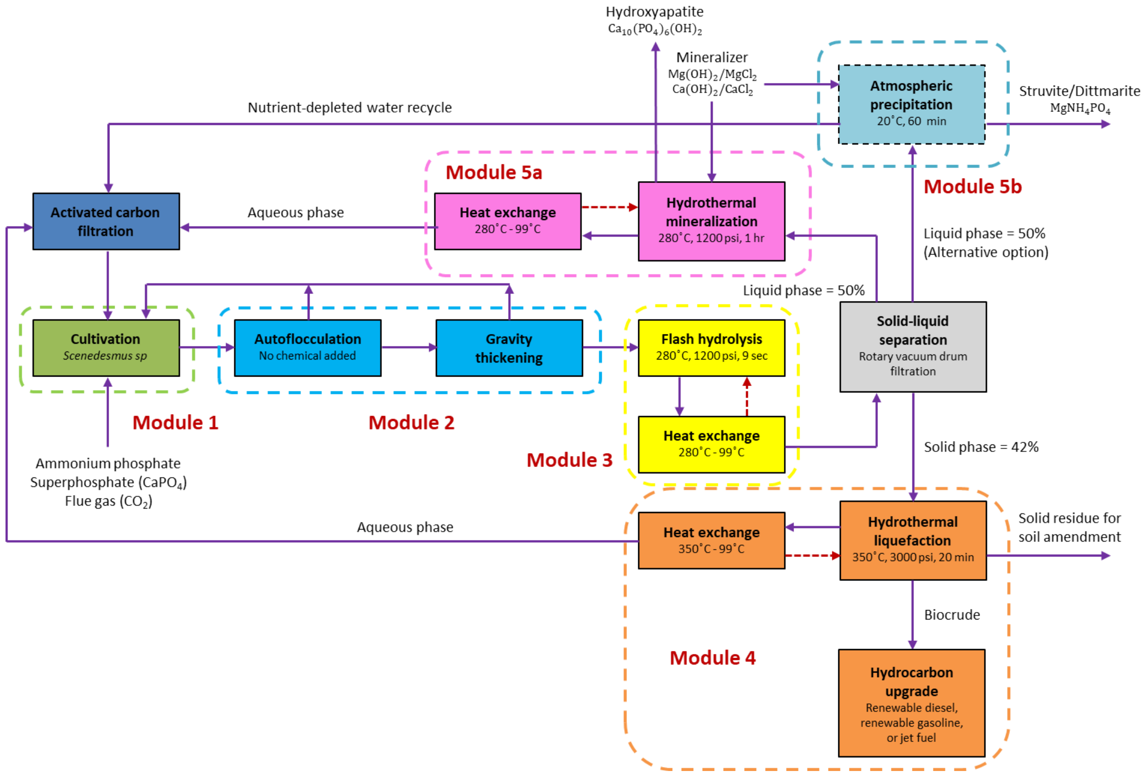

Figure 3.1. Overall Schematic for the LCA and TEA of RDII, RG, or HRJ Fuel

Algae yields for each of the evaluated systems were computed using the protocol of Clarens et al. (2010), Clarens et al. (2011), and Resurreccion et al. (2012), whereby radiation use efficiency (RUE) is multiplied by photosynthetically active radiation (PAR). RUE is in units of “g dry weight (DW)/MJ PAR” and PAR units are “MJ/m^2-day”, such that algae yields are reported as “g DW/m^2-day”. All RUE values for this study were based on data from sustained outdoor algae cultivation trials in open pond systems. These were computed by taking the direct ratio of reported algae yield (in Mg dry weight (DW)/m^2-d) to PAR irradiance (in MJ PAR/m^2-d) using the atmospheric conditions at the location of Roanoke, VA. Table 3.1 summarizes annual average algae and lipid yields. RUE and lipid content are “likeliest values” from respective triangular distributions. Biomass yield and lipid yield are annual averages, as taken from respective models. N (nitrogen), P (phosphorus), and CO_2 demands are based on algae yields and assumed stoichiometry.

Table 3.1. Summary of RUE Values, Lipid Contents, Biomass Yields, Lipid Yields, and Nutrient Demand

System	Likeliest RUE, g DW/MJ PAR	Likeliest Lipid Content, %	Biomass Yield, Mg DW/ha-yr	Lipid Yield, Mg/ha-yr	N Demand, Mg/ha-yr	P Demand, Mg/ha-yr	CO_2 Demand, Mg/ha-yr
Open Pond	1.40	13	41.6	4.7	1.5	0.5	92.3

The CO_2 required for the microalgae cultivation is supplied from flue gas assumed to be co-located with the algae ponds. The flue gas is assumed to have a 12.5% CO_2 concentration based upon Kadam (2002). The flue gas requires compression in order to be delivered to the open pond. The work required to compress flue gas is 39 kJ/kg flue gas (Clarens et al., 2011) or 314 kJ/kg CO_2, since flue gas is only 12.5% CO_2. Equation used in calculating compressor energy requirement for gas delivery is seen in Equation 3.1:

Equation 3.1

$$W = \frac{C_p * T}{n_c}\left[\left(\frac{P_{out}}{P_{in}}\right)^{\left(\frac{\gamma-1}{\gamma}\right)} - 1\right]$$

where: W = compressor energy requirement (kJ/kg)
Cp = specific heat of CO_2 (J/kg-K)
T = temperature (^oC)
n_c = compressor efficiency (0.85)
P_{out}/P_{in} = minimum pressurization for pumping CO_2 as liquid (2)
γ = compressor work equation constant (1.27)

Due to atmospheric loses, the carbon dioxide utilization efficiency is assumed to be 0.7 (Resurreccion et al., 2012). The final amount of flue gas required and the subsequent energy demand for pumping it will determined based on annual algae yield calculated using meteorological conditions in Virginia.

Nutrient demands were computed stoichiometrically, based on the so-called Redfield ratio ($C_{106}H_{181}O_{45}N_{15}P$) (Redfield, 1958) and model-computed algae yields for each system. Resulting values are summarized in Table 3.1. It was assumed that N and P sources are delivered by ammonium phosphate, $(NH_4)_3PO_4$ and any additional P requirement would be delivered by superphoshate ($CaPO_4$). Table 3.2 summarizes a water balance for all models. Q's are volumetric flow rates of algae slurry (algae + water) in units of L/ha, as numbered according to Figure 3.1.

Table 3.2. Water Balance for Algae Cultivation, Conversion, and Post-Processing

Algae	Open Pond
Raw well water intake Q1	8,207,188
Influent to cultivation Q2	41,265,455
Effluent from cultivation, Q3	41,571,421
Effluent from autoflocculation, Q4	4,157,142
Effluent from thickening into flash hydrolysis, Q5	415,714
Effluent from flash hydrolysis into separator, Q6	415,714
Effluent from separator into hydrothermal mineralization/atmospheric precipitation, Q7A	207,857
Effluent from separator into hydrothermal liquefaction, Q7B	174,600
Effluent from hydrothermal mineralization, Q8A	166,286
Effluent from hydrothermal liquefaction, Q8B	139,680
Recycle from hydrothermal mineralization/atmospheric precipitation, Q9A	41,571
Recycle from hydrothermal liquefaction, Q9B	34,920
Recycle from thickening, Q10	3,741,428
Recycle from autoflocculation, Q11	37,414,279
Evaporation, Q12	8,173,931

The cultivation utilizes paddle wheels mixing at total electrical consumption of 1,167 MJ/ha. It is assumed that 10 paddle wheels are utilized per hectare and are operated at 10 rpm (Clarens et al., 2011). An electrical demand of 0.0037 kW/paddle wheel is assumed based upon the triangular distribution over the range of 0.0001 kW to 0.01 kW per paddle wheel (J. R. Benemann & Oswald, 1996). The paddle wheel mixing electricity requirement is calculated using the following Equation 3.2:

Equation 3.2

$$P = \frac{0.0037\ \mathrm{kJ/s}}{\mathrm{PW}} * \frac{10\ \mathrm{PW}}{\mathrm{ha}} * \frac{60\ \mathrm{s}}{\mathrm{min}} * \frac{60\ \mathrm{min}}{\mathrm{hr}} * \frac{24\ \mathrm{hrs}}{\mathrm{day}} * \frac{365\ \mathrm{days}}{\mathrm{yr}} * \frac{\mathrm{MJ}}{1000\ \mathrm{kJ}} = 11{,}668\,\frac{\mathrm{MJ}}{\mathrm{ha{-}yr}}$$

The head (17.78 m) was estimated based on average distances that would be needed to transport the fluid between unit operations assuming moderate head losses associated with pipe fittings. The system head is generated from the following Equation 3.3:

Equation 3.3

$$h = \frac{P_2 - P_1}{\rho g}$$

where: h = system head (m)
P2 and P1 = pressure at the pump inlet (0.1 MPa) and pump outlet (0.2 MPa)
ρ = density of water (kg/m^3)
g = acceleration due to gravity (9.8 m/s^2)

The water pumping energy requirement is then calculated using the following Equation 3.4:

Equation 3.4

$$W = \frac{hg}{\eta} * \dot{m}$$

where: W = water pumping energy requirement (MJ/ha)
h = system head (m)
g = acceleration due to gravity (9.8 m/s^2)
η = pump efficiency (85%)
$\dot{m}$= the total mass of circulating pond water

The cultivation methodology and variables were held constant for each variation of the models evaluated. The open pond system utilized ten paddle wheels per hectare at 10 rotations per minute (rpm) (Clarens et al., 2011), assuming an electrical demand of 0.0037 kW/paddle wheel (Benemann & Oswald, 1996). The carbon dioxide requirement for the microalgae cultivation was supplied via flue gas at a 12.5% CO2 concentration (Kadam, 2002). Nitrogen and phosphorus nutrient requirements were assumed to be supplied by ammonium phosphate [$(NH_4)_3PO_4$)] and by superphosphate [($CaPO_4$)]. Preliminary dewatering of the algae biomass in Module 2 is a two-step process that generates 20% algae biomass slurry for the FH continuous flow reactor. The first step is an autoflocculation (AF) process that increases the pH of the slurry to approximately 10.5 via the addition of phosphate (PO_{4-}) (Spilling, Seppälä, & Tamminen, 2011). The second step is gravity thickening (TH) settling process (Soda, Iwai, Sei, Shimod, & Ike, 2010).

The dewatering of the algae biomass is accomplished through AF and TH. AF parameters are based on the research conducted by Spilling et al. (2011) where the increase in pH of the slurry to approximately 10.5 would cause the algae biomass to flocculate to a concentration factor of 10 via the addition of PO_4^-. The requirement is 0.2 mM PO_4^- in excess of the stoichiometric P demand. No additional chemical flocculants or energy is required. The thickening by gravity settling is based on an empirical regression equation developed by Soda et al. (2010). The Equation 3.5 was used and the resulting concentration factor of 10 is utilized in the model.

Equation 3.5

$$y = 636x^{-1.04}$$

where: y = electricity use rate for 100x sludge load rate (kWh/ton dry solids)
x = 100x sludge loading (ton dry solids/ha-day)

The energy use for this process is 7,582 MJ/ha-yr based upon a 42 Mg/ha-yr loading rate. The output concentration was approximately 100 g/L and it was assumed that this concentration is suitable for continuous flow hydrothermal extraction techniques without additional concentration steps.

3.2.3 Flash Hydrolysis (Module 3)

FH (Module 3) is a hydrothermal process that utilizes wet algae biomass in a continuous flow reactor and fractionates macromolecules into liquid and solid phases (Garcia-Moscoso et al., 2013; Garcia-Moscoso et al., 2015). The FH process utilizes water at subcritical conditions (280°C; 1,200 psi) where water exhibits solvent like properties and quickly hydrolyzes algae biomass for 9 seconds in a continuous flow reactor. A 20% algae biomass slurry was assumed for the FH continuous flow reactor (Davis, 2016). The fractionation at this short residence time preserves the proteins and soluble peptides into the liquid phase which can be used for nutrient recycle. FH is advantageous over an HTL system because the longer residence time of HTL (Elliott, Biller, Ross, Schmidt, & Jones, 2015; Elliott et al., 2013; Zhang, 2010) causes the formation of unwanted tar, phenols, oxygenated hydrocarbons, and aromatic compounds

(Garcia-Moscoso et al., 2013), a fact that is non-existent in the FH reaction. The solid phase is lipid rich, up to 74% reported (Garcia-Moscoso et al., 2015), and is non-perishable (Garcia-Moscoso et al., 2013).

The energy required to heat the water for the 20% slurry to conditions of 280 °C and 1200 psi is calculated by measuring the enthalpy change between the atmospheric water condition at 25 °C and 14.7 psi and the hydrothermal FH condition at 280 °C and 1200 psi. The total energy required to heat the system is measured by the change in heat capacity (Cp) multiplied by the mass (m). In order to calculate the power requirement for the continuous flow reactor, the mass flow rate is utilized in Equation 3.6. The specific enthalpy for water at 280 °C and 1200 psi is 1,235 kJ/kg. The specific enthalpy for water at 25 °C and 14.7 psi is 105 kJ/kg. The total change in enthalpy for water is calculated to be 1,130 kJ/kg. The flash hydrolyzer is assumed to process 20% algae slurry at a rate of 48 kg/h. The water input rate at 80% is 38.40 kg/hr.

Equation 3.6

$$P_W = \Delta C_p * \dot{m}_w = \frac{1.130\text{MJ}}{\text{kg}} * \frac{38.4\text{kg}}{\text{h}} = \frac{43.39\text{MJ}}{\text{h}}$$

where: P_w = power required to heat the incoming water (MJ/h)
ΔC_p= change in enthalpy (MJ/(kg*K_{out}-K_{in})
$\dot{m}_w$ = mass flow rate of incoming water (kg/h)

The algae biomass power requirement for the FH reaction is calculated similarly as the water calculation using Equation 3.7. The algae mass input rate at 20% is 9.60 kg/h when compared to the total 48 L/h continuous flow reactor. The heat capacity of algae is 1.80 kJ/kg °K.

Equation 3.7

$$P_B = C_p * \dot{m}_b * \Delta T = \frac{1.8\text{kJ}}{\text{kg}*^\circ\ \text{K}} * \frac{9.6\text{kg}}{\text{h}} * 255^\circ\ \ \text{K} = 4.41\,\frac{\text{MJ}}{\text{h}}$$

where: P_B = power required to heat the algae biomass (MJ/h)
C_p = specific heat of algae biomass (MJ/kg*K)
$\dot{m}_b$= mass flow rate of incoming algae biomass (kg/h)
ΔT = change in temperature (K)

The total power requirement for heating 20% algae biomass slurry to 280°C and 1200 psi is found by Equation 3.8.

Equation 3.8

$$P_{in} = P_W + P_B = \frac{43.39\text{MJ}}{\text{h}} + \frac{4.41\text{MJ}}{\text{h}} = 47.79\,\frac{\text{MJ}}{\text{h}}$$

where: P_{in} = total power required for water and algae biomass reaction (MJ/h)

The thermal energy embodied in the FH reaction products may be utilized for heat recovery in the form of a heat exchanger in order to preheat the incoming FH biomass slurry from Module 2, gravity thickening. The FH liquid product leaves the FH reactor at a temperature of 280°C and must be cooled to atmospheric liquid conditions prior to downstream processing. It is assumed that the heat exchange is accomplished through a shell-and-tube heat exchanger at an efficiency of 85%. The preheating of the incoming slurry is accomplished through the avoidance of the "flash off" of the subcritical water. The rapid depressurization of the subcritical water would waste the latent heat of evaporation energy contained in this exothermic reaction. Instead, the difference in the enthalpy of the 280°C subcritical water and the 99°C liquid water is captured in the heat exchanger for incoming 25°C water preheat.

The FH liquid leaving the reactor is utilized for heat recovery in order to preheat the incoming slurry to the FH reactor. The temperature of the liquid leaving the FH reactor and entering the heat exchanger is 280 °C with an enthalpy of 1,235 kJ/kg. The temperature of the FH liquid leaving the heat exchanger is assumed to be 99 °C with an enthalpy of 415 kJ/kg. The mass of the recycle portion of the FH is 38.40 kg/h. The total heat recovery is calculated to be 31.49 MJ/h. Assuming an 85% for the heat exchanger, the heat recovery equals 26.76 MJ/h. See Equation 3.9 below:

Equation 3.9

$$P_{\text{recycle 85\% eff}} = \Delta C_p * \dot{m}_w * 0.85 = \left(\frac{1.235\text{MJ}}{\text{kg}} - \frac{0.415\text{MJ}}{\text{kg}}\right) * \frac{38.4\text{kg}}{\text{h}} * 0.85 = \frac{26.76\text{MJ}}{\text{h}}$$

where: $P_{\text{recycle 85\% eff}}$ = total power recovered for water and algae biomass reaction (MJ/h)

The total power requirement is calculated by subtracting the 85% heat exchanger recovery power from total FH reaction power requirement. In order to find the total energy per unit mass, the total power requirement is divided by the assumed continuous reactor flow of 48L/h using Equation 3.10.

Equation 3.10

$$U_{FH} = \frac{P_{in} - P_{\text{recycle 85\% eff}}}{\frac{48\text{L}}{\text{h}}} = \frac{\frac{47.8\text{MJ}}{\text{h}} - \frac{26.76\text{MJ}}{\text{h}}}{\frac{48\text{L}}{\text{h}}} = 0.4383\text{MJ/L}$$

where: U_{FH} = total energy demand for FH reaction (MJ/L)

In order to find the energy demand in terms of MJ/ha-yr, the U_{FH} is multiplied by the total annual sum of slurry entering the FH reactor. The total volumetric flow into the FH reactor was found to be 415,298 L/ha-yr from the water balance calculations. Equation 3.11 shows the total FH annual energy demand.

Equation 3.11

$$U_{FH\ Total} = U_{FH} * Q_{FH} = \frac{0.4383MJ}{L} * \frac{415{,}714L}{ha*yr} = \frac{182{,}249MJ}{ha*yr}$$

where: $U_{FH\ Total}$ = total annual energy demand for FH reaction (MJ/ha-yr)
Q_{FH} = annual volumetric flow rate of slurry into FH reactor (L/ha-yr)

The FH product has two phases and must be separated therefore a solid liquid separation process must be included. The solid phase product is lipid-rich. This stream is also known as biofuel intermediate (BI) and must be further treated by HTM in order to yield the biocrude which then can be upgraded to a hydrocarbon fuel product. The aqueous phase product, on the other hand, is nutrient-rich and contains solubilized protein and carbohydrate macromolecules that will be precipitated out with further processing either by HTM or AP. The addition of a mineralizer catalyst yields valuable co-products either in the form of dittmarite when AP is performed or hydroxyapatite when HTM is performed.

The total mass entering the solid-liquid separation (SLS) process is found by multiplying the total FH inlet mass flow from the thickening process by the individual fractions of the products. The BI fraction from the FH process was found to be 42% (input to HTL) from laboratory experiments and the hydrolysate fraction was found to be 50% (input to HTM or AP). The remaining 8% is lost as the gaseous phase. From the water balance conducted, the total volumetric flow into the FH reactor is 415,714 L/ha-yr. Equations 3.12, 3.13 and 3.14 show how the incoming mass flow is calculated.

Equation 3.12

$$Q_{BI} = Q_{FH} * 20\% * 42\%$$

$$Q_{BI} = \frac{415{,}714L}{ha*yr} * 20\% * 42\% = 34{,}920\,\frac{L}{ha*yr}$$

where: Q_{BI} = volumetric flow rate of BI out of FH reactor (L/ha-yr)
Q_{FH} = volumetric flow rate of slurry entering FH reactor (L/ha-yr)

Equation 3.13

$$Q_{Hydrolysate} = (Q_{FH} * 50\% * 20\% + Q_{FH} * 80\%)$$

$$Q_{Hydrolysate} = \frac{415{,}714L}{ha-yr} * (50\% * 20\% + 80\%) = 374{,}143\,\frac{L}{ha-yr}$$

where: $Q_{Hydrolysate}$ = volumetric flow rate of hydrolysate out of FH reactor (L/ha-yr)

Equation 3.14

$$Q_{SLS} = Q_{BI} + Q_{Hydrolysate}$$

$$Q_{SLS} = 34{,}920\,\frac{L}{ha-yr} + 374{,}143\,\frac{L}{ha-yr} = 409{,}063\,\frac{L}{ha-yr}$$

where: Q_{SLS} = volumetric flow rate of slurry entering SLS process (L/ha-yr)

The separation of the solid and liquid phases is accomplished using rotary vacuum drum filtration. This method of SLS was chosen because of it relatively simple design, application, and operation and the fact that it can filter solids in continuous operation at relatively low labor costs (Haug, 2000). According to Grima, Belarbi, Fernández, Medina, and Chisti (2003) in *Recovery of Microalgal Biomass and Metabolites: Process Options and Economics*, the energy demand of a non-precoat continuous vacuum drum filter is 5.9 kWh/m^3. This is equivalent to 0.02124 MJ/L. The total energy demand is found using Equation 3.15.

Equation 3.15

$$U_{SLS} = Q_{SLS} * U_{Filter}$$

$$U_{SLS} = 409{,}063 \frac{L}{ha-yr} * 0.02124 \frac{MJ}{L} = 8{,}689 \frac{MJ}{ha-yr}$$

where: U_{SLS} = total annual energy demand for SLS (MJ/ha-yr)
U_{Filter} = energy demand required for rotary vacuum drum filtration per unit volume (MJ/L)

3.2.4 Hydrothermal Liquefaction (Module 4).

The BI is processed to yield a suitable biocrude that is catalytically upgraded to a "drop-in" biofuel product. One of the methods for extracting the biocrude from the BI is with hexane extraction. An alternative method is with HTL. This model utilized HTL to refine the BI because hexane extraction has considerable environmental impacts due to the energy-intensive dewatering requirements and the significant burden associated with solvent use and recovery (Alam, Mobin, & Chowdhury, 2015; Amer, Adhikari, & Pellegrino, 2011). The HTL process employed conditions of 350 °C; 3,000 psi; and a 20-minute residence time (Elliott et al., 2013). All models utilized a rotary vacuum drum filtration system due to its relatively simple design, application, and operation and it can filter solids in a continuous mode at low labor costs (Haug, 2000). The energy demand was estimated to be 5.9 kWh/m3 (Grima et al., 2003) for the rotary vacuum drum filtration system.

The solid stream of the FH process is approximately 42% of the algae biomass input and is 74% lipid (Garcia-Moscoso et al., 2015). This lipid can be extracted through either solvent extraction or HTL. This model utilizes HTL in order to minimize the use of solvent products such as hexane. The specific enthalpy for water at 350 °C and 3000 psi is 1642 kJ/kg. The specific enthalpy for water at 99 °C and 14.5 psi is 415 kJ/kg. The total change in enthalpy for water is 1227 kJ/kg. The heat capacity of algae is 1.80 kJ/kg°K. The HTL reactor is assumed to process slurry at 20.4 kg/h (4.08 kg/h of BI and 16.32 kg/h of water) in order to make a 20% slurry for the HTL reactor.

The power required for the water heating was found using Equation 3.6 from section 3.2.3:

$$P_W = \Delta C_p * \dot{m}_w = \frac{1.227\text{MJ}}{\text{kg}} * \frac{16.32\text{kg}}{\text{h}} = \frac{20.03\text{MJ}}{\text{h}}$$

where: P_w = power required to heat the incoming water (MJ/h)
ΔC_p = change in enthalpy (MJ/(kg*K_{out}-K_{in})
$\dot{m}_w$ = mass flow rate of incoming water (kg/h)

The power required for the biomass heating was found using Equation 3.7 from section 3.2.3:

$$P_B = C_p * \dot{m}_b * \Delta T = \frac{1.8\text{kJ}}{\text{kg}*^\circ\ \text{K}} * \frac{4.08\text{kg}}{\text{h}} * 251^\circ\ \ \text{K} = 1.843\,\frac{\text{MJ}}{\text{h}}$$

where: P_B = power required to heat the algae biomass (MJ/h)
C_p = specific heat of algae biomass (MJ/kg*K)
$\dot{m}_b$= mass flow rate of incoming algae biomass (kg/h)
ΔT = change in temperature (K)

The total energy required for heating the 20% BI slurry for the HTL reaction from 99°C to 350°C is found using Equation 3.8 from section 3.2.3:

$$P_{in} = P_W + P_B = \frac{20.03\text{MJ}}{\text{h}} + \frac{1.843\text{MJ}}{\text{h}} = 21.87\,\frac{\text{MJ}}{\text{h}}$$

where: P_{in} = total power required for water and algae biomass reaction (MJ/h)

The HTL liquid leaving the reactor is then able to be utilized for heat recovery in order to preheat the incoming slurry to the HTL reactor. The temperature of the liquid leaving the HTL reactor and entering the heat exchanger is 350 °C with an enthalpy of 1642 kJ/kg and the temperature of the HTL liquid leaving the heat exchanger is assumed to be 99 °C with an enthalpy of 415 kJ/kg. The mass of the recycle portion of the HTL is 16.32 kg/h. The total heat recovery is then found to be 21.32 MJ/h assuming an 85% for the heat exchanger using Equation 3.9 from section 3.2.3.

$$P_{\text{recycle 85\% eff}} = \Delta C_p * \dot{m}_w * 0.85 = \left(\frac{1.642\text{MJ}}{\text{kg}} - \frac{0.415\text{MJ}}{\text{kg}}\right) * \frac{16.32\text{kg}}{\text{h}} * 0.85 = \frac{17.02\text{MJ}}{\text{h}}$$

where: $P_{\text{recycle 85\% eff}}$ = total power recovered for water and BI reaction (MJ/h)

The total energy demand required for the HTL reactor is then found using Equation 3.10 from section 3.2.3:

$$U_{\text{HTL}} = \frac{P_{\text{in}} - P_{\text{recycle 85\% eff}}}{\dot{m}_{\text{HTL}}} = \frac{\frac{21.87\text{MJ}}{\text{h}} - \frac{17.02\text{MJ}}{\text{h}}}{\frac{20.4\text{L}}{\text{h}}} = 0.2377\text{MJ/L}$$

where: U_{HTL} = total energy demand for FH reaction (MJ/L)
$\dot{m}_{\text{HTL}}$ = mass flow rate into HTL reactor (kg/h)

In order to find the energy demand in terms of MJ/ha-yr, the U_{HTL} is multiplied by the total annual sum of slurry entering the HTM reactor. The total volumetric flow into the HTL reactor was found to be 174,600 L/ha-yr from the water balance calculations. The total HTL annual energy demand was found using Equation 3.11 from section 3.2.3.

$$U_{\text{HTL Total}} = U_{\text{HTL}} * Q_{\text{HTL}} = \frac{0.2377\text{ MJ}}{\text{L}} * \frac{174{,}600\text{ L}}{\text{ha}*\text{yr}} = \frac{41{,}510\text{ MJ}}{\text{ha}*\text{yr}}$$

where: $U_{\text{HTL Total}}$ = total annual energy demand for HTL reaction (MJ/ha-yr)

Q_{HTL} = annual volumetric flow rate of slurry into HTL reactor (L/ha-yr)

3.2.5 Hydrothermal Mineralization/Atmospheric Precipitation (Module 5a/Module 5b)

This study evaluated HTM and AP as methods of solid nutrient precipitation. The aqueous phase of the FH process is nutrient-rich in carbohydrate and protein macromolecules. The hydrolysate contains 80% of the phosphorus of the microalgae, of which 85% of this is in the form of phosphate (Garcia-Moscoso et al., 2015). It is important to recover the phosphorus because phosphorus is a limited resource of which the Earth's supply is dwindling quickly. Retaining the phosphorus in the liquid state has a limited shelf life due to the contamination of microorganisms (Talbot et al., 2016) so the mineralization of the phosphorus into a preserved form extends the usage of the product.

HTM is a hydrothermal process that recovers and stores the macromolecules as valuable co-products in the form of hydroxyapatite through crystallization (Koutsopoulos, 2002; Koutsoukos, Amjad, Tomson, & Nancollas, 1980). The process requires the addition of a calcium mineralizer. The Ca mineralizer-to-phosphate ratio is 1.67, ideal for maximum phosphorus removal and hydroxyapatite (HAp) production (Elliott, 2013; Teymouri et al., 2017, 2018). The HTM process in this study utilized 280 °C; 1,200 psi; and 1-hour residence time in a continuous flow reactor. A heat exchanger operating at 85% efficiency was used to preheat the incoming hydrolysate into the HTM reactor using the heat recovered as a result of lowering the temperature from 280 °C to 99 °C. AP is executed at atmospheric conditions rather that hydrothermal conditions. The process requires addition of magnesium mineralizer at a 2:1 ratio relative to phosphate (Teymouri et al., 2017, 2018). The product from the AP mineralization is called struvite/dittmarite, a solid form of fertilizer which can be used as a nutrient source for the algae cultivation (Moed, Lee, & Chang, 2015) or can be sold as a valuable coproduct (Rahman et al., 2014). The AP process does not require heating as is required in the HTM process but has an energy demand associated with mixing the hydrolysate for the required 60-minute reaction time. Following the HTM/AP process, the nutrient-depleted hydrolysate was recycled back to the cultivation pond (Cashman et al., 2014).

The density of calcium hydroxide, $Ca(OH)_2$, is 2.21 kg/L, or 2,210,000 mg/L. The ratio of $Ca(OH)_2$ to hydrolysate received from the flash hydrolysis process was reported to be 217.4 mg $Ca(OH)_2$/100 L hydrolysate. The ratio of $Ca(OH)_2$ to hydrolysate in L:L is therefore found by the Equation 3.15.

Equation 3.15

$$(217.4\ \mathrm{mgCa(OH)_2/100L\ hydrolysate}) * \left(\frac{\mathrm{1LCa(OH)_2}}{\mathrm{2210000mgCa(OH)_2}}\right) = \frac{\mathrm{0.000098\ L\ Ca(OH)_2}}{\mathrm{L\ Hydrolysate}}$$

This shows that the mineralizer material demand is 0.000098 L Ca mineralizer for every liter of hydrolysate processed. In order to find the ratio of HAp production for every liter of hydrolysate processed, equation S23 was used. The HTM reaction yields 147.39 mg HAp for every liter of processed hydrolysate. The density of HAp is 3.2. The yield of HAp is found by Equation 3.16.

Equation 3.16

$$(147.39\ \mathrm{HAp/100L\ hydrolysate}) * \left(\frac{\mathrm{1L\ HAp}}{\mathrm{3200000mgCa(OH)_2}}\right) = \frac{\mathrm{0.000046\ LHAp}}{\mathrm{L\ Hydrolysate}}$$

The HTM process utilizes parameters of 280 °C, 1200 psi, and 1-hour residence time in a continuous flow reactor (Teymouri et al., 2017, 2018). The specific enthalpy for water at 280 °C and 1200 psi is 1235 kJ/kg. The hydrolysate leaving the flash hydrolysis heat exchanger will be at 99 °C and is heated to the required 280 °C. The specific enthalpy for water at 99 °C and 14.5

psi is 415 kJ/kg. The total change in enthalpy for water is 820 kJ/kg. The energy requirement of heating the $Ca(OH)_2$ is considered negligible because the portion is only 0.0098%. The incoming liquid mass was determined to be 207,857 L/ha-yr. This equates to 24.4 L/h, or 24.4 kg/h, when operating at 355 days a year (with 1 day reserved for maintenance) using Equation 3.6.

The power required for the HTM heating:

$$P_W = \Delta C_p * \dot{m}_w = \frac{820\ kJ}{kg} * \frac{24.4\ kg}{h} = \frac{20.01\ MJ}{h}$$

where: P_w = power required to heat the incoming slurry (MJ/h)
ΔC_p = change in enthalpy (MJ/(kg*K_{out}-K_{in})
$\dot{m}_w$ = mass flow rate of incoming slurry (kg/h)

The HTM liquid leaving the reactor is then able to be utilized for heat recovery in order to preheat the incoming slurry to the HTM reactor. The temperature of the liquid leaving the HTM reactor and entering the heat exchanger is 280 °C with an enthalpy of 1235 kJ/kg and the temperature of the HTM liquid leaving the heat exchanger is assumed to be 99 °C with an enthalpy of 415 kJ/kg. The mass of the recycle portion of the HTM is approximately 24.4 kg/h because the product fraction is only 0.0098%. The total heat recovery is then found to be 21.32 MJ/h assuming an 85% for the heat exchanger using Equation 3.7.

$$P_{recycle\ 85\%\ eff} = \Delta C_p * \dot{m}_w * 0.85 = \left(\frac{1.235\ MJ}{kg} - \frac{0.415\ MJ}{kg}\right) * \frac{24.4\ kg}{h} * 0.85 = \frac{17.01\ MJ}{h}$$

where: $P_{recycle\ 85\%\ eff}$ = total power recovered from HTM reaction (MJ/h)

The total energy demand required for the HTM reactor is then found using Equation 3.8.

$$U_{HTM} = \frac{P_{in} - P_{recycle\ 85\%\ eff}}{\dot{m}_{HTM}} = \frac{\frac{20.01\ MJ}{h} - \frac{17.01\ MJ}{h}}{\frac{24.4L}{h}} = 0.123\ MJ/L$$

where: U_{HTM} = total energy demand for HTM reaction (MJ/L)
$\dot{m}_{HTM}$ = mass flow rate into HTM reactor (kg/h)

In order to find the energy demand in terms of MJ/ha-yr, the U_{HTM} is multiplied by the total annual sum of slurry entering the HTM reactor. The total volumetric flow into the HTM reactor was found to be 207,857 L/ha-yr from the water balance calculations. The total HTM annual energy demand was found using Equation 3.9.

$$U_{HTM\ Total} = U_{HTM} * Q_{HTM} = \frac{0.123\ MJ}{L} * \frac{207{,}857\ L}{ha*yr} = \frac{25{,}566\ MJ}{ha*yr}$$

where: $U_{HTM\ Total}$ = total annual energy demand for HTM reaction (MJ/ha-yr)
Q_{HTM} = annual volumetric flow rate of slurry into HTM reactor (L/ha-yr)

An alternative to HTM is evaluated in order to compare life cycle costs associated with the HTM process. This alternate is the AP process. This process is conducted atmospheric conditions at approximately 20 °C and 1 atm and requires a 1-hour residence time. The process requires addition of magnesium mineralizer at a 2:1 ratio relative to phosphate (Teymouri et al., 2017, 2018). The product produced from the AP mineralization is a struvite/dittmarite product which is a solid form of fertilizer which can be used as a nutrient source for the algae cultivation (Moed et al., 2015) or sold as a valuable coproduct (Rahman et al., 2014). This solid form of the product is more economical for transport as with the hydroxyapatite product from the HTM and is also a more stable product than the FH liquid product. It is also important to once again consider the phosphorus recovery responsibility associated with the process considering the limited phosphorus resource availability. Magnesium chloride is used as the magnesium mineralizer. The density of magnesium chloride, $Mg(Cl)_2$, is 2.32 kg/L, or 2,320,000 mg/L. The ratio of $Mg(Cl)_2$ to hydrolysate received from the flash hydrolysis process was 353.3 mg $Mg(Cl)_2$/100 L hydrolysate according to experiments conducted at Old Dominion University in 2016. The ratio of $Mg(Cl)_2$ to hydrolysate in L:L is therefore calculated using the Equation 3.17.

Equation 3.17

$$(353.3\ \text{mgMg(Cl)}_2/100\text{L hydrolysate}) * \left(\frac{1\text{LMg(Cl)}_2}{2320000\text{mgMg(Cl)}_2}\right) = \frac{0.000152\ \text{L Mg(Cl)}_2}{\text{L Hydrolysate}}$$

In order to find the ratio of dittmarite production for every liter of hydrolysate processed, equation S29 was used. The AP reaction yields 288.2 mg dittmarite for every liter of processed hydrolysate. The density of dittmarite is 2.2. The yield of dittmarite is found by using Equation 3.18.

Equation 3.18

$$\left(288.2\ \text{mg}\frac{\text{dittmarite}}{100\text{L}}\text{hydrolysate}\right) * \left(\frac{1\text{L dittmarite}}{2200000\text{mgCa(OH)}_2}\right) = \frac{0.000131\ \text{L dittmarite}}{\text{L Hydrolysate}}$$

This shows that our mineralizer material demand is 0.000131 L Mg mineralizer for every liter of hydrolysate processed. The aqueous portion remaining which has been depleted of nutrients is then available for recycling to the cultivation pond following activated carbon filtration.

The hydrolysate which has been processed through HTL and HTM/AP is assumed to be nutrient depleted and now available for recycling back to the algae cultivation pond. Although the hydrolysate has been deprived of nutrients, it still has the potential for bacterial growth.

Contamination of the algae pond with contaminated aqueous phase could be detrimental to the algae growth. The aqueous phase will then be processed by activated carbon filtration.

According to the 2014 EPA report, *Environmental and Cost Life Cycle Assessment of Disinfection Options for Municipal Drinking Water Treatment* (Cashman et al., 2014), the granulated activated carbon (GAC) from bituminous coal requirement for adsorption of contaminants is 0.0030 kg GAC/ m^3 of drinking water. The inlet liquid mass from both the HTL and HTM/AP processes was determined to be 513,806 L/ha. This yields an annual GAC requirement of 1.54 kg GAC/ha-yr. The GAC also needs to be reactivated which requires 0.0026 m^3 of natural gas/m^3 of drinking water. This yields an annual requirement of 1.34 m^3 of natural gas/ha-yr.

AP is conducted at atmospheric temperature and pressure therefore no additional heating energy is required. There is a requirement for stirring of the mineralizer and FH hydrolysate during the 60-minute reaction time however. This requires determining the number of reactors required and the energy consumption required per stirring agitator. The volume of the reactor required is determined by identifying the amount of incoming hydrolysate per hour. The incoming volume of liquid is 207.9 m^3/ha-yr. The atmospheric precipitation reactor is assumed to have a diameter at 1m and a height of 2m therefore the volume is found by using Equation 3.19.

Equation 3.19

$$V_{AP} = \pi * r^2 * h = 3.142 * 0.5^2 m * 2m = 1.57 m^3$$

where: V_{AP} = AP reactor volume
r = AP reactor radius
h = AP reactor height

The number of AP reactors for processing the annual volumetric flow to the AP reactor is found by dividing the annual volumetric flow by the volume of the reactor. The annual volumetric flow to the AP reactor was found to be 207.9 m^3/ha-yr based on water balance calculations. The number of cylindrical reactors required is found using Equation 3.20.

Equation 3.20

$$n_{AP} = Q_{AP}/V_{AP} = \frac{\frac{207.9m^3}{ha*yr}}{\frac{1.57m^3}{reactor}} = 132.4\frac{reactors}{ha*yr}$$

where: n_{AP} = number of reactors per ha-year

Q_{AP} = volumetric flow rate of slurry entering AP reactor (L/ha-yr)

The agitator diameter for the mixing is found by multiplying the diameter of the reactor (1m) by the (D/T) ratio (0.5 assumed) of the reactor which yields a diameter of 0.5m (Equation 3.21). The power number is assumed to be 1.37 from McCabe et al., 2004 . The agitator speed is assumed to be 5 rotations per second from Popov, Abdel-Fattah, and Kumar (2016). The energy consumption is then found by the following equation:

Equation 3.21

$$P_{AP} = N_p * \rho * N^3 * D^5 = 1.37 * \frac{1000kg}{m^3} * \frac{5^3 rot}{s} * 0.5^5 m * \frac{1kw}{1000w} = 5.352kw/unit$$

where: P_{AP} = power required for each agitator (kw/unit)

N_P = power number

ρ = liquid density (kg/m^3)

N = agitator speed (rot/s)

D = agitator diameter

The power requirement for each agitator is 5.352 kw/unit which is also equal to 5.352 kJ/s-unit. The total energy demand is then found by multiplying the power requirement for each agitator, by the number of agitators required for the years' worth of volumetric flow, by the reaction time of the AP process (Equation 3.22).

Equation 3.22

$$U_{AP} = P_{AP} * t * \eta_{AP} = \frac{5.352\text{kJ}}{\text{s}} * \frac{1\text{MJ}}{1000\text{kJ}} * 60\text{min} * \frac{60\text{s}}{\text{min}} * \frac{132.4\text{units}}{\text{ha}*\text{yr}} = \frac{2551\text{MJ}}{\text{ha}*\text{yr}}$$

where: U_{AP} = total annual energy demand for AP reaction (MJ/ha-yr)
t = mixing time (m)

The mixing is assumed to have an 80% efficiency therefore total energy for the mixing is 2551 MJ/ha-yr/0.8 for a total annual energy demand of 3189 MJ/ha-yr.

3.2.6 Bio-oil Post Processing

The bio-oil can then be upgraded into a drop-in fuel through several processes. In this model, the drop-in fuel can either be RDII, RG, or HRJ while the energy co-products include naphtha, propane, etc. To calculate direct land use associated with each modeled system, the calculated per hectare energy production (MJ/ha-yr) for each of the pathways was divided by the total energy produced (MJ/yr) for a small-sized refinery in the United States (Natelson, Wang, Roberts, & Zering, 2015). Each model was evaluated on two environmental endpoints: energy use in megajoules (MJ) and global warming potential (in kg CO2-equivelents). Energy-based allocation method applied for co-product handling was evaluated.

The catalytic upgrade of the biocrude generated from HTL and necessary for drop-in fuels production was modeled using parameters associated with studies performed by Argonne

National Laboratory which were incorporated in the GREET model 2016. The RDII production was based off of the hydrogenation process developed by Universal Oil Products (UOP), a wholly owned subsidiary of Honeywell International (Honeywell UOP). The process scheme was modeled and published by Argonne National Laboratory in 2008 (Huo et al., 2008). The RG production was modeled using catalytic cracking, also based upon UOP technology. The bio-oil was fed into the fluidized catalytic cracker (FCC) with inputs of vacuum gas oil (VGO), steam, and electricity. This stand-alone model uses algae oil as the feedstock rather than in combination with vacuum gas oil (Huo et al., 2008). The hydroprocessed renewable jet (HRJ) fuel, also known as jet fuel from hydroprocessed esters and fatty acids (HEFA), was modeled utilizing processes and parameters in GREET 2016. The data and assumptions for energy use and emissions associated with HRJ fuel production were sourced from a study conducted by Pearlson et al. in 2011 (Pearlson, 2011). The hydrotreatment and catalytic treatment required a catalyst (5% Pd/C and 0.5% Pt/ZSM-22, respectively) (Galadima & Muraza, 2015).

The renewable diesel II production is based off of the hydrogenation process developed by Universal Oil Products (UOP) which is a wholly owned subsidiary of Honeywell International (Honeywell UOP). The hydrogenation process is conducted in a standalone unit and the process scheme was modeled by Argonne National Laboratory in ASPEN in 2008 and the results were published in *Life-Cycle Assessment of Energy and Greenhouse Gas Effects of Soybean-Derived Biodiesel and Renewable Fuels* (Huo et al., 2008). The process takes the bio-oil into the diesel hydrotreater and adds steam and hydrogen. Electricity is used to produce renewable diesel and a co-product known as propane fuel mix. Honeywell UOP reports that the renewable diesel II product has a cetane value of 75-90, excellent cold flow properties, excellent oxidative stability, and similar energy content to petro-diesel, which allows the product to be used interchangeably in traditional petro-diesel trucks and automobiles without vehicle technology changes. UOP also reports that renewable diesel II has lower emissions than petro-diesel, up to 80% lower. This study assumes that the production of algae oil-based renewable diesel II requires the same material and energy inputs as soy oil-based renewable diesel II. Table 3.3 shows material inputs and outputs used in the production of renewable diesel II. These values were used in this modeling scheme.

Table 3.3. Material Inputs and Outputs for the Production of RDII

Inputs	Quantity
Algae oil (lb)	1.174
Hydrogen (lb)	0.032
Natural gas for steam (MJ)	0.082
Electricity (kWh)	0.095
Outputs	Quantity
Renewable diesel II (lb)	1
Propane fuel mix (lb)	0.059

The total energy output in MJ/ha is then calculated by multiplying the fuel product produced in Mg/ha by the LHV in MJ/kg and multiplying by 1000 kg/Mg (Table 3.4).

Table 3.4. Energy Output Results for the Production of RDII

Product	LHV (MJ/kg)	Quantity (Mg/ha-yr)	Energy output (MJ/ha-yr)
Renewable diesel II	44.0	25.84	968,933
Propane fuel mix	43.2	1.52	65,848

Renewable gasoline, also referred to as green gasoline, can be produced by a process called catalytic cracking. The production is again based off of a process developed by

Honeywell UOP. This process uses a fluidized catalytic cracker (FCC). The bio-oil is fed into the FCC with inputs of vacuum gas oil (VGO), steam, and electricity. This stand-alone model only uses algae oil as the feedstock rather than a dual processing with vacuum gas oil and is based off of the results in the Argonne National Laboratory study (Huo et al., 2008). The outputs are renewable gasoline and the co-products are product gas, light cycle oil (LCO), and clarified slurry oil (CSO). A significant portion of the energy content is in the co-products. The values were produced from the study conducted by Argonne National Laboratory in 2008 (Huo et al., 2008) and data were gathered from GREET 2016. This study assumes that the production of algae oil-based renewable gasoline requires the same material and energy inputs as soy oil-based renewable gasoline and can be seen in Table 3.5.

Table 3.5. Material Inputs and Outputs for the Production of RG

Inputs	Quantity
Algae oil (lb)	2.231
Electricity (kWh)	0.029
Outputs	**Quantity**
Renewable gasoline (lb)	1
Product gas (lb)	0.345
LCO (lb)	0.245
CSO (lb)	0.291

The total energy output in MJ/ha is then calculated by multiplying the fuel product produced in Mg/ha by the LHV in MJ/kg and multiplying by 1000 kg/Mg (Table 3.6).

Table 3.6 Energy Output Results for the Production of RG

Product	LHV (MJ/kg)	Quantity (Mg/ha-yr)	Energy output (MJ/ha-yr)
Renewable gasoline	43.5	11.58	503,231
Product gas	42.6	8.91	379,452
LCO	44.9	6.34	284,726
CSO	43.6	7.53	328,233

The hydroprocessed renewable jet fuel (HRJ), also known as hydroprocessed esters and fatty acids (HEFA) is modeled utilizing the processes and parameters established in GREET 2016. The data and assumptions for energy use and emissions associated with HRJ fuel production are sourced from the MIT study conducted by Pearlson (2011) entitled *A Techno-Economic and Environmental Assessment of Hydroprocessed Renewable Distillate Fuels*. The HEFA jet fuel that is produced from algae oil must meet ASTM D7566 and are composed of paraffins and are therefore grouped as synthetic paraffinic kerosene (SPK) because their molecules boil in the range of jet fuel.

The production of HRJ involves deoxygenating the oil consisting of free fatty acids through (1) hydrotreatment to create straight chain alkanes and (2) tandem catalytic cracking and isomerization to produce isoparaffins representative of SPK. The hydrotreatment of the algae oil consists of feeding the oil into a reactor fed with hydrogen in the presence of a catalyst which removes oxygen, saturates double bonds, and cleaves the propane backbone of triglycerides. In order to produce maximum SPK, hydrogen is fed at a rate of 4% (Pearlson, 2011). Water, carbon dioxide, propane, and straight chain alkanes are produced from the reaction. The product is cooled by steam generation and then sent to an isomerization and catalytic cracking unit in the presence of a catalyst. Cooling water is used to cool the isomerized product. The mixture is sent to a separation tower where excess gases (mixed paraffin gases, carbon dioxide, hydrogen) are recovered and recycled, and then the liquid paraffin product is separated into SPK and naphtha.

The hydrotreatment which creates the straight chain alkanes requires a Pd/C catalyst at a ratio of 0.05 unit weight of catalyst per unit weight of free fatty acid (Galadima & Muraza, 2015). The tandem catalytic cracking and isomerization requires a Pt/ZSM-22 catalyst which is also applied at a 0.005 ratio (Galadima & Muraza, 2015). The total HEFA process requires electricity to power pumps, compressors, and various electrical controls. It also requires natural gas to produce heat and steam required in each of the unit operations. The total energy requirements and the product sums are shown in Table 3.7.

Table 3.7. Material Inputs and Outputs for the Production of HRJ

Inputs	Quantity
Algae oil (lb)	1.31
Electricity (kWh)	0.028
Natural gas (MJ)	3.570
Hydrogen (MJ)	2.970
Outputs	**Quantity**
HRJ (lb)	1
Propane mix (lb)	0.142
Naphtha (lb)	0.097

The total energy output in MJ/ha is then calculated by multiplying the fuel product produced in Mg/ha by the LHV in MJ/kg and multiplying by 1000 kg/Mg (Table 3.8).

Table 3.8. Energy Output Results for the Production of HRJ

Product	LHV (MJ/kg)	Quantity (Mg/ha-yr)	Energy output (MJ/ha-yr)
HRJ	44.1	18.59	819,813
Propane mix	43.2	3.67	158,518
Naphtha	44.4	2.51	111,241

3.2.7 Infrastructure

The three main materials required for algae open pond cultivation are polypropylene, aggregates, and polyvinyl chloride (PVC). Other equipment required are water pumps, flue gas pumps, and paddle wheels. The methodology for the evaluation of the open pond material and equipment requirements follows the methodology conducted in the research conducted by Resurreccion et al. (2012). Values obtained in Resurreccion et al. (2012) were calculated using 2011 values therefore the 2017 cost of cultivation construction and materials was calculated using the historical inflation value equal an average of 1.45% over the last 6 years in the United States ("US Inflation Calculator", 2017).

The open pond liner utilized for this model was a polypropylene geotextile which was used to prevent erosion and percolation of culture medium through the earthen base. Only 5% of the of the open pond geometry was lined due to geotextiles cost and is in agreement with the methodology utilized in Benemann and Oswald (1996) and Resurreccion et al. (2012). The resulting mass of polypropylene required as liner was found to be 5,520 kg/ha. Assuming the environmental burdens for this and other materials can be amortized over a 30-year useful life, the annualized liner requirement is 184 kg/ha-yr. This value was multiplied by open pond direct land uses and then the life cycle impact factors from the Ecoinvent® database (see Table 3.11) to compute energy use and other environmental burdens associated with manufacture of the required liners.

The pond base is stabilized using gravel aggregates in order to prevent erosion of the compacted soil near the paddle wheels. A 0.05-m thick layer of medium-sized, concrete construction-quality gravel is placed underneath 5% of the base area, principally underneath the paddle wheels. This coverage requires 22,380 kg aggregates per 1-ha open pond. Assuming the environmental burdens for this and other materials can be amortized over a 30-year useful life, the annualized aggregate requirement is 746 kg/ha-yr. This value was multiplied by open pond direct land uses and life cycle impact factors from the Ecoinvent® database (see Table 3.11) to compute energy use and other environmental burdens associated with manufacture of the required aggregates.

It was assumed that PVC piping would be used for all conveyances of culture medium, nutrients, flue gas, and air in the open pond system. The total mass of PVC required for each 1-ha module was calculated based on the total length and thickness of each pipe and PVC density of 1.35 g/cm^3 (Perry & Green, 1999).

Liquid Pipes***:*** The pipe thickness required for conveyance of culture medium into and out of the open pond system was computed using Barlow's Formula (Equation 3.23) (Perry & Green, 1999).

Equation 3.23

$$t_{MIN} = \frac{PD}{2S}$$

where: t_{MIN} = minimum acceptable pipe thickness (in)
P = internal pressure (psi)
D = outside diameter (in)
S = PVC material design stress (psi)

Values for Equation 3.23 were as follows: P = 275,790 N/m^2 (40 psi), based on inlet and outlet pressures of 1 and 2.72 atm, respectively (to be compatible with pump head loss calculations above); D = 3.5 in; and S = 2000 psi for PVC 2120 (Perry & Green, 1999). Resulting t value was 0.035 in. Comparing this value with pipe specifications for "off the shelf" commercial products, the closest available thickness for PVC 2120 is 0.135 in (0.0034 m) (Perry

& Green, 1999). Final specifications for the water pipes were thus as follows: nominal size = 3 in, schedule 40, outer diameter = 3.5 in, t = 0.135 in. A conservative estimate for total tube length was 100 ft/ha (30.48 m/ha). Taken together, these dimensions correspond to a PVC mass of 1.1 kg/ha-yr for the model, after amortizing over 30 years.

Gas Pipes: The pipe thickness required for flue gas conveyance was also computed using Equation 3.23. It was assumed that the internal pressure required for flue gas transport is 20% of the that required for water ($40 \times 0.20 = 8$ psi). Values for Equation 3.23 were thus as follows: P = 55,158 N/m^2 (8 psi); D = 2.875, and S = 2000 psi for PVC 2120 (Perry & Green, 1999). Resulting t value was 0.0058 in. Comparing this value with pipe specifications for "off the shelf" commercial products, the closest available thickness for PVC 2120 is 0.11 in (2.8 mm). Final specifications for the gas pipes were thus as follows: nominal size = 2.5 in, schedule 40, outer diameter = 2.875 in, t = 0.11 in. Total tube length was 2624 ft/ha (800 m/ha) (Weissman, Tillett, & Goebel, 1989). These dimensions correspond a PVC mass of 22.2 kg/ha-yr for the model, after amortization over 30 years.

Total PVC demand is on the order of 23.3 kg/ha-yr for the model, assuming materials burdens can be annualized over 30-year plant life. This mass was multiplied by direct land uses and then by life cycle impact factors from the Ecoinvent® database (see Table 3.11) to compute energy use and other environmental burdens associated with manufacture of the required PVC.

From Section 3.2.2, the number of water pumps (1.5-kW rating) and gas pumps (0.75-kW rating) required per 1-ha open pond were as follows: 0.4 water pumps and 1.64 gas pumps. These values were scaled by the direct land use (ha) required to produce one functional unit and then multiplied by life cycle impact factors from the Ecoinvent® database (see Table 3.11) to compute energy use and other environmental burdens associated with manufacture of the required pump. It must be noted that the burdens calculated for both water and flue gas pumps were reported on an annual basis since it was assumed that the same pumps were used each year for 30 years.

The paddle wheel design used for this study was based on J. R. Benemann and Oswald (1996). This comprises a cylindrical six-bladed PVC paddle wheel with blade diameter equal to 0.5 and total length of 24.5 m. It was assumed that the six "spiked" blades comprise 25% of the volume of a cylinder with the same diameter. The total mass of PVC required to produce 10 paddle wheels/ha was 64,950 kg for the open pond system. Assuming that the environmental burden for this material can be amortized over 30 years, the annualized burden is computed using 2,165 kg PVC/ha-year times PVC life cycle impact factors from the Ecoinvent® database.

The infrastructure required for converting algae biomass into usable energy is a series of tanks which consist of the processes of autoflocculation, thickening, flash hydrolysis, solid liquid separation, hydrothermal liquefaction, mineralization (HTM/AP), catalytic upgrade, and activated carbon filtration. The methodology used for tank steel calculation was based on the study conducted by Resurreccion et al. (2012) using the flow rate through each unit operation and the residence times for each process. Table 3.9 shows the values for calculating the tank steel demands for the operations. Flow rates (Q), residence times (τ), capacity volumes (V_{TANK}), capacity liquid weights (M_{LIQUID}), and internal tank pressures (P_{TANK}) are required to compute tank steel demand (M_{TANK}) for conversion unit operations following algae cultivation systems. M_{TANK} values are represented using units of "per hectare per year" because it is assumed that burdens associated with steel manufacture can be amortized over a 30-year useful life to compute the fraction of overall burden which should be charged to each year.

Table 3.9 Mass of Steel Required for Unit Operations Following Cultivation

Unit Operations	Q , m^3/ha-d	τ , d	$V_{LIQUID,}$ m^3/ha	M_{LIQUID}, kg/ha	P_{TANK}, Pa	M_{TANK}, kg/ha-yr
Autoflocculation	113.9	0.1	11.1	11,100	21,843	42.0
Thickening	11.4	0.1	1.1	1,100	10,139	9.0
Flash Hydrolysis	1.14	0.0001	0.0001	0.1	482	0.10
Solid Liquid Separation	1.14	0.014	0.016	16	2,467	0.54
Hydrothermal Liquefaction	0.48	0.014	0.007	7	1,847	0.30
Atmospheric Precipitation	0.57	0.042	0.024	24	2,824	0.70
Hydrothermal Mineralization	0.57	0.042	0.024	24	2,824	0.70
Catalytic Upgrade	0.38	0.042	0.016	16	2,473	0.54
Activated Carbon Filtration	112.0	0.014	1.58	1,580	11,418	1.58

3.2.8 Life Cycle Assessment

Life cycle models were created for each of the six compared systems (RDII-AP, RDII-HTM, RG-AP, RG-HTM, HRJ-AP, and HRJ-HTM). The system boundary for each modeled system was "well-to-pump" incorporating all processes upstream of the delivered energy product. These upstream processes have corresponding environmental impacts. These impacts were determined using materials and energy flows derived from the life cycle inventory (materials and energy accounting including infrastructure related costs (Canter et al., 2014)) and impact factors obtained from either EcoInventTM, GREET, TRACI, or any open source LCA databases.

The functional unit (FU) for this LCA study was 1 MJ of usable energy. This LCA is conducted on a "well-to-pump" basis. Table 3.10 shows the results of weighted average calculations for densities and LHV's for each of the fuel pathways (RD II, RG, and HRJ). The FU represents the production of usable energy products in terms of MJ from algae per year. In order to calculate the direct land use, the calculated total energy production (in MJ/ha-yr) for each of the pathways was divided into the functional unit (MJ/yr) to yield the direct land use in ha. Additionally, the total energy is also calculated based upon an additional FU of 100,000 m^3

of energy product which is equivalent to the fuel production of a small-sized refinery in the U.S. in 1 year (Natelson et al., 2015).

Table 3.10. Functional Unit and Direct Land Use Calculations

Pathway	Product	Fraction	Density (kg/L)	LHV (MJ/kg)	Total Energy (MJ/ha-yr)[1]	Total Energy (MJ/yr)[2]	Direct Land Use (ha)
RD II	RD II	93.6%	0.840	44.1			
	Propane (gas)	6.4%	0.002	43.2			
	weighted avg		**0.786**	**44.0**	**1,034,780**	**345,477,000**	**333.84**
RG	RG	33.6%	0.745	43.5			
	Product Gas	25.4%	0.002	42.6			
	LCO	19.0%	0.880	44.9			
	CSO	22.0%	0.890	43.6			
	weighted avg		**0.614**	**43.6**	**1,495,642**	**267,704,000**	**178.99**
HRJ	HRJ	75.3%	0.810	44.1			
	Propane (gas)	14.5%	0.002	43.2			
	Naphtha	10.2%	0.740	44.4			
	weighted avg		**0.686**	**44.0**	**1,089,572**	**301,840,000**	**277.03**

[1] Total energy produced as biofuel in 1 hectare in 1 year.

2 Total energy produced as biofuel from a small-sized refinery in the U.S. in 1 year.

The representative energy consumption was calculated using the EROI method. Energy ratios of the type reported by Hall and Klitgaard (2006), Hall, Balogh, and Murphy (2009), Luo et al. (2010), Clarens et al. (2011), and Resurreccion et al. (2012) were computed to determine the energy production in terms of net positive or negative energy totals. The EROI was computed using the energy output as the numerator and energy input is used as denominator. Values greater than one are said to be net energy-producing which is desirable, and values less than one are said to be net-energy consuming. Larger values are deemed more desirable from a life cycle perspective, and it's been suggested that the minimum tenable EROI is roughly 3 (i.e., 3 MJ energy delivered per 1 MJ consumed) but that values between 5 and 10 will ultimately be required to maintain the present quality of life once fossil fuels are no longer readily abundant (Resurreccion et al., 2012). The EROI numerator included biofuel production (RDII, RG, or RJF) and the energy coproducts (propane, LCO, CSO, product gas, or naphtha). Components of the EROI denominator (energy input) included: direct electricity and heat use; and upstream energy use for materials and energy inputs (as computed using Ecoinvent® impact factors).

The representative greenhouse gas emissions were calculated using the GWP. The GWP was calculated similarly to the calculations performed in Resurreccion et al. (2012). The GWP ratio evaluates GHG emissions performance on a normalized basis. The GHG outputs (emitting processes) are used as numerator and GHG uptakes (sequestering processes) are used as denominator. A favorable GWP is expressed as a number less than one. This equates to a net-GHG consuming system. The NGR numerator consists of energy inputs (electricity and natural gas) and material inputs (fertilizer, mineralizer, hydrogen, granulated carbon, etc.). The NGR denominator consists of the sequestration of the photosynthesis CO_2.

The LCA impact factors are representative inputs that are required to produce the energy and materials in the systems. Impact factors used in this study were taken from the industry-standard Ecoinvent® database. These are summarized in Table 3.11 expressed using μ/σ notation, where μ is mean value and σ is standard deviation. All data were from Ecoinvent® v. 3.0 (Weidema).

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Table 3.11. Life Cycle Impact Factors for Materials and Energy Inputs

Item	Unit Basis	Energy Use (MJ)	Water Use (m^3)	GHG (kg CO_2 eq)
Aggregates	1 kg gravel	0.04/0.007	0.04/0.007	0.003/0.0004
Bleach	1 kg 15% NaOCl in H_2O (m/m)	10.2/4.0	5.4/0.9	0.9/0.1
Carbon Dioxide	1 kg CO_2	8.3/2.0	2.2/0.6	0.8/0.1
Concrete	1 m^3	1180.0/836.0	561.0/87.1	265.0/47.7
Electricity	1 kWh from US grid	12.5/10.1	0.8/0.1	0.2/0.01
Fertilizer - N_2H_4CO	1 kg as N	62.1/11.8	4.0/1.3	3.4/0.3
Fertilizer - $H_{12}N_3O_4P$	1 kg P_2O_5	37.5/5.4	0.7/0.1	0.8/0.07
Fertilizer - $CaH_2P_2O_8$	1 kg P_2O_5	33.8/14.5	12.4/2.4	2.7/0.5
Granulated Carbon	1 kg GC	1.6	0.003	8.66
Heating Oil	1 MJ from light heating oil	1.3/0.2	0.03/0.004	0.01/0.01
Hydrogen	1 kg Hydrogen	13	0.00001	1.22
Mineralizer (Ca)	1 kg Ca Mineralizer	.02	0.0000001	0.008
Mineralizer (Mg)	1 kg Mg Mineralizer	.1	0.0000006	0.01
Natural Gas	1 kg Natural Gas	4.2	0.00000001	0.007
Polypropylene	1 kg $(C_3H_6)_n$	70.7/0.01	0.05/0.0008	2.0/0.0007
Polyvinyl chloride	1 kg $(C_2H_3Cl)_n$	47.2/3.6	0.5/0.04	2.0/0.1
Pump (Water/Flue Gas)*	1 piece	0.3/0.06	0.9/0.2	0.01/0.002
Steel	1 kg steel (>10.5% Cr)	62.3/19.9	59.3/3.1	5.2/0.3

3.2.9 Techno-economic Analysis

The economic assessment was conducted over a 30-year project life assuming a likeliest 12% discount rate. The initial outlay and capital costs included infrastructure costs, major equipment costs, and miscellaneous expenses (Grima et al., 2003). Infrastructure costs are costs associated with establishment of physical assets including land, buildings, roads, and electrical distribution. Major equipment costs (MEC) are costs of procuring heavy machinery and other unit operations paraphernalia. The cost of land was based upon current economic data provided for commercial farmland in Virginia at a rate of $1,590/ha ("US Department of Agriculture," 2017), the costs of utilities were determined from U.S. Energy Information Administration ("US Energy Information Administration - Electricity," 2017; "US Energy Information Administration - Natural Gas," 2017). Construction and major equipment costs were extracted from the study conducted by Resurreccion et al. (2012) and were updated using average inflation rate over the last 6 years (1.45%) ("US Inflation Calculator," 2017). Process costs, indirect costs, energy costs, and depreciation represent total operating costs. The cost data values for each or the renewable fuel products can be seen in Appendix C.

Annual cash flows (annuities) were calculated by subtracting the operating costs from the revenues which included the sale of the biofuel product and the associated co-product. Operating costs are negative cash flows. There are four major categories of operating costs: process costs, energy costs, indirect costs, and depreciation. Process costs include procurement of raw materials (e.g., CO_2, mineralizer, and nutrients) and labor. Energy costs include payments for electricity and heat required to operate cultivation and conversion equipment. Indirect costs include fees for contingency, infrastructure maintenance, and insurance. Annual depreciation is the percentage of initial outlay apportioned to the use of major equipment during one year of operation (Ross, 2007). Although depreciation may be viewed as a “non-cash” cost, it is categorized as a negative cash flow and counted against annual revenue. A prevailing statutory tax rate of 39% was assumed for this study which is equivalent to 23.6% as the effective marginal tax rate (EMTR). This is a suitable measure of tax rate because it applies to investment projects where the pretax return is just enough to break even after taxes (Hassett & Mathur, 2011). Overhead costs were assumed to be 60% of labor costs, contingency costs were calculated to be 10% of total infrastructure costs, and annual maintenance and insurance was assumed to be 3.5% of the respective depreciable bases (J. R. Benemann & Oswald, 1996; Resurreccion et al., 2012).

The three main materials for algae open pond cultivation were polypropylene (for the pond liner), aggregates (0.05m thick under 5% of the base area), and polyvinyl chloride (PVC).

Other equipment required were water pumps (1.5-kW rating), flue gas pumps (0.75-kW rating), and paddle wheels (cylindrical six-bladed PVC paddle (J. R. Benemann & Oswald, 1996)). The FH systems ($53M per 221,920 Mg lipid extracted algae per year) and HTL/catalytic upgrade systems ($117.8M per 221,920 Mg per year) were modeled after the estimation based on Zhu, Albrecht, Elliott, Hallen, and Jones (2013). Heat exchangers were utilized for the FH, HTL, and HTM systems and the associated costs were based upon the process design by Knorr, Lukas, and Schoen (2013) and was inflated to a 2017 installed price of $10.95M per 200 Mg algae dry solids produced per day. These models assumed a heat exchanger system redundancy factor of 2. Although both industrial-scale FH-HTM or FH-AP systems are emerging technologies, all six modeled systems can appropriately be compared with established medium- to large-scale petrochemical refineries thereby foregoing the associated start-up and pioneering costs. Storage systems modeled for the biocrude lasts for 1 year, intermediate products for 30 days, and drop in fuels for 30 days at a rate of $50/barrel (Albahri, 2016).

3.3 Results and Conclusions

3.1.1 Life Cycle Implications

The LCA evaluated energy use and GHG emissions. For energy use, total life cycle energy input and energy output for all three pathways are presented in Figure 3.2. Energy efficiency was evaluated in terms of the “well-to-pump” energy-return-on-investment (EROI), a ratio reported by other similar studies: (Hall & Klitgaard, 2006; Hall et al., 2009; Luo et al., 2010; Clarens et al., 2011; Resurreccion et al., 2012). These values were also presented in Figure 3.2. EROI was calculated as the ratio of energy output versus energy input. EROIs greater than one indicate net-energy producing systems (i.e., desirable from a life cycle perspective) while values less than one are net-energy consumers. Total energy input includes:

operations energy use, specifically direct electricity and heat consumption, and upstream energy use or the energy/heat associated with electricity and nutrients delivery or the energy/heat associated with manufacture of materials of construction for each unit operation. Total energy output includes embodied energy in each biofuel produced and each co-product associated with the catalytic upgrade process.

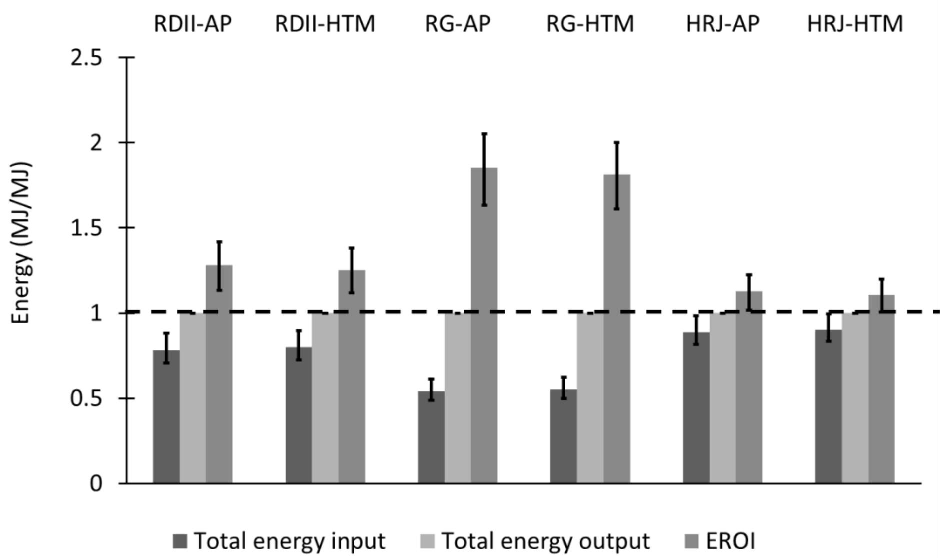

Figure 3.2. Total Energy Input, Total Energy Output, and EROI for all FH-Based Pathways

The total energy use profile shown in Figure 3.3 shows that in both RD and RG models, operations energy (i.e., electricity + heat) is within 42-67% of their upstream energy while HRJ model's operations energy is 12% higher than its upstream energy. This is not surprising considering that the production of renewable biojet fuel necessitates the use of 1.5 times more heat than the production of renewable diesel or gasoline using the data from GREET 2016 and as a result, significantly increases its upstream energy burden. Co-products differ across the biofuel pathways. RD pathway involves the co-production of propane fuel mix, RG pathway co-generates product gas, light cycle oil (LCO), and clarified slurry oil (CSO), and HRJ pathway co-generates both propane fuel mix and naphtha as co-products. It is for this reason that the gasoline co-product as an energy equivalent is eight times that of a diesel or twice that of jet fuel. Consequently, this makes the net energy use for RG pathway to be negative (i.e., surplus energy) even when combined with energy associated with infrastructure materials and construction. This LCA uses an energy-based allocation method of treatment for the co-products. Of RD's and HRJ's positive total energy use, the operations energy contributed the greatest share (RDII-86%, HRJ-88%) when compared to the infrastructure energy (RDII-14%, HRJ-11%), annualized over a 30-year life.

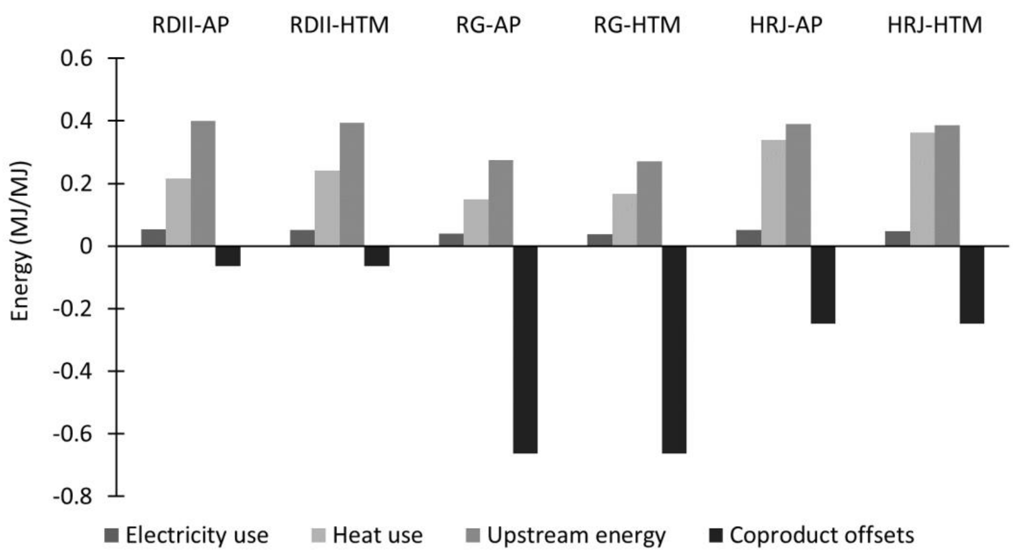

Figure 3.3. Total Energy Use Profile for all Modeled FH-Based Pathways

Of the operations upstream energy, nitrogen fertilizer contribution has the most impact of around 50% across all six modeled biofuel pathways while about 41-46% is associated with electricity. Previous studies have recommended the use of alternate sources of fertilizer such as nutrients derived from co-location with wastewater treatment, a potential viable source of water and nutrients for mass algal cultivation (M. O. P. Fortier & Sturm, 2012). It is important to note that for each biofuel pathway (RD, RG, or HRJ), energy outputs are equivalent whether AP or HTM was employed due to the identical post-processing catalytic upgrade parameters.

The allocation between drop-in fuel energy versus co-product energy, as presented in Table 3.10, varies widely across all biofuel pathways due to significant differences in product streams. A HTL only model in lieu of FH was also evaluated in conjunction with AP or HTM, excluding any of the co-product upgrading processes and maintaining the same energy/mass balance parameters and economic factors. Results showed that the EROI for the HTL only system increased by an average of 7.4% when compared to the RDII, RG, and HRJ systems. This is expected due to the reduced energy demand necessary for further processing of the hydrolysate co-products.

The major operations contributing to LC-GHG emissions for all six modeled pathways include nitrogen delivery, electrification, natural gas use, and hydrogen delivery. Upstream LC-GHG impacts of nitrogen (1.34 kg CO_2 equivalents/kg), electricity (0.21 kg CO_2 equivalents/kWhr^{-1}), natural gas (0.00691 kg CO_2 equivalents/kg), and hydrogen (1.22 kg CO_2 equivalents/kg) were extracted from EcoInvent™, GREET[26], TRACI, or any open source LCA databases. Similarly, the use of polypropylene and polyvinyl chloride (as liner and paddle wheel material) contributed significantly to infrastructure LC-GHG emissions. Comparative LC-GHG emissions results are presented in Figure 3.4. LC-GHG emissions has a direct relationship between total energy input and inverse relationship between EROI. Among the pathways, RD emits almost twice more CO_2 than RG and 12% more CO_2 than HRJ. The additional burden imposed by providing hydrogen to diesel processing is the main reason for this trend. GHG offset is calculated as the stoichiometric CO_2 requirement to produce a functional unit of algae energy. This work assumed that algae ponds are co-located with coal-fired power plants thereby harnessing the latter's CO_2 emissions. This assumption is reasonable given the considerable energy and cost of CO_2 compression, transportation, and delivery and allows for overall system sustainability improvement within the context of emissions avoidance. On a per hectare basis, algae consumes 112 Mg CO_2/ha across all pathways, using stoichiometric molecular weight of algae biomass via Redfield's molecular composition (Redfield, 1958) and the calculated annual algae biomass yield. RD production has the largest footprint (333.84 ha/FU) compared to RG (178.99 ha/FU) or HRJ (277.03 ha/FU) as a result of renewable diesel's high energy density (RD = 0.786 kg/L; RG = 0.614 kg/L; HRJ = 0.686 kg/L). Consequently, RD is seen to have the lowest total GHG offset among the three pathways.

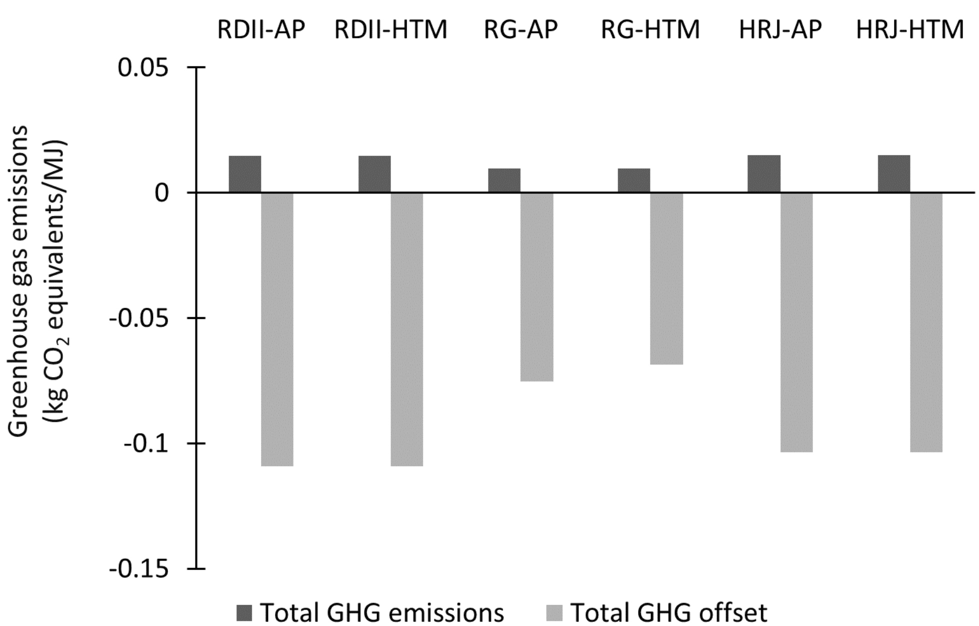

Figure 3.4. GHG Emission Profiles for all Modeled FH-Based Pathways

3.3.2 Techno-economic Implications.

The working capital (around 20% of the total initial outlay) of the systems represents 25% of the total direct capital (Benemann & Oswald, 1996; Resurreccion et al., 2012). This is the largest cost driver in the initial outlay. Similarly, engineering and contingencies is calculated to be 15% of the total infrastructure cost and total cost for construction and major equipment. This represents 9.6% of the total initial outlay. The infrastructure costs associated with the FH, HTL, and catalytic upgrade systems represent either 2nd or 3rd most significant cost drivers within all models. These costs were derived from Zhu et al. (2013) and appropriately scaled to the models in the study represented by their individual functional units. The average cost percentages for all of the HTM models can be seen in Figure 3.5. This model assumes nth plant economics (Davis et al., 2014) where the processing plant technology is mature and several units have already been established in order to avoid the risk associated with longer start-up costs (5% of total infrastructure cost and total cost for construction and major equipment) in this study (Benemann & Oswald, 1996; Resurreccion et al., 2012), pioneer investment risks, and equipment design modifications/redesign/overdesign. It should be noted that neither commercial-scale HTL nor FH facilities have been established in private industry.

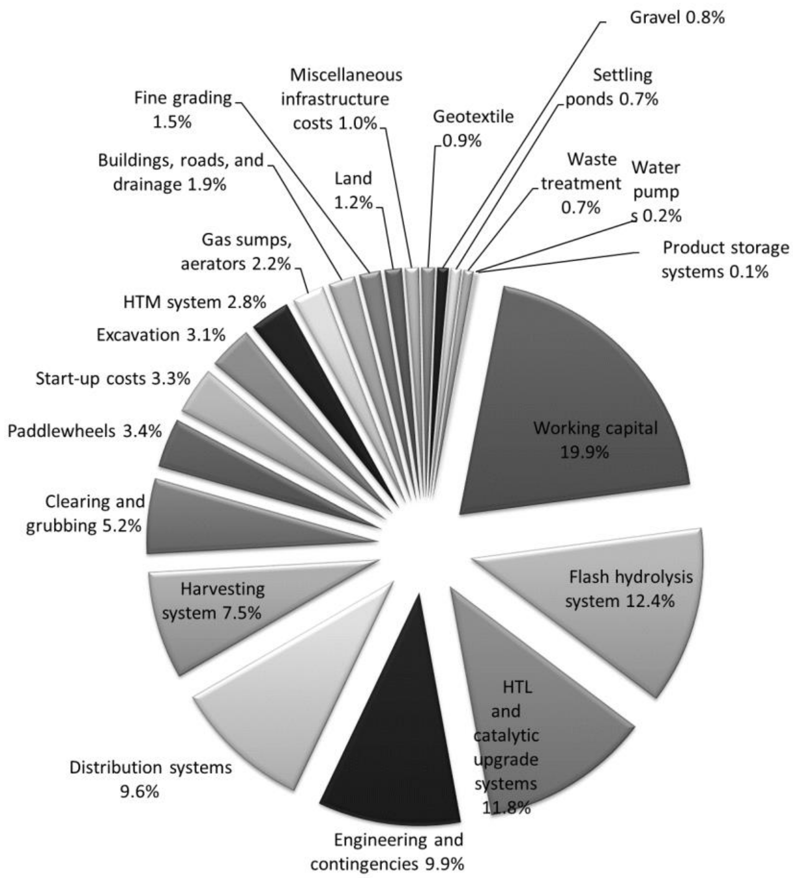

Figure 3.5. Average Cost Allocation for each of the HTM Models

Results from the simulation gave the following baseline values for HTM cash flows (annual operating costs, annual revenues) and total initial outlay, respectively: RDII, $4.1 million, $8.5 million, and $55.4 million; RG, $2.2 million, $4.0 million, and $29.7 million; HRJ, $3.4 million, $7.4 million, and $46.0 million. The allocation of initial outlay/capital costs for the HTM models can be seen in Figure 3.6. From these cash flows and total initial outlay, profitability index (PI) is derived. PI is calculated as the ratio of the net present value (NPV) of the expected future cash flows and the total initial outlay. This ratio is meaningful insofar as it reflects the relative share of expected income throughout project's life as a percent of total expenditure incurred at the beginning of the project. An economically-feasible project has PI>1. Projects with PI<1 are considered not profitable.

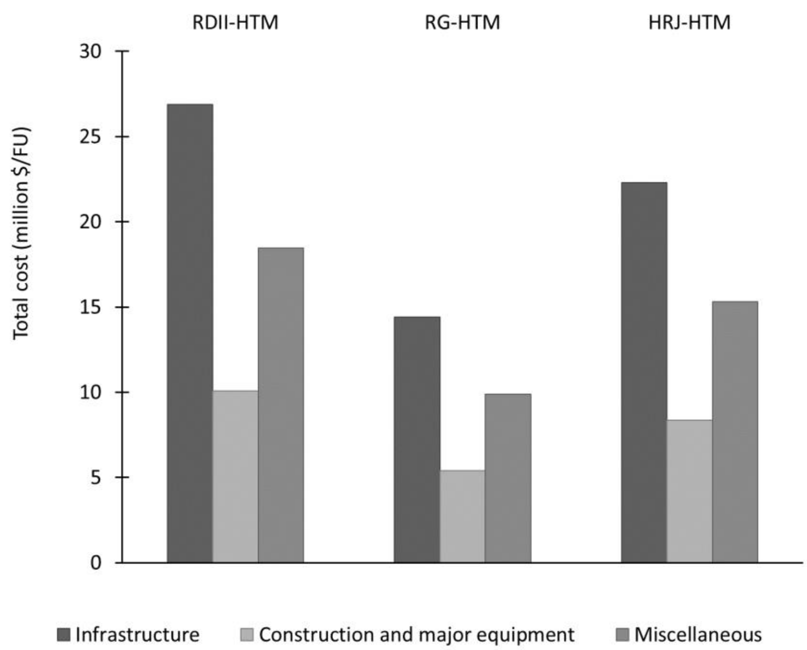

Figure 3.6. The Allocation of Initial Outlay/Capital Costs for the HTM Models

3.3.3 Sensitivity Analysis

A sensitivity analysis was conducted on EROI and Profitability Index (PI) for the HTM models. All input parameters in Figures 3.7 and 3.8 were adjusted by +/- 10% for the sensitivity range. The AP models for each drop-in fuel is considered to be relatively similar as seen from the results of previous analyses. The most significant drivers to EROI included thickening concentration and autoflocculation. The results of Monte Carlo analysis can be seen in Figure 3.7.

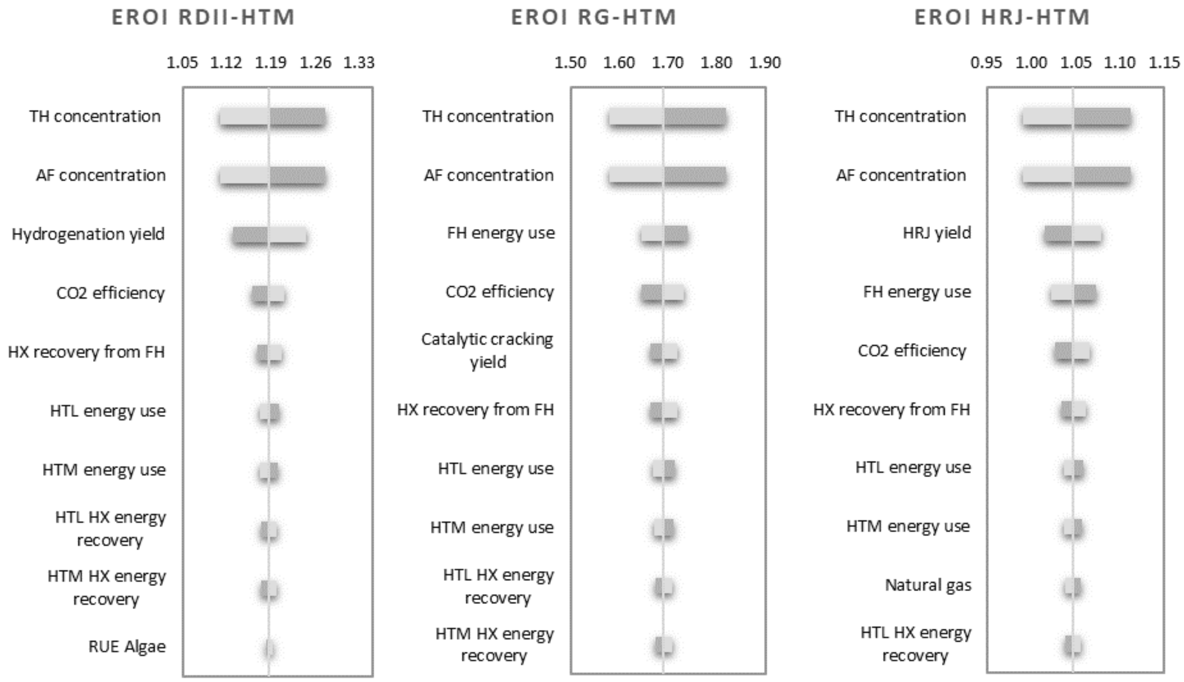

Figure 3.7. Tornado Plots Showing the Sensitivity of HTM EROI Output

The dewatering factors had the most impact to the EROI sensitivity model outputs. The concentration factor for both the AF and TH was set to 10%. Increasing either of these factors by 10% reduced the EROI by approximately 6% and the PI by approximately 14% for all models. The concentration factors effectively determine the amount of mass that will enter FH reactor. While initially it could be inferred that more mass entering the reactor would result in more product and resultantly, more profit, infrastructure costs and heat exchange reactions associated with the aqueous phase of the algae slurry offset additional profits resulting in total system losses.

CO_2 uptake efficiency also had an impact on EROI sensitivity. CO_2 pumping energy use from flue gas source to the open pond system represents approximately 45% of the total electricity use in the total system operations. The models utilize a value of 72% efficiency of

CO_2 uptake by the algae in the open pond (Kadam, 2002). This requires that extra CO_2 is pumped into the open pond due to losses associated with non-utilization of the flue gas. Increasing the utilization efficiency of the CO_2 by the microalgae by 10% reduces the energy consumption by an average of 2.2% for all models. Although utilization efficiency of algae in open pond systems can vary considerably, it should be noted that a +/- decease in efficiency does not alter the EROI significantly.

A Monte Carlo analysis was performed on the HTM PI for all biofuel pathways and results showed that PIs are controlled by dewatering concentration factors (AF and TH), investment discount rate, carbon dioxide utilization efficiency, the yield ratios of energy end products including energy co-products, the infrastructure costs associated with major hydrothermal systems (FH and HTL), and the selling price of hydroxyapatite. These results are found in Figure 3.8.

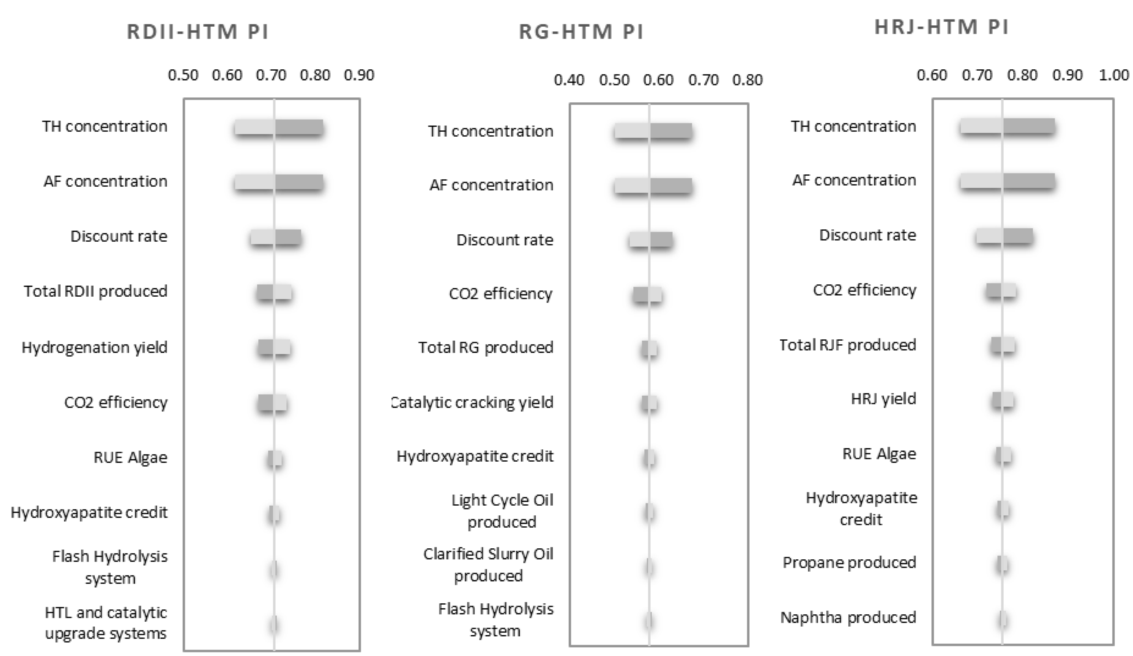

Figure 3.8. Tornado Plots Showing the Sensitivity of HTM PI Output

The algae dewatering factors (AF and TH) are the top cost drivers for all models. This trend is similar to that of EROI's which is expected due to energy usage and its relation to profit. The minimum selling price of the drop-in renewable transportation fuel product in order to reach a $0 NPV was determined to be $4.10 for RDII, $5.64 for RG, and $3.43 for HRJ. Adjusting the AF or TH concentrations by +/- 10% on the RDII, RG, or HRJ processes has a considerable impact on minimum fuel selling price, resulting in a raise or lower of fuel selling price by 13.4%, 18.3%, or 18.1% for RDII, RG, or HRJ, respectively. This is related to processing costs and associated labor, overhead, and miscellaneous costs. The price of HRJ could potentially be reduced to $2.81 which is $0.57 higher than the market value utilized in this study.

The discount rate proved to be the next most influential techno-economic parameter. Although the outlook for US biofuels, particularly algal biofuels, is less promising than other bioenergy sources, these economic results provide benchmark data on commercialization aspects of algae biomass conversion technology while overcoming technical barriers in large-scale biofuels deployment. The discount rates at $0 NPV are 7.8%, 5.9%, and 8.6% for RDII, RG, and HRJ, respectively. The baseline discount rate was assumed to be 12%, however, reduced rates above are shown to increase profitability to acceptable investment standards given national strategic alignment with renewable transportation fuel technology and production. Figure 3.9 shows the relationship between NPV and the variance between discount rate and fuel selling price for the HRJ-HTM model. It is evident that the NPV is significantly increased by gradually reducing the discount rate or increasing biojet fuel selling price. The 2017 Annual Energy Outlook by the U.S. Energy Information Administration projects that the North Sea Brent oil price will rise from its current selling price of $50/barrel to approximately $75/ barrel by the year 2020 and $100/barrel by around 2030 (*Inernational Energy Outlook 2017*, 2017). It is likely that transportation fuel costs will increase over the near future. Increased production of petroleum fuel products has momentarily reduced the cost of gasoline and diesel fuels. However, this scenario is considered temporary and long-term solutions such as this technology has the potential to sell renewable transportation fuel at a competitive market cost.

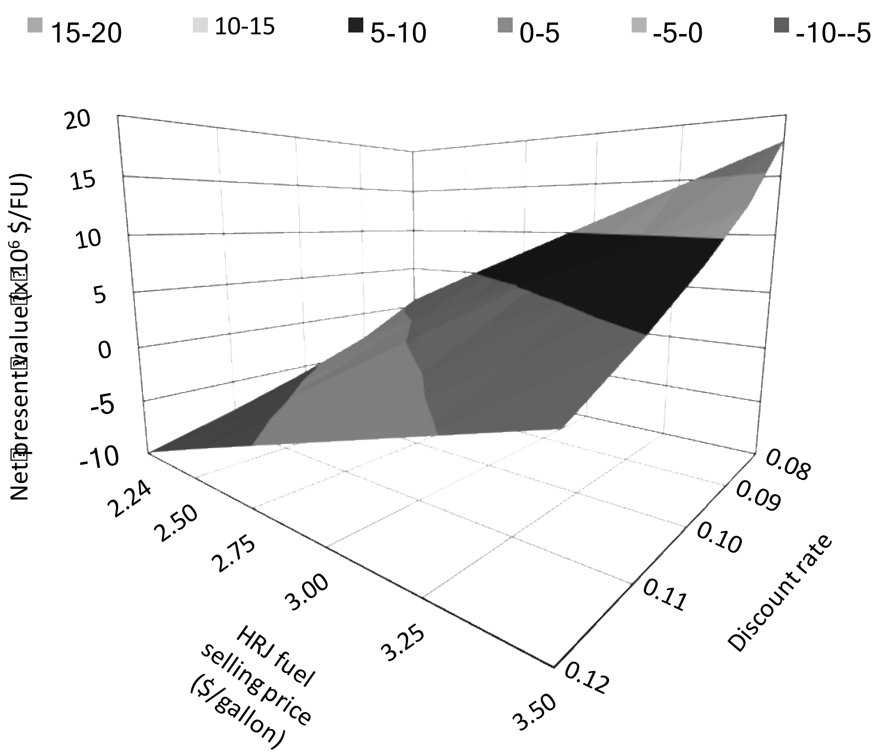

Figure 3.9. Relationship between NPV to Discount Rate and HRJ Fuel Selling Price using HTM Method

The relationship between fuel selling price and PI/NPV are presented in Figure 3.10 and 3.11. While it is apparent that increasing the selling price increases both PI and NPV, the HRJ-HTM model has the highest PI and NPV among the three models. At approximately $2.25/gal, the PIs of both RDII and RG are 0.5, after which the values diverge. The PIs of HRJ are higher than those for RDII and RG regardless of fuel selling price. The break-even fuel selling price (i.e., selling price at NPV = $0 or PI = 1) for HRJ-HTM is at $3.43/gal, lower than RDII's at $4.10/gal and RG's at $5.64/gal. Taken together, this observation indicates that although FH-based algae transportation fuel is an emerging technology, economics favor the early commercialization of biojet fuel compared to renewable diesel or gasoline. A standalone HTL model was compared to this study's FH-HTL-HTM model. Results indicate that PI for HTL is 4% lower. In a similar manner, the PI of the standalone HTL model was found to be 16% below RG PI and 8.6% below RDII PI. PI comparison is critical because it determines if the additional hydrothermal processing of FH hydrolysate to produce HTM hydroxyapatite is a good investment compared to producing biocrude via HTM. In this study, additional heat requirements and infrastructure capital costs afforded by HTM-based biofuel pathways are offset by co-product market value. The NPV, PI and fuel selling price at $0 can be seen in Figure 3.12.

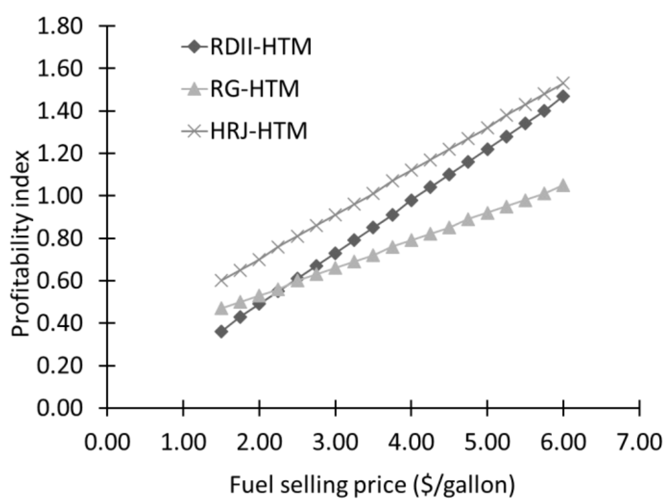

Figure 3.10. Relationship between PI and Fuel Selling Price

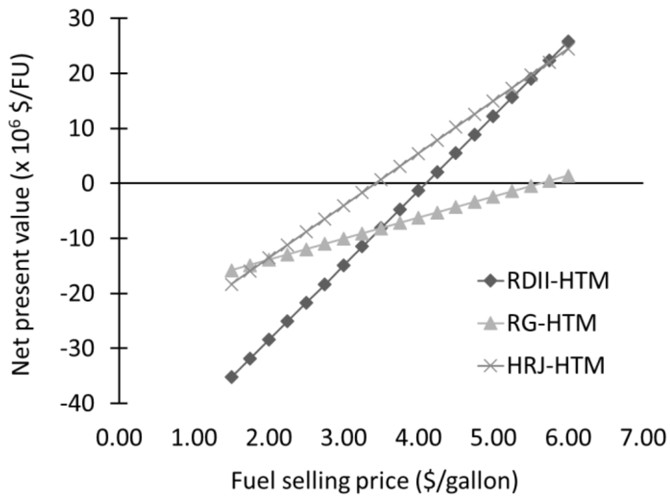

Figure 3.11. Relationship between NPV and Fuel Selling Price

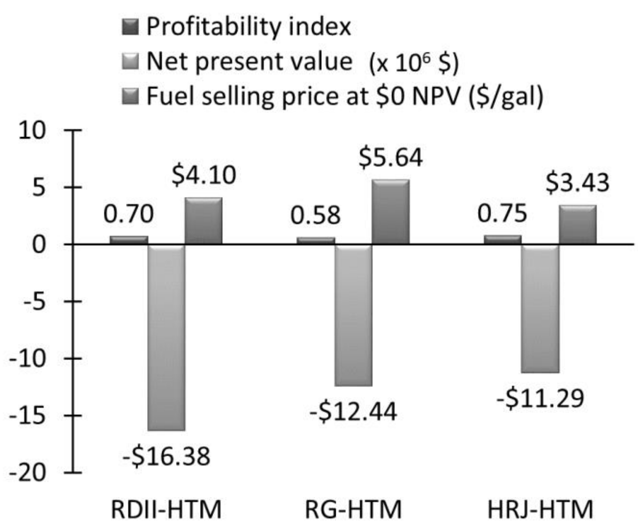

Figure 3.12. PI, NPV, and Fuel Selling Price at $0 NPV for all HTM Models

CHAPTER 4

LIFE CYCLE ASSESSMENT AND TECHNO-ECONOMIC ANALYSIS OF ALGAE-POWERED SUSTAINABLE COMMUNITY DESIGN

4.1 Background of the Study

There has been increased focus in net-zero energy homes recently as developers strive to build houses and facilities that are increasingly sustainable. The general concept of a net-zero energy building is that over a period of time which is typically one year, the building will produce as much energy as it consumes from the supply grid thus achieving a neutral energy balance. This area is of interest because according to the United States Department of Energy Buildings Energy Data Book, 41% of all energy used in the United States was attributed to buildings (United States Department Energy, 2011). Musall et al. (2010) summarizes much of the research that has been completed and found that over the last 20 years, there have been more that 200 building projects all over the world that have achieved a net-zero energy budget. In 2012, NIST completed the construction of a Net-Zero Energy Residential Test Facility (NZERTF) on its campus in Gaithersburg, MD to demonstrate that it was possible to achieve a net-zero fora house with conventional architecture, amenities, and size comparable to those being constructed in the surrounding area (Fanney et al., 2015).

There is an opportunity to go beyond the individual net-zero building and expand to a net-zero community design. This opportunity expands beyond the concept of net-zero energy and provides an opportunity to lower whole life cycle costs associated with greenhouse gases and waste generation. Zero waste management is being researched and implemented in various sectors such as waste management and treatment, mining, manufacturing, and urban development and the zero waste concept has been embraced by policymakers because it stimulates sustainable production and consumption, optimum recycling and resource recovery (Zaman, 2015). There are even some cities such as Adelaide, San Francisco, and Vancouver that have adopted zero waste goals as a part of their waste management strategies (Connett, 2006). Waste streams generally contain high levels of total nitrogen (TN) and total phosphorus (TP) which, when released into waterways, have a negative effect on the environment. These nutrients are actually considered pollutants and contribute to eutrophication in waterbodies such as lakes and rivers (Correll, 1998; Schindler, 2006). In addition, phosphorus is a limited resource that is currently being over harvested and the Earth's natural phosphorus reserves are depleting (Reijnders, 2014). Every effort needs to be made to recycle phosphorus.

Communities require food, electricity, and heat and produce solid and liquid waste. The infrastructure required to provide these resources include generators and food production such as poultry, dairy, and aquaculture. This model considers algae ponds and downstream algae processing in order to utilize the waste streams associated with the municipal waste streams. The algae processing in this model produces a biodiesel product through transesterification which can then be used for generators or sold as a source of revenue for the community. The remaining biomass can be used in biogas digesters to produce methane which can then be used to power gas turbines. Additionally, any remaining biomass is still rich in nutrients and can be used as a nutrient source for the algae cultivation and food production. The electricity generation processes also produce flue gas which is rich in carbon dioxide and can be used for the algae cultivation. The sustainability of food, energy, and water systems via algae cultivation in a systems approach is purported to reduce GHG emissions and improve the life cycle costs associated with the community.

4.2 Materials and Methods

This model simulates a rural community. The rural town of Fairburn, located in the greater Atlanta region, has been chosen based upon the research conducted by Georgia Tech University under the direction of Dr. Ben Stuart (Yang, Quan, Castro-Lacouture, & Stuart, 2018). The community has a population of 902 people based on calculations published by Yang et al. (2018). The FU for this LCA study is effectively 902 people. This unit represents the energy and food products required to sustain the community, the waste stream generated from those individuals, and processes required to keep the community functioning.

Figure 4.1 describes the overall process of the sustainable community design managed through algae cultivation. The community is designed around a rural community with a population of 902 people. The community is sustained with food through aquaculture, poultry and dairy products, and terrestrial crops. Electricity and heat are provided through solar thermal, wind (optional), photovoltaic arrays, biodiesel generators (optional), and combustion gas turbine generators through the combustion of biogas. The housing is energy-efficient sustainable housing. The algae is cultivated in open raceway ponds. Waste streams are segregated and processed through anaerobic digestion which produces biogas produces a nutrient-rich liquor which can be disinfected and used as a nutrient source for the algae cultivation. A solid product is also produced as a co-product which can be used as a soil amendment for terrestrial agriculture. Nutritional sustainment for the community is provided by aquaculture, poultry and dairy products and fruits and vegetables produced from terrestrial agriculture. The following processes are included in the LCA: upstream manufacture of material and energy inputs, cultivation of algal biomass, pre-processing and concentration of algal biomass, lipid extraction of algal biomass, processing and conversion of residential waste, and conversion of algae biomass into usable energy product and usable co-products. Process inputs include freshwater culture medium, energy, heat, nutrient recycle, and community municipal solid waste (MSW). Process outputs include both energy (algae biodiesel or methane-derived bioelectricity) and wastes (purge water and land filled activated sludge).

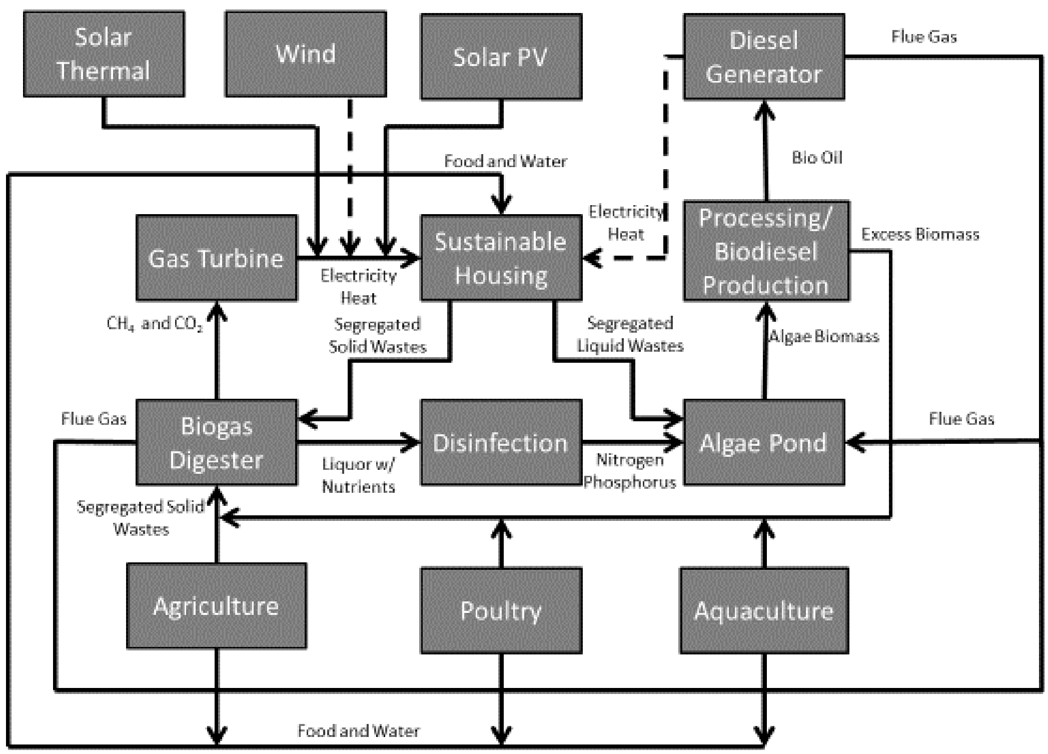

Figure 4.1. Overall Schematic for the LCA and TEA of the Sustainable Community Design Managed through Algae Cultivation

4.2.1 Community Design.

The rural community of Fairburn has a total residential area of 1,726,329 m^2. Of that, 52,813 m^2 is consumed for residential building footprint according to GIS (Yang et al., 2018). That leaves 1,673,517 m^2 available for the rest of the community functions. This model is based on a sustainable community, therefore all agricultural, food generation, and energy generation must be considered in space planning. The community is provided with heat and electricity from solar photovoltaic arrays, solar thermal systems, and gas turbine generators. Wind and diesel generators are considered for alternative options. Fuel for the diesel generators is generated from biodiesel derived from algae grown in open pond systems. Fuel for the combustion turbine generators is provided from methane biogas produced from anaerobic digestion of MSW and lipid extracted algae (LEA) biomass. Food is sourced from terrestrial crops, fish, poultry, and dairy. The total ground space for each of these requirements in this neighborhood must be calculated in order to determine what amount of land is available for energy generation. Building energy use is calculated for the net community energy demand. In addition, waste streams must be evaluated for nutrient recycling and anaerobic digestion (AD) potential biogas generation.

The average individual has a demand of 2000 lbs. of food per year. The average individual's diet consists of 34.4% fruits and vegetables, 9.6% grains, 31.5% dairy, 5.5% fish (includes oils), and 10.8% poultry ("One Acre Feeds a Person- Farmland LP," ; "USDA Food Patterns," 2018). The remaining fraction (other) is attributed to artificial sweeteners and similar products which will not be simulated in this model. With a population of 902 people, the community's food demand is shown in Figure 4.2.

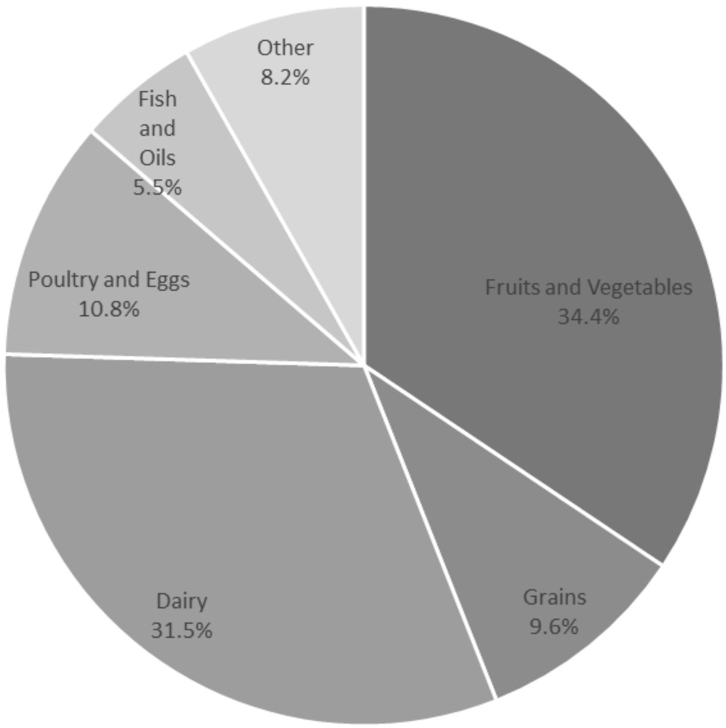

Figure 4.2. Average US Food Consumption

Based upon a population of 902 people, Table 4.1 shows the total demand of food based upon a 2000 lb./year diet.

Table 4.1. Total Annual Demand of Each Food Type for a 902-Person Community

Food Type	Total Demand (kg)
Fruits and Vegetables	281,742
Grains	78,626
Dairy	257,990
Poultry and Eggs	88,454
Fish and Oils	45,046
Other	67,159

Based upon the 2016 Virginia State Agricultural overview, the following fruits, vegetables, and grains are the most widely grown in the state and the land use associated with them is shown in Table 4.2 (USDA, 2016).

Table 4.2. Land Use Associated with Virginia Grown Representative Crops

Fruits and Vegetables (kg/m^2)	Grains (kg/m^2)
Apple (0.51)	Corn (1.72)
Tomato (0.42)	Wheat (2.8)
Potato (0.31)	Barley (2.77)
Grapes (1.78)	
Pumpkin (0.53)	
Peaches (1.37)	

The average land use was calculated for fruits and grains and the land use for the animal products was sourced from Flachowsky, Meyer, and Südekum (2017). Table S3 shows the total land use requirement for the 902-person community.

Table 4.3. Land Use Requirement for the 902-Person Community

Food Type	Total Demand (kg)	Land Use (m^2/kg product)	Land Use (m^2)
Fruits and Vegetables	281,742	0.82	231,028
Grains	78,626	2.43	191,060
Dairy	257,990	1.55	399,885
Poultry and Eggs	88,454	7.18	635,098
Fish and Oils	45,046	1.78	80,182

The total agricultural requirement is 1,537,252 m^2 based on the sum of the land use required for each of the products (Flachowsky et al., 2017; USDA, 2016) in Table 4.3. The total available ground space after residential housing requirements calculated is 1,673,517 (1,726,329 m^2 - 52,812 m^2) leaving a surplus of 136,265 m^2 or 13.6 hectares. This is the land that is available for algae cultivation in open raceway ponds and associated peripherals outside of the pond area. The peripherals around the pond area account for an additional 25% of space (Livanis, Moss, Breneman, & Nehring, 2006) (2.72 hectares) which reduces the available land to 10.88 hectares.

4.2.2 Sustainable Housing

The building energy use was calculated based upon Yang et al. (2018). The energy use intensity (EUI) was sourced from the Department of Energy Building Dataset (Deru et al., 2011) for the Atlanta residential building type. The EUI and the total floor area of each building was calculated to yield the average energy use of residential buildings which was then used to calculate the cumulative energy use of the neighborhood using Equation 4.1 below. The total floor area was found to be 69,734 m^2 and the total annual residential building energy use was found to be 28,523 MBtu/yr (30,094 MJ/yr):

Equation 4.1

$$\text{Annual Neighborhood Residential Building Energy Use} = \text{Annual Residential EUI} * \text{Neighborhood Total Floor Area}$$

The utilization of energy efficient residencies has the potential to reduce total building energy consumption by up to 45% (Heidner & Heidner, 2013). This magnitude of reduction is accomplished through lighting improvements (high efficiency ballasts and bulbs and room sensors), radiant barrier insulation, argon-filled low-emissivity double paned glass windows, daylighting, energy efficient appliances and electronics, photovoltaic solar panels, and tankless hot water systems equipped with solar hot water preheat systems (reduces the energy consumption on the tankless by 50% annually (Heidner & Heidner, 2013)). With these improvements to building design, the total annual residential building energy use is reduced to 15,688 MBtu/yr (16,552 MJ/yr).

This model assumes 2.54 people per household ("U.S. Census Historical Households Tables," 2018). This yields 355.12 households in the community. At an average electrical load of 16 kW/household (Bishop, 2010), this equals a 5.7 MW requirement for the entire community. At $1,021/kW for diesel generators ("US Energy Information Administration- Generator Construction Cost Data," 2018), this would cost $5.8M for the diesel generators. This study considers alternative options where diesel generators are purchased for emergency backup power at 50% of the average demand (8 kWh/household) at a cost of $2.9M. While diesel generators are operating, the algae cultivation ponds are supplied with CO_2 rich flue gas at a rate of 662.7 g/kWh according to the 2500kW generator model MTU 16V4000 emissions data sheet. (2012). In. incomplete reference If the generators are running at 80% capacity for 24 hours, it would produce 54,546 kWh in energy or 36.15 Mg CO_2/day. Wind turbines average a unit price of $3/W (Kaabeche & Ibtiouen, 2014) which can also be considered for augmented energy supply and increased community resiliency. Location must be carefully considered however because heavily forested areas compared to flat land or water can increase the roughness factor by up to 250% (Kaabeche & Ibtiouen, 2014) thereby reducing the turbine power output.

4.2.3 Waste Streams

The annual residential municipal solid waste (MSW) per person in the city of Atlanta was found to be 272.41 kg/person based on the 2012 reported data of 191,414.19 mTons (60% residential) by a population of 421,600 individuals' kg by using the following equation:

Equation 4.2

$$\text{Annual Residential MSW per Person} = \frac{\text{Annual Total City MSW} * \text{Residential MSW Ratio}}{\text{City Population}}$$

The town of Fairburn has a population of 902 individuals according to calculations by Yang et al. (2018) which yields a total of 409,525 kg of MSW per year when relatively compared to the total city of Atlanta of which, 245,715 kg is residential MSW. The density of residential MSW is approximately 300 kg/m^3 which yields 819 m^3 of MSW waste per year or 2.24 m^3 of MSW per day. This value is factored into the sizing of the anaerobic digestor along with the daily mass of algae biomass being processed in the digestor. The composition of the total MSW can be seen in Figure 4.3, below.

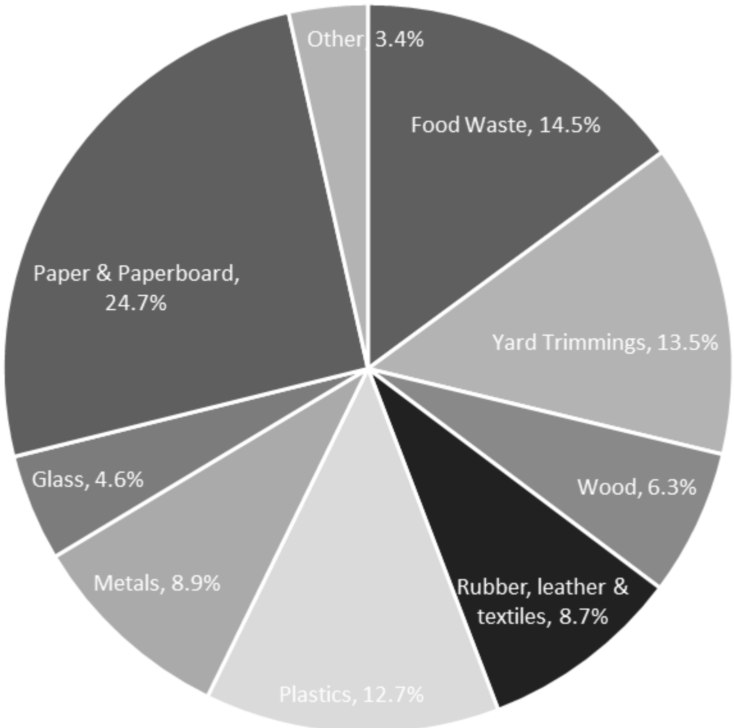

Figure 4.3. The City of Atlanta MSW Characterization

The organic portion of the waste stream is available for use as a feedstock for the algae cultivation system. The organics included in this model include paper and cardboard, food waste, yard trimmings, and wood (57%). This organic portion of the waste stream is fed into an anaerobic digestor which produces waste products in the form of a nutrient rich liquid effluent and a nutrient rich solid product used as a soil amendment. It also produces biogas which is an important energy source for the community. 1 kg of MSW volatile solids produces 468.21 L of biogas, 60% of which is methane (Pecorini et al., 2012). The proportion of volatile solids in each portion of the organic waste stream can be seen in Table 4.4, below.

Table 4.4. Volatile Solids Portion of the Organic Waste Stream Categories

Waste Category	Volatile Solids %
Paper and Cardboard	50%
Food Waste	27.3%
Yard Trimmings	46%
Wood	42.5%

The volatile portion of the organic waste stream is what determines the amount of methane that is theoretically able to be produced. The mass of the volatile solids in the type of waste is found using Equation 4.3.

Equation 4.3

$$\text{Mass of Volitile Solid} = \text{Mass \% of Type of Waste} * \text{Total Mass of Waste} * \text{Volitile Solid \% of Type of Waste}$$

The total volatile solids for the year equals 25% of the total MSW. The total amount of methane produced is based upon the percentage of each category of waste stream and the volatile fraction of each waste stream from Table 4.4. 1 kg of MSW produces 115.72 L of biogas which equals 69.43 L of methane for every 1 kg of MSW. In this modeled city, this yields 17,060,100 L (17,060 kg/yr assuming a density of 1,000L/kg of methane) of annual methane production.

The liquid digestion effluent product produced from the anaerobic digestion process is to be used for a nitrogen and phosphorus source in the algae cultivation system. For the MSW, 75% of the N and 25% of the P are retained in the product (Clarens et al., 2011; Resurreccion et al., 2012). Therefore, since the household waste stream contains 57% organic waste, this yields a total of 175,072 kg/yr of N and 58,357 kg/yr of P available for the algae cultivation pond found by using Equation 4.4.

Equation 4.4

$$\text{Mass of Nutrient} = \text{Organic Mass }\% * \text{Max}(\text{P Retainment }\%, \text{N Retainment }\%)$$

An additional waste stream is processed in the anaerobic digestion system which is the remaining biomass that is available after the harvested algae is dewatered and the lipids have been extracted, also known as LEA. For the LEA, the removal efficiencies for algae biomass were derived from Clarens et al. (2011) and Resurreccion et al. (2012). The VSS removal efficiency is 41%, the biogas methane fraction is 72%, the biogas CO_2% is 22%, the N available in the digestate effluent is 75%, and the P available in the digestate effluent is 25%. This yields a total of 0.7 Mg N/ha-yr of and 0.05 Mg P/ha-yr.

The post processing of the remaining mass after anaerobic digestion requires a solid/liquid separation process and is accomplished through belt filter pressing with an electricity demand of 25,569 MJ/ha-yr derived from Soda et al. (2010). The liquids can be recycled to the algae pond and the solids can be used as a soil amendment. The solid digestate is used as a fertilizer supplement in terrestrial agriculture (Clarens et al., 2011). This solid product is to be used on the agricultural sites within the community. The digestate solid product is characterized by having a phosphorus content of 12 mg P/g digestate and 42.5 mg N/g digestate. The bioavailability of the nutrients in the product is assumed to be 25% for N and 8% for P (Clarens et al., 2011; Resurreccion et al., 2012).

Additional N and P are sourced from a conventional activated sludge wastewater treatment system for the incoming cultivation water which assumes a N content on 25 mg/L and a P content of 7 mg/L (Carey & Migliaccio, 2009). This yields a total of 1.3 Mg N/ha-yr and 0.4 Mg P/ha-yr. The total nutrient flows from waste streams can be seen in Table 4.5 below.

Table 4.5. Annual Waste Stream Nutrient Flows of MSW AD, LEA AD, and Wastewater Effluent

Waste Stream	Annual Production	
	N (Mg)	P (Mg)
MSW AD (per yr)	175.10	58.36
LEA AD (per ha-yr)	0.70	0.05
WW Effluent (per ha-yr)	1.30	0.40

The total annual nutrient requirement per acre is 3.6 Mg/ha of N and 0.5 Mg/ha of P according to demand requirements summarized in Table 4.6 below. Excluding the MSW AD effluent, this leaves a deficiency of 1.6 Mg/ha of N and 0.1 Mg/ha of P. This is provided by the MSW AD effluent. Equation S5 used to find the maximum number of hectares of algae pond that the MSW AD effluent can support.

Table 4.6. Summary of RUE Values, Lipid Contents, Biomass Yields, Lipid Yields, and Nutrient Demands for Sustainable Algae Cultivation

System	Likeliest RUE, g DW/MJ PAR	Likeliest Lipid Content, %	Biomass Yield, Mg DW/ha-yr	Lipid Yield, Mg/ha-yr	N Demand, Mg/ha-yr	P Demand, Mg/ha-yr	CO_2 Demand, Mg/ha-yr
Open Pond	1.40	13	41.6	4.7	3.6	0.5	111.7

Equation 4.5

$$\text{Maximum Number of Hectares} = \text{Annual MSW/Nutrient Shortage}$$

$$\text{For N: } 109.44\ \text{hectares/yr} = (175.10\text{Mg}/1.6\text{Mg})/\text{ha}\cdot\text{yr}$$

$$\text{For P: } 583.6\ \text{hectares/yr} = (58.36\text{Mg}/0.1\text{Mg})/\text{ha}\cdot\text{yr}$$

The N in the MSW was found to be the limiting nutrient therefore a maximum of 109.44 ha can be used for algal cultivation. It was found in Section 4.2.1 that a maximum of 10.88 ha is available for cultivation after food production therefore the algae cultivation is unrestrained by waste streams and a functional unit of 10.88 acres was used to calculate the LCA and TEA.

The anaerobic digestion process requires heat and electricity. The electricity and heat demands were derived from Soda et al. (2010) and calculated to be approximately 38,000 MJ/ha-yr for electricity (Equation 4.6) and approximately 1,500 MJ/ha-yr for heat (Equation 4.7) using the following equations:

Equation 4.6

$$y = 25876x^{0.944}$$

Equation 4.7

$$z = -5640\ln(x) + 27100$$

The methane which is produced is utilized in a combustion turbine generator to produce energy for the community. The combustion turbine generator is assumed to have an efficiency of 0.53 (Masters & Ela, 1991). The methane energy content is assumed to be 50 MJ/kg (Masters & Ela, 1991). The methane combustion (MC) of the algae biomass was found to produce 287,551 MJ/ha-yr of bioenergy and the MC of the MSW was found to produce 452,093 MJ/yr of bioenergy (17,060.10 kg/yr * 50MJ/kg * 53%).

The MC generates CO_2 which is recycled to the algae cultivation. The amount of CO_2 recycled is based off of a complete combustion using stoichiometric conversion (44g CO_2 per

18g CH_4 combusted). This yields 16 Mg CO_2/ha-yr for the algae derived combustion and 47 Mg/yr for the MSW combustion. AD also produces CO_2 at a rate of 3.5 Mg/ha-yr for the algae combustion and 10.4 Mg/yr for MSW AD.

There is also a waste stream generated from the food waste from the raw agricultural products that are not consumed, animal manure, and fish carcasses not consumed. It is assumed that these waste streams are utilized for animal feed and composing for returning required nutrients to the soil. Nigussie, Kuyper, and Neergaard (2015) suggests that the internal agricultural demand for animal feed and soil amendment can be satisfied with intensified crop and livestock production.

4.2.4 Algae Cultivation and Processing

The methodology executed in this model is in accordance with the methods used in Chapter 3. The same cultivation conditions of the algae open pond growing conditions in Chapter 3 apply to this model. The preliminary dewatering is accomplished through autoflocculation and gravity thickening using the same parameters as in Chapter Three and the energy use was found to be 7,600 MJ/ha-yr based upon a 39 Mg/ha-yr loading rate. The output concentration was approximately 100 g/L and it was assumed that this concentration is suitable for downstream processing (Golueke & Oswald, 1965; Stephenson et al., 2010).

The biofuel product produced in this model is biodiesel. The dewatered algae biomass must have the lipids extracted in order to produce a biofuel product. This model uses homogenization to break down the algae cell walls for the subsequent lipid extraction. This model assumes mechanical homogenization with an energy demand of 67 MJ/m^3 algae slurry for each homogenization pass and a cooling water consumption of 0.045 m^3/m^3algae slurry per homogenization pass (Stephenson et al., 2010). This model assumes two homogenization passes with a total energy demand of 52,059 MJ/ha-yr. The homogenization passes are followed by a hexane extraction using a countercurrent cascade system of settler mixers. This model is based off of Stephenson et al. (2010). This process uses 0.02 MJ electricity/L algae slurry, 0.75L hexane/L algae slurry, and assumes a 99% efficiency. The extracted lipids have the free fatty acids removed by alkali refining which requires an input of heat (155 MJ/Mg algae oil), NaOH (24 kg NaOH/Mg algae oil), and water (0.15 m^3 wash water/Mg algae oil).

The refined algae oil is upgraded to biodiesel through the transesterification reaction. A glycerin coproduct is also produced however this model does not account for any offsets. The process is a chemical cleavage of algae triglycerides into their constituent fatty acids (plus glycerin) and a subsequent conversion of each acid functional group into a fatty acid methyl ester (FAME). This is accomplished through a heated, base-catalyzed reaction of algae lipids and methanol. The material and energy inputs can be seen in Table 4.7. The process assumes 96.3% efficiency. Post processing steps include washing with water to remove impurities, heat to recover methanol, and glycerin recovery. The total biodiesel produced in 4.4 Mg/ha and with a lower heating value of 37.7 MJ/kg (Stephenson et al., 2010) this yields a total energy output of 166,775 MJ/ha.

Table 4.7. Transesterification and Post Processing Material and Energy Inputs

Material/Energy	Quantity
Electricity	118 MJ/Mg bio oil
Heat	1,134 MJ/Mg bio oil
Acid (37% HCl in H_2O)	10 kg/Mg biodiesel
Base (KOH to algae oil mass/mass)	1.27%
Methanol	103 kg/Mg biodiesel
Cooling Water	0.5725 m^3/Mg biodiesel
Post process wash water	278 kg/Mg biodiesel
Heat for methanol/glycerin recovery	653 MJ/Mg biodiesel
Acid for Glycerin recovery 10% HCl in H_2O	75 kg/Mg biodiesel

The infrastructure used for cultivation and conversion is once again modelled in the same manners as in Chapter three. The annualized liner requirement is 184 kg/ha-yr. The aggregate requirement is 746 kg/ha-yr, The liquid piping requirement is 1.1 kg/ha-yr and the gas pipe requirement is 23.3 kg/ha-yr. The number of water pumps (1.5-kW rating, 85% efficient) and gas pumps (0.75-kW rating, 85% efficient) required per 1-ha open pond were 0.45 water pumps and 1.29 gas pumps. The total mass of PVC required to produce 10 paddle wheels/ha was 64,950 kg for the open pond system.

The liquid nutrient stream which has been processed through the AD which is to be recycled back to the algae cultivation pond must be disinfected in order to prohibit bacterial growth. Contamination of the algae pond with contaminated aqueous phase could be detrimental to the algae growth. This model assumes an activated carbon filtration disinfection. According to the 2014 EPA report, Environmental and Cost Life Cycle Assessment of Disinfection Options for Municipal Drinking Water Treatment, the granulated activated carbon (GAC) from bituminous coal requirement for adsorption of contaminants is 0.0030 kg GAC/ m3 of drinking water. The inlet liquid mass from AD process was determined to be 320,213 L/ha. This yields an annual GAC requirement of 0.96 kg GAC/ha-yr. The GAC also needs to be reactivated which requires 0.0026 m3 of natural gas/m3 of drinking water. This yields an annual requirement of 0.83 m3 of natural gas/ha-yr.

The infrastructure required for converting algae biomass into usable energy is a series of tanks which consist of the processes of autoflocculation, thickening, homogenization, lipid extraction, transesterification, biodiesel processing, solvent recovery, and activated carbon filtration. The methodology used for tank steel calculation was based on the study conducted by Resurreccion et al. (2012) using the flow rate through each unit operation and the residence times for each process as seen in Table 4.8. M_{TANK} values are represented using units of "per hectare per year" because it is assumed that burdens associated with steel manufacture can be amortized over a 30-year useful life to compute the fraction of overall burden which should be charged to each year.

Table 4.8. Flow rates (Q), Residence Times (τ), Capacity Volumes (V_{TANK}), Capacity Liquid Weights (M_{LIQUID}), and Internal Tank Pressures (P_{TANK}) Required to Compute Tank Steel Demand (M_{TANK}) for Conversion Unit Operations following Algae Cultivation Systems

Unit Operations	Q , m^3/ha-d	τ , d	$V_{LIQUID,}$ m^3/ha	M_{LIQUID}, kg/ha	P_{TANK}, Pa	M_{TANK}, kg/ha-yr
Autoflocculation	118.1	0.1	11.5	11,100	22,112	43.0
Thickening	10.7	0.1	1.0	1,100	9,942	8.7
Homogenization	1.1	0.2	0.2	200	5,507	2.7
Lipid Extraction	1.1	0.03	0.04	40	3,264	0.9
Solvent Recovery	1.1	0.03	0.04	40	3,250	0.9
Transesterification	1.1	0.03	0.04	40	3,264	0.9
Biodiesel Post-Processing	1.1	0.03	0.04	40	3,264	0.9
Anaerobic Digestion	1.3	14	17.6	17,600	25,485	57.1
Activated Carbon Filtration	0.88	0.014	0.012	12	2,261	0.5

4.2.5 Calculation of Reported LCA Metrics

The FU for this LCA study is effectively 902 people. This unit represents the required energy and food products required to sustain the community as well as the waste stream generated from those individuals and processes required to keep the community functioning. The base model is created in a way that inputs and outputs are on a per hectare basis. By choosing to modify the amount of land designated to algae cultivation, all results are subsequently modified. The initial model uses the total remaining land available for algae cultivation (10.88 ha) available after the population has had all residential and nutritional sustainment needs met. Further iterations of this model are evaluated for the effect of reducing the amount of resources allocated for algae cultivation.

The EROI and NGR were both calculated using the same methodology used in Chapter three. The EROI numerator included biofuel production (biodiesel and methane). Components of the EROI denominator (energy input) included: direct electricity and heat use, residential energy usage, and upstream energy use for materials and energy inputs (as computed using Ecoinvent® impact factors). The GHG outputs (emitting processes) are used as numerator and GHG uptakes (sequestering processes) are used as denominator. A favorable GWP is expressed as a number less than one. This equates to a net-GHG consuming system. The NGR numerator consists of energy inputs (electricity and natural gas) and material inputs (fertilizer, infrastructure materials, hexane, granulated carbon, etc.). The NGR denominator consists of the sequestration of the photosynthesis CO_2 and soil amendment offsets. Inputs are required to produce the energy and materials one functional unit in the systems. Impact factors used in this study were taken from the industry-standard Ecoinvent® database. These are summarized in Table 4.9 expressed using μ/σ notation, where μ is mean value and σ is standard deviation. All data were from Ecoinvent® v. 3.0 (Weidema).

Table 4.9. Life Cycle Impact Factors for Materials and Energy Inputs

Item	Unit Basis	Energy Use (MJ)	GHG (kg CO_2 eq)
Aggregates	1 kg gravel	0.04/0.007	0.003/0.0004
Bleach	1 kg 15% NaOCl in H_2O (m/m)	10.2/4.0	0.9/0.1
Carbon Dioxide	1 kg CO_2	8.3/2.0	0.8/0.1
Concrete	1 m^3	1180.0/836.0	265.0/47.7
Electricity	1 kWh from US grid	12.5/10.1	0.2/0.01
Fertilizer - N_2H_4CO	1 kg as N	62.1/11.8	3.4/0.3
Fertilizer - $H_{12}N_3O_4P$	1 kg P_2O_5	37.5/5.4	0.8/0.07
Fertilizer - $CaH_2P_2O_8$	1 kg P_2O_5	33.8/14.5	2.7/0.5
Glycerin	1 kg $C_3H_5(OH)_3$	8.7/1.2	1.7/0.2
Granulated Carbon	1 kg GC	1.6	8.66
Heat	1 MJ from light heating oil	1.3/0.2	0.1/0.01
Hexane	1 kg C_6H_{14}	59.7/3.3	0.9/0.09
Hydrochloric acid	1 kg 30% HCl in in H_2O (m/m)	10.4/3.1	0.9/0.2
Methanol	1 kg CH_3OH	37.7/5.5	0.8/0.07
Natural Gas	1 kg Natural Gas	4.2	0.007
Polymethyl methacrylate	1 kg $(C_3H_8O_2)_n$	132.0/0.08	8.3/0.009
Polypropylene	1 kg $(C_3H_6)_n$	70.7/0.01	2.0/0.0007
Polyvinyl chloride	1 kg $(C_2H_3Cl)_n$	47.2/3.6	2.0/0.1
Pump (Water/Flue Gas)*	1 piece	0.3/0.06	0.01/0.002
Sodium hydroxide	1 kg 50% NaOH in H_2O (m/m)	11.2/4.6	8.0/1.3
Steel	1 kg steel (>10.5% Cr)	62.3/19.9	59.3/3.1

4.2.6 Economics

The economic analysis for this study was conducted using the same methodology in Chapter three. The model calculates annual cash flows over a 30-year project life span. The project assumes a 12% discount rate and a 39% prevailing tax rate. Annual cash flows (annuities) are calculated as the difference between revenues and operating costs. Revenues are positive cash flows from sale of the biofuel product and the biofuel co-products and may also include credits. Operating costs are negative cash flows. There are four major categories of operating costs: process costs, energy costs, indirect costs, and depreciation. Process costs include procurement of raw materials (e.g., CO_2 and nutrients) and labor. Energy costs include payments for electricity and heat required to operate cultivation and conversion equipment.

Indirect costs include fees for waste disposal, infrastructure maintenance, and insurance. Annual depreciation is the percentage of initial outlay apportioned to the use of major equipment during one year of operation (Ross, 2007). Although depreciation may be viewed as a “non-cash” cost, it is categorized as a negative cash flow and counted against annual revenue.

It is important to note that this community is designed to be self-sustaining and revenue/profitability is not the ultimate goal of this project. It has been found that there is a shortfall of the CO_2 requirement for the algae cultivation without diesel generator operation therefore the sale of biodiesel may offset the cost of CO_2.

Every effort was made to ensure that economic models were based on current economic data. The cost of land was calculated using the average value of commercial farmland in Virginia ("US Department of Agriculture," 2017) ($1,590/ha). Many construction and major equipment costs (e.g., clearing, excavation, grading) were extracted the study conducted by Resurreccion et al. (2012) and updated using the average inflation rate over the last 6 years (1.45%) ("US Inflation Calculator," 2017). Costs for some items specific to the algae industry were taken from J. R. Benemann and Oswald (1996) and updated using average historical inflation values ("US Inflation Calculator," 2017). Costs for electricity and heat were determined from US Energy Information Administration.

4.3 Results and Conclusions

The model simulation showed that at 10.88 hectares, the system had an EROI of 0.94 and a NGR of 0.06. This EROI value is very close to a value of 1 which is a net energy neutral model where the energy inputs equal the energy outputs. The energy output consists of biodiesel (46.2%) and methane (53.8%). The allocation of energy use for the model consists of infrastructure and operations (heat and electricity). The operations consist of 67.5% of the energy input.

The initial outlay and capital costs are $1,427,343. The model was evaluated to determine if reducing the algae cultivation would improve the PI. At 10.88 ha, the PI is 0.05 and the community produces $38,681 in biodiesel and is able to sell $4,414 worth of excess electricity to the grid annually. The algae cultivation requires additional CO_2 to be purchased in excess of the CO_2 that is produced from AD and MC. $22,067 of CO_2 purchasing is required.

Figure 4.5 shows how reducing the magnitude of the algae cultivation improves NPV, EROI, and PI. At 0.418 ha, the community reaches a NPV of 1 and has an EROI of 3.85. At approximately 6.7 ha, the community reached an EROI of 1 but still an unprofitable NPV. The total initial outlay and capital costs is $102,575. Additionally, at approximately 1 ha, no additional CO_2 is required to be purchased thereby a self-sustainable CO_2 level.

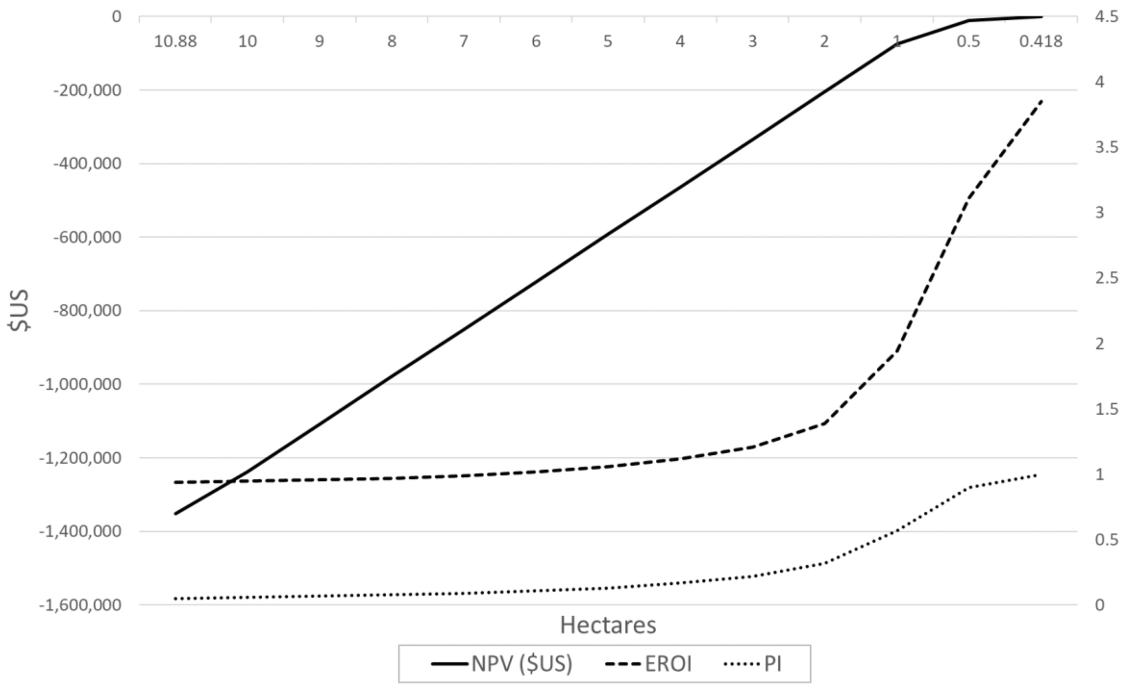

Figure 4.4. Sensitivity Analysis of Cultivation Magnitude to EROI, NPV, and PI

As discussed in Chapter 3 in Section 3.3.3, the cost of fuel is expected to increase by the year 2020. Figure 4.6 shows how variations in biodiesel selling price and decreasing discount rates can affect the overall NPV. This simulation is conducted at an EROI of one, an energy neutral community, which equals an algae cultivation area of 6.7 ha. At an EROI of one, the NPV equals -$811,556. The NPV only breaks $0 and a NPV of one at a biodiesel selling price of $14.00/gal and a discount rate of 0.09. The PI, NPV and fuel selling price at $0 NPV for the maximum algae production at 10.88 ha, the minimum algae production for $0 NPV at 0.43 ha, and the algae production at an EROI of one can be seen in Figure 4.7.

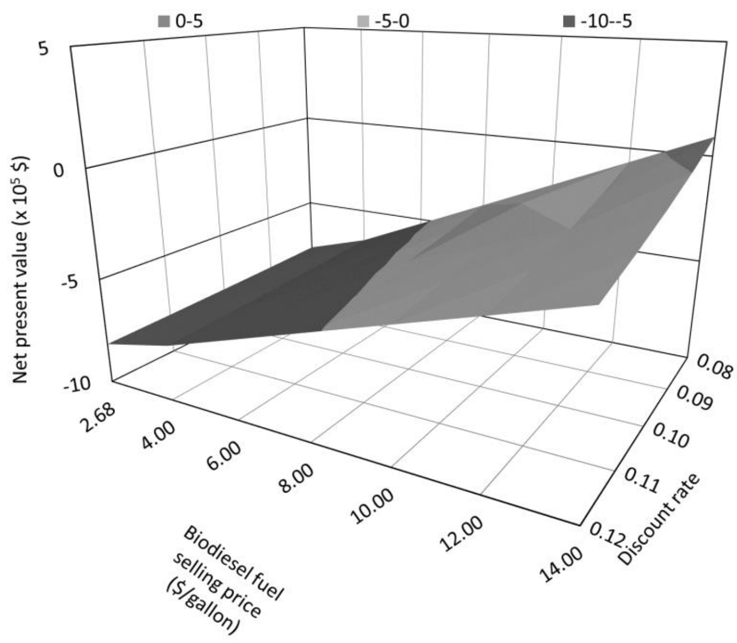

Figure 4.5. Relationship between NPV to Discount Rate and Biodiesel Fuel Selling Price at an EROI Equal to One

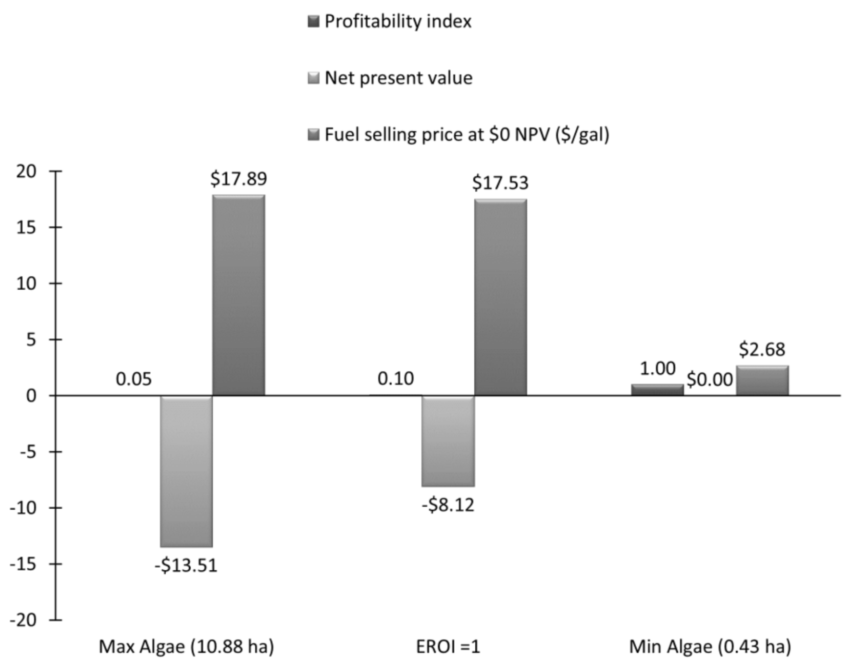

Figure 4.6. PI, NPV, and Fuel Selling Price at $0 NPV for Algae Cultivation Size Options

The total initial outlay and capital costs allocation for 10.88 ha system can be seen in Table 4.10. Of the infrastructure costs, distribution system, the harvesting system, and the digestion systems were the largest expenditures, in that particular order. Table 4.11 shows the cost data for the 10.88 ha system and the 0.418 ha system. Table 4.12 shows the cash flows for both operations.

Table 4.10 Initial Outlay and Capital Costs Allocation for 10.88 ha System

Initial Outlay/Capital Costs	
Steel - tanks	0.02%
Water pumps	0.25%
Miscellaneous infrastructure costs	0.26%
Waste treatment	0.87%
Settling ponds	0.93%
Gravel	0.99%
Geotextile	1.16%
Land	1.51%
Extraction system	1.83%
Fine grading	1.88%
Gas sumps, aerators	2.23%
Buildings, roads, and drainage	2.39%
Start-up costs	3.33%
Excavation	3.91%
Paddlewheels	4.37%
Generator (methane-powered)	5.96%
Clearing and grubbing	6.64%
Digestion system	8.80%
Engineering and contingencies	10.00%
Harvesting system	10.40%
Distributon system	12.23%
Working capital	20.00%

Table 4.11. Cost Data for Initial Outlays for Open Pond System Generating a Maximum Amount of Algae (10.88 ha) and a Minimum Amount of Algae (0.418 ha)

Item	Unit Price	Total Outlay – Max Algae	Total Outlay – Min Algae	Notes
INFRASTRUCTURE				
Buildings, roads, drainage	$3,139/ha	$34,150	$1,350	
Distribution system - electricity	$3,139/ha	$34,150	$1,350	
Distribution system - water	$8.90/linear m	$2,965	$117	A
Distribution system - gases	$15.60/linear m	$135,695	$5,363	B
Distribution system - nutrients	$8.90/linear m	$1,779	$70	C
Extraction system	$2,407/ha	$26,190	$1,035	D
Harvesting system	$13,646/ha	$148,471	$5,868	E
Digestion system	$8,391/ha	$125,652	$37,962	F
Generator (methane-powered)	$7,822/pc	$85,170	$3,364	G
Miscellaneous infrastructure costs	$342/ha	$3,721	$147	H
Land (total = pond area + peripherals)	$1,590/ha	$21,624	$855	
Waste treatment (blow down)	$1,146/ha	$12,473	$493	
TOTAL INFRASTRUCTURE COST		**$631,978**	**$57,973**	
CONSTRUCTION AND MAJOR EQUIPMENT COSTS				
Clearing and grubbing	$8,713/ha	$94,793	$3,746	
Excavation	$9.50/bank m^3	$55,859	$2,208	I
Fine grading – lagoon bottoms (@ 90%)	$3.80/$m^2$	$25,315	$1,000	J
Fine grading – lagoon tops (@ 10%)	$0.5/$m^2$	$369	$15	
Fine grading – slopes (gentle finish)	$0.2/$m^2$	$1,104	$44	
Gas sumps, aerators (for CO_2 delivery)	$2,288/piece	$31,811	$0	K
Geotextile	$3/$m^2$	$16,573	$655	L
Gravel	$0.02/kg	$14,160	$560	M
Paddle wheels	$573/piece	$62,391	$2,466	
Steel – tanks	$0.28/kg	$356	$27	
Settling ponds (for algae harvest)	$2,293/ha	$13,325	$527	
Water pumps	$716/piece	$3,529	$139	N
TOTAL COST FOR CONSTRUCTION AND MAJOR EQUIPMENT		**$319,584**	**$11,387**	
MISCELLANEOUS COSTS				
Start-up		$47,578	$3,468	O
Engineering and contingencies		$142,734	$10,404	P
Working capital		$285,469	$20,808	Q
TOTAL MISCELLANEOUS COSTS		**$475,781**	**$34,680**	R
TOTAL INITIAL OUTLAY		**$1,427,343**	**$104,039**	

A. Assume 100 ft/ha (30.5 m/ha) for algae media, water supply; PVC Class 150, 3”-diameter; excludes excavation or backfill.
B. Assume 800 m/ha; polyethelyene, 60 PSI, 1.25”-diameter, @100’ ft, coupling, SDR 11, excludes excavation or backfill.
C. Assume 60 ft/ha (18.3 m/ha) for inflows of nutrient solution.
D. $16,000,000 extraction cost per 34,065 Mg oil produced/year. Our oil yield is 4.7 Mg oil/year. Assume linearity.
E. $41,000,000 harvesting cost per 136,260 Mg DS produced/year. Our DS yield is 41.6 Mg DS/year. Assume linearity.
F. $23,000,000 digestion cost per 102,195 Mg TSS produced/year. Our TSS yield is 34.2 Mg TSS/year. Assume linearity.
G. $15,167 generator cost per 12.26 Mg CH4 produced/yr. Our CH4 yield is 5.8 Mg CH4/year Assume linearity.
H. Assumed price per hectare includes service facilities, instrumentation, and machinery.
I. Excavated areas are as follows: long ends, cones, divider levees, interior levees, top circles, bottom circles. Total excavated volume is 47.7 m^3 per 1-ha. Total area to be excavated is 481 m^2 per ha. Price assumes trench or continuous footing, common earth, 3/8 CY excavator, 1-4' deep; excludes sheeting or dewatering.

Table 4.11. Continued.

J. Lagoon bottoms to be graded for paving with grader; lagoon tops to be graded for compaction.
K. Lake aeration system, 110/220-volt motor, 9.2 amp @ (110v), 4.8amp @ (220v), 10psi-10.0 cfm open air flow (pumps air to 20' depth).
L. Geotextile dimensions are calculated as twice the walkway area to account for the slopes: (2*4658*x ha/FU*0.05) = 41 m^2/ha @ 5%.
M. Compacted gravel layer is 4'-deep, covering 10% of pond area, mostly near paddlewheels and other erosion-prone areas.
N. Price based on *Pentair Whisperflo* pool pump: controllable, single phase, 2 HP.
O. 5% of total infrastructure cost AND total cost for construction and major equipment.
P. 15% of total infrastructure cost AND total cost for construction and major equipment.
Q. 25% of total direct capital.
R. Sum of total infrastructure cost, total cost for construction and major equipment, start-up, and engineering and contingencies.

Table 4.12. Annual Cash Flows for Open Pond System Generating a Maximum Amount of Algae (10.88 ha) and a Minimum Amount of Algae (0.418 ha)

Item	Annual Cash Flow – Max Algae (10.88 ha)	Annual Cash Flow – Min Algae (0.43 ha)	Notes
REVENUES			
Total biodiesel produced @ $2.68/gallon	$38,681	$1,529	A
Net bioelectricity to grid @ $0.12/kWh	$8,833	$15,093	B
Fertilizer substitute credits @ $425/Mg	$124	$5	C
TOTAL REVENUES	**$47,638**	**$16,627**	
EXPENSES AND OPERATING COSTS			
PROCESS COSTS			
CO_2 (from recycled flue gas) @ $44/Mg CO_2	$22,067	$0	
Nutrients @ $463/Mg $H_{22}N_3O_4P$	$0	$0	
Labor and overhead	$10,019	$396	D
Other miscellaneous materials	$1,002	$40	E
ENERGY COSTS			
Direct electricity @ $0.12/kWh	$4,415	$174	
Other power	$3,750	$61	F
INDIRECT COSTS			
Waste Disposal	$4,083	$118	G
Maintenance and insurance	$1,665	$120	H
TOTAL EXPENSES AND OPERATING COSTS	**$47,000**	**$910**	
INCREMENTAL CASH FLOWS			
(-) Depreciation	$38,062	$2,751	I
Operating income	$37,424	$12,967	
(-) Tax (at 23.6%)	$8,832	$3,060	
Net operating profit after tax (NOPAT)	$28,592	$9,907	
(+) Depreciation	$38,062	$2,751	
GROSS ANNUAL CASH FLOW	**$9,470**	**$12,657**	

A. Biodiesel yield (in Mg/ha) × direct land use (in ha) × 7.14 barrels/Mg biodiesel) × 42 gallon/barrel × $2.68/gallon.
B. Total energy (in MJ/ha) - Methane yield (in kg/ha) x Methane energy (50 MJ/kg) × direct land use (in ha) × $0.04/kWh.
C. Fertilizer substitute revenues are computed based on quantities of diammonium phosphate and urea that could be supplanted via use of digestate as alternative fertilizer, based on bioavailabilty equivalence between commercial fertilizers and the algae digestate on an N basis.
D. $10/hr x 8 hrs/day x 330 days/yr x 1 person/50 ponds x 1 pond/ha x direct land use. Overhead assumed to be 60% of labor.
E. Assumed to be 10% of labor and overhead.

Table 4.12. Continued.

F. Assumed to be 10% of process cost and direct energy.
G. Assumed to be 50% of total energy cost.
H. Annual maintenance and insurance is assumed to be 3.5% of the respective depreciable bases (Benemann and Oswald (1996).
I. Calculated assuming an 11-year MACRS depreciation schedule (*How to Depreciate Property – IRS Instructional Form CAT No. 13081F*, 2011) and a 23.6% average marginal tax rate for the US (Hassett & Mathur, 2011).

The model utilizes a conventional transesterification method to produce biodiesel rather than hydrothermal processing in an effort to reduce overall infrastructure costs. This also produces LEA as a coproduct allowing for the combustion of methane for bioenergy. FH produces valuable coproducts with further downstream processing (HTM and AP) however because of the goal of a net zero energy and waste community, it is more advantageous to provide energy through MC rather than sell struvite or hydroxyapatite.

In this model, 75% of the MSW is not available for AD because it is not part of the organic and volatile portion of the MSW so 184,286 kg of waste must still be disposed of. This waste is categorized as rubber, textiles, leather (8.7%), plastics (12.7%), glass (4.6%), and metal (8.9%). It is assumed that the plastics, glass, and metal can be recycled and that the rubber, textiles, and leather can be reused. Waste disposal cost is factored in for contingency waste that cannot be reused or recycled at a cost of 50% the total energy cost.

CHAPTER 5

CONCLUSION

The results from Chapter 2 have shown that FH is favorable over HTL when comparing total energy use and only slightly higher than its conventional fuel counterpart when evaluating renewable diesel and biodiesel. It is even slightly lower than gasoline when comparing renewable gasoline and gasoline produced using the FH process. While the total GHG emissions are lower when comparing the FH and HTL processes, they are still significantly reduced when comparing its conventional fuel counterpart (44.1% the total GHG emissions of LSD and 48.6% the total GHG emissions of RFG).

Considering the positive results in Chapter 2, Chapter 3 has gone on to show that the further downstream processing of the algae biomass for valuable co-products through AP or HTM has produced an EROI greater than 1 for all models indicating a net positive energy production and a NGR of less than 1 for all models indicating an overall reduction in GHG emissions. The techno-economic analysis indicated that the models were all not profitable with PI's of less than 1 with the HTM models being the most profitable. A sensitivity analysis of the correlation to discount rate and fuel selling price to PI showed that moderate reductions in either discount rate or fuel selling price could bring the PI above one and into the positive profit range.

The feasibility of developing a self-sustaining community around algae cultivation was explored in chapter 4 in an effort to achieve a net zero energy and net zero waste balance. The initial maximum algae cultivation threshold of 10.88 hectares showed that the PI and EROI of the community were both less than 1 indicating an overall loss in profit and energy. Results showed that reduced algae production could increase the PI and EROI above 1 in order to reach a sustainable community through biodiesel generation and methane combustion utilizing MSW and harvested algae.

Future work is planned in further evaluation of the sustainable community in order to determine the effect of including the residential infrastructure life cycle impact factors such as energy and GHG usage in upstream materials processing and also the effect of the cost of construction into the community TEA. There are also other options to explore with the biodiesel. The current model assumes that the biofuel is sold at market value but what if the biodiesel was utilized within the community in order to develop a ride share program or profitable enterprise consisting of a fleet of taxi service vehicles.

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APPENDIX A: GREET RAW DATA OUTPUT

Table A1 Conventional LS Diesel GREET Raw Data Output

CIDI Vehicle: Conventional and LS Diesel								
	Btu/mile or Gallon/mile or g/mile				Btu/mmBtu or Gallon/mmBtu or g/mmBtu			
Item	Feedstock	Fuel	Vehicle (	Total	Feedstock	Fuel	Vehicle (	Total
Total Energy	308.1431556	492.9405	3768.58	4569.659	81766.48623	130802.9	1000000	1212569
Fossil Fuels	294.7845501	486.4739	3768.58	4549.834	78221.74993	129087	1000000	1207309
Coal	47.46385207	23.43484	0	70.8987	12594.64095	6218.489	0	18813.13
Natural Gas	187.4378233	317.035	0	504.4728	49737.05215	84125.96	0	133863
Petroleum	59.88287475	146.0041	3768.58	3974.462	15890.05683	38742.52	1000000	1054633
Water Consumption	0.093574117	0.015699	0	0.109273	24.83010457	4.165765	0	28.99587
CO2 (w/ C in VOC & CO)	20.76786803	30.71043	297.732	349.2101	5510.800952	8149.084	79003.8	92663.69
CH4	0.457645758	0.072283	0.0938	0.623729	121.4373414	19.18044	24.89	165.5078
N2O	0.000386805	0.000603	0.0007	0.00169	0.10263959	0.15999	0.18575	0.448376
GHGs	34.5997441	33.0387	300.731	368.3697	9181.120683	8766.894	79799.7	97747.74
VOC: Total	0.01625024	0.015663	0.075	0.106914	4.31203803	4.156335	19.9014	28.36979
CO: Total	0.036753393	0.026458	2.7274	2.790611	9.752596303	7.020652	723.722	740.495
NOx: Total	0.107087323	0.049367	0.2339	0.390355	28.41586451	13.09972	62.0659	103.5815
PM10: Total	0.007596561	0.005166	0.0231	0.035863	2.015764745	1.370881	6.12964	9.516284
PM2.5: Total	0.006352139	0.003995	0.0095	0.019848	1.685554538	1.060214	2.52085	5.266615
SOx: Total	0.055110422	0.047203	0.00205	0.104366	14.62367554	12.52541	0.5447	27.69378
BC Total	0.01030366	0.002007	0.00163	0.013936	2.73409958	0.532535	0.43129	3.69792
OC Total	0.001958205	0.000739	0.0045	0.007199	0.519614161	0.196088	1.19467	1.910373
VOC: Urban	0.00270481	0.008899	0.05175	0.063354	0.717727544	2.361461	13.732	16.81117
CO: Urban	0.001756504	0.01188	1.88191	1.895543	0.466092352	3.152435	499.368	502.9866
NOx: Urban	0.006827246	0.019578	0.16139	0.187796	1.81162525	5.195095	42.8255	49.83219
PM10: Urban	0.000837561	0.002668	0.01594	0.019444	0.222248684	0.707876	4.22945	5.159574
PM2.5: Urban	0.000647878	0.002021	0.00656	0.009224	0.171915836	0.536407	1.73938	2.447707
SOx: Urban	0.008040066	0.027786	0.00142	0.037242	2.133449904	7.372952	0.37584	9.882244
BC: Urban	0.000248204	0.000173	0.00112	0.001542	0.065861537	0.045841	0.29759	0.409289
OC: Urban	0.000122028	0.000355	0.00311	0.003583	0.032380317	0.094164	0.82432	0.950868

Table A2 Reformulated Gasoline GREET Raw Data Output

Gasoline Vehicle: Gasoline								
	Btu/mile or Gallon/mile or g/mile				Btu/mmBtu or Gallon/mmBtu or g/mmBtu			
Item	Feedstock	Fuel	Vehicle (	Total	Feedstock	Fuel	Vehicle (	Total
Total Energy	297.724	1036.526	4522.29	5856.541	65834.783	229203.8	1000000	1295038.61
Fossil Fuels	284.817085	951.0019	4220.77	5456.592	62980.717	210292.1	933326	1206599.26
Coal	45.8589705	68.2485	0	114.1075	10140.652	15091.58	0	25232.2315
Natural Gas	181.100042	567.0586	0	748.1586	40046.09	125391.9	0	165437.989
Petroleum	57.8580723	315.6948	4220.77	4594.326	12793.976	69808.61	933326	1015929.04
Water Consumption	0.09041012	0.230743	0	0.321153	19.992109	51.02341	0	71.01552
CO2 (w/ C in VOC & CO)	-2.5255481	68.0655	346.883	412.4226	-558.4666	15051.11	76705.1	91197.7229
CH4	0.44217151	0.204376	0.0106	0.657148	97.776013	45.19307	2.34395	145.313031
N2O	0.00037373	0.017242	0.0067	0.024315	0.0826409	3.812602	1.48155	5.37679335
GHGs	10.8386347	78.76584	348.976	438.5806	2396.7136	17417.24	77168	96981.9641
VOC: Total	0.01570078	0.121429	0.1701	0.30723	3.4718636	26.85119	37.6137	67.9367392
CO: Total	0.03551066	0.077035	2.8656	2.978146	7.8523621	17.03458	633.661	658.548165
NOx: Total	0.10346641	0.137404	0.1205	0.36137	22.879206	30.38366	26.6458	79.9086592
PM10: Total	0.0073397	0.016392	0.0257	0.049431	1.6230052	3.624662	5.68296	10.9306283
PM2.5: Total	0.00613736	0.010656	0.0117	0.028493	1.3571345	2.356297	2.58718	6.30061591
SOx: Total	0.05324699	0.137257	0.00524	0.195744	11.774341	30.35111	1.15883	43.2842849
BC Total	0.00995527	0.005882	0.00215	0.017986	2.2013769	1.300619	0.47523	3.97722277
OC Total	0.00189199	0.002001	0.00636	0.010254	0.4183705	0.442533	1.40655	2.26745701
VOC: Urban	0.00261335	0.070105	0.11737	0.190088	0.5778827	15.50219	25.9534	42.0335125
CO: Urban	0.00169711	0.025806	1.97726	2.004767	0.3752771	5.70631	437.226	443.307831
NOx: Urban	0.0065964	0.042837	0.08315	0.132578	1.4586411	9.472351	18.3856	29.3165874
PM10: Urban	0.00080924	0.005735	0.01773	0.024277	0.1789449	1.268134	3.92124	5.36832194
PM2.5: Urban	0.00062597	0.004371	0.00807	0.01307	0.1384191	0.966503	1.78516	2.89007938
SOx: Urban	0.00776821	0.067106	0.00362	0.07849	1.7177601	14.8389	0.79959	17.3562586
BC: Urban	0.00023981	0.000394	0.00148	0.002117	0.0530288	0.087086	0.32791	0.46802138
OC: Urban	0.0001179	0.000746	0.00439	0.005253	0.0260712	0.16494	0.97052	1.16153255

Table A3 HTL Model Biodiesel GREET Raw Data Output

CIDI Vehicle: Algae-based BD20 HTL Study								
	Btu/mile or Gallon/mile or g/mile				Btu/mmBtu or Gallon/mmBtu or g/mmBtu			
Item	Feedstock	Fuel	Vehicle (	Total	Feedstock	Fuel	Vehicle (	Total
Total Energy	837.8691263	531.0859	3768.58	5137.53	222330.4757	140924.8	1000000	1363255
Fossil Fuels	392.1131674	502.1417	3061.86	3956.113	104048.1196	133244.4	812471	1049764
Coal	84.61809196	30.25093	0	114.869	22453.6029	8027.153	0	30480.76
Natural Gas	249.480316	348.4309	0	597.9112	66200.16849	92456.93	0	158657.1
Petroleum	58.01475942	123.4599	3061.86	3243.333	15394.34818	32760.37	812471	860625.7
Water Consumption	0.100165005	0.046657	0	0.146822	26.57901171	12.38058	0	38.95959
CO2 (w/ C in VOC & CO)	-28.44327901	31.90952	298.382	301.8487	-7547.48869	8467.265	79176.5	80096.25
CH4	0.414919772	0.072739	0.0938	0.581459	110.099904	19.30146	24.89	154.2914
N2O	0.000573502	0.000594	0.0007	0.001868	0.152179967	0.157654	0.18575	0.495581
GHGs	-15.8437079	34.24914	301.382	319.7874	-4204.16388	9088.087	79972.4	84856.32
VOC: Total	0.024363394	0.014992	0.075	0.114356	6.464881925	3.978191	19.9014	30.34449
CO: Total	0.060746168	0.025333	2.7274	2.81348	16.11913363	6.722282	723.722	746.5632
NOx: Total	0.119487754	0.048535	0.2339	0.401923	31.70634691	12.87896	62.0659	106.6512
PM10: Total	0.010327379	0.005385	0.0231	0.038812	2.740393467	1.428897	6.12964	10.29893
PM2.5: Total	0.008441362	0.004229	0.0095	0.02217	2.239934508	1.122059	2.52085	5.88284
SOx: Total	0.105109045	0.044746	0.00167	0.151523	27.89092388	11.87348	0.44255	40.20696
BC Total	0.009019051	0.002092	0.00163	0.012737	2.393225604	0.555225	0.43129	3.379737
OC Total	0.0029213	0.000707	0.0045	0.008131	0.775173516	0.187605	1.19467	2.15745
VOC: Urban	0.002340932	0.007771	0.05175	0.061862	0.621171665	2.062171	13.732	16.41532
CO: Urban	0.002218234	0.010043	1.88191	1.894168	0.588613503	2.665017	499.368	502.6217
NOx: Urban	0.008731399	0.017119	0.16139	0.187241	2.316896643	4.542476	42.8255	49.68484
PM10: Urban	0.001248638	0.00236	0.01594	0.019548	0.33132904	0.626336	4.22945	5.187115
PM2.5: Urban	0.000933172	0.001798	0.00656	0.009286	0.247619211	0.476996	1.73938	2.464
SOx: Urban	0.012385151	0.023997	0.00115	0.037533	3.286428029	6.367749	0.30536	9.959539
BC: Urban	0.000238808	0.000154	0.00112	0.001514	0.063368191	0.04079	0.29759	0.401745
OC: Urban	0.000143633	0.000302	0.00311	0.003552	0.038113355	0.080155	0.82432	0.942592

Table A4 HTL Model Renewable Diesel II GREET Raw Data Output

CIDI Vehicle: Algae-based RDII 100 HTL Study								
	Btu/mile or Gallon/mile or g/mile				Btu/mmBtu or Gallon/mmBtu or g/mmBtu			
Item	Feedstock	Fuel	Vehicle (	Total	Feedstock	Fuel	Vehicle (	Total
Total Energy	3203.74	883.262	3768.58	7855.577	850119.695	234375.6	1000000	2084495
Fossil Fuels	832.18834	1101.22	0	1933.409	220823.066	292211.3	0	513034.4
Coal	251.14141	47.72332	0	298.8647	66640.9447	12663.49	0	79304.43
Natural Gas	529.99718	1025.957	0	1555.954	140635.955	272240.1	0	412876
Petroleum	51.049747	27.53994	0	78.58969	13546.1664	7307.786	0	20853.95
Water Consumption	0.1316302	0.056189	0	0.18782	34.928367	14.90999	0	49.83835
CO2 (w/ C in VOC & CO)	-227.56674	68.41614	288.47	129.3191	-60385.351	18154.38	76546.1	34315.11
CH4	0.2350046	0.131336	0.0938	0.460141	62.359	34.85036	24.89	122.0994
N2O	0.0014136	0.000593	0.0007	0.002707	0.37510698	0.157349	0.18575	0.718203
GHGs	-220.14199	72.51337	291.469	143.8405	-58415.178	19241.59	77342	38168.41
VOC: Total	0.0608592	0.014122	0.075	0.149981	16.149123	3.747285	19.9014	39.79783
CO: Total	0.1684185	0.030937	2.7274	2.926756	44.6902272	8.209262	723.722	776.6213
NOx: Total	0.1771287	0.058562	0.2339	0.46959	47.0015043	15.53943	62.0659	124.6068
PM10: Total	0.0226596	0.011072	0.0231	0.056832	6.01278488	2.938079	6.12964	15.0805
PM2.5: Total	0.0178884	0.010224	0.0095	0.037612	4.74673171	2.712953	2.52085	9.980532
SOx: Total	0.3290021	0.028129	0	0.357131	87.3014604	7.464046	0	94.76551
BC Total	0.0035315	0.004759	0.00163	0.009916	0.9371038	1.262772	0.43129	2.631162
OC Total	0.0072543	0.000699	0.0045	0.012456	1.92494346	0.18555	1.19467	3.305164
VOC: Urban	0.0007817	0.001748	0.05175	0.05428	0.20742835	0.463861	13.732	14.40327
CO: Urban	0.0043141	0.004217	1.88191	1.890438	1.14474559	1.119121	499.368	501.6319
NOx: Urban	0.0173651	0.009353	0.16139	0.188109	4.60786033	2.481857	42.8255	49.91519
PM10: Urban	0.0030981	0.002692	0.01594	0.021729	0.82209559	0.714372	4.22945	5.765918
PM2.5: Urban	0.0022183	0.002522	0.00656	0.011295	0.58861796	0.669178	1.73938	2.99718
SOx: Urban	0.0319159	0.006351	0	0.038267	8.46894799	1.68534	0	10.15429
BC: Urban	0.0002026	0.000105	0.00112	0.00143	0.05375415	0.027989	0.29759	0.37933
OC: Urban	0.0002426	0.00012	0.00311	0.00347	0.064375	0.031967	0.82432	0.920664

Table A5 HTL Model Renewable Gasoline GREET Raw Data Output

SI Vehicle: Algae-based RG100 HTL Study								
	Btu/mile or Gallon/mile or g/mile				Btu/mmBtu or Gallon/mmBtu or g/mmBtu			
Item	Feedstock	Fuel	Vehicle (	Total	Feedstock	Fuel	Vehicle (	Total
Total Energy	3910.33716	182.5396	4522.29	8615.167	864680.71	40364.4	1000000	1905045.11
Fossil Fuels	1015.73066	94.66625	0	1110.397	224605.37	20933.25	0	245538.62
Coal	306.531614	47.13058	0	353.6622	67782.383	10421.84	0	78204.2222
Natural Gas	646.890086	26.62741	0	673.5175	143044.79	5888.036	0	148932.831
Petroleum	62.3089645	20.90826	0	83.21723	13778.188	4623.379	0	18401.5671
Water Consumption	0.16066172	0.019832	0	0.180494	35.526627	4.385358	0	39.9119844
CO2 (w/ C in VOC & CO)	-265.21081	10.04793	339.832	84.66892	-58645.24	2221.868	75145.9	18722.5742
CH4	0.28683574	0.013309	0.0106	0.310745	63.427097	2.942966	2.34395	68.7140079
N2O	0.0017254	0.000135	0.0067	0.00856	0.3815319	0.029796	1.48155	1.89287784
GHGs	-256.1485	10.48291	341.925	96.25969	-56641.32	2318.053	75608.9	21285.607
VOC: Total	0.07428191	0.006398	0.1701	0.25078	16.425728	1.414801	37.6137	55.4542135
CO: Total	0.20556382	1.318953	2.8656	4.390117	45.45569	291.6561	633.661	970.772981
NOx: Total	0.21619512	2.100438	0.1205	2.437133	47.806555	464.4634	26.6458	538.915756
PM10: Total	0.0276573	0.002377	0.0257	0.055735	6.115773	0.525664	5.68296	12.3243977
PM2.5: Total	0.02183377	0.00157	0.0117	0.035104	4.8280346	0.347214	2.58718	7.76243353
SOx: Total	0.4015648	0.017754	0	0.419319	88.796776	3.925939	0	92.7227152
BC Total	0.00431044	0.000315	0.00215	0.006775	0.9531547	0.069725	0.47523	1.4981072
OC Total	0.00885426	0.000374	0.00636	0.015589	1.9579143	0.08265	1.40655	3.44711719
VOC: Urban	0.00095412	0.001343	0.11737	0.119666	0.2109812	0.296883	25.9534	26.4613067
CO: Urban	0.00526554	0.001144	1.97726	1.983673	1.164353	0.252898	437.226	438.643496
NOx: Urban	0.021195	0.004826	0.08315	0.109166	4.6867846	1.067235	18.3856	24.1396148
PM10: Urban	0.00378143	0.000616	0.01773	0.022131	0.8361766	0.136281	3.92124	4.89370058
PM2.5: Urban	0.00270749	0.000449	0.00807	0.01123	0.5986999	0.099316	1.78516	2.48317365
SOx: Urban	0.03895503	0.006142	0	0.045097	8.6140057	1.3582	0	9.97220607
BC: Urban	0.00024726	3.93E-05	0.00148	0.001769	0.0546749	0.008696	0.32791	0.39127779
OC: Urban	0.00029611	6.45E-05	0.00439	0.00475	0.0654776	0.014259	0.97052	1.05025807

Table A6 Flash Hydrolysis Model Biodiesel GREET Raw Data Output

CIDI Vehicle: Algae-based BD20 Flash Process								
	Btu/mile or Gallon/mile or g/mile				Btu/mmBtu or Gallon/mmBtu or g/mmBtu			
Item	Feedstock	Fuel	Vehicle (	Total	Feedstock	Fuel	Vehicle (	Total
Total Energy	418.0639921	531.0859	3768.58	4717.725	110934.2299	140924.8	1000000	1251859
Fossil Fuels	659.5595644	502.1417	3061.86	4223.559	175015.6285	133244.4	812471	1120731
Coal	95.78394782	30.25093	0	126.0349	25416.48811	8027.153	0	33443.64
Natural Gas	457.8684303	348.4309	0	806.2993	121496.428	92456.93	0	213953.4
Petroleum	105.9071863	123.4599	3061.86	3291.225	28102.71242	32760.37	812471	873334.1
Water Consumption	0.104079071	0.046657	0	0.150736	27.61761785	12.38058	0	39.9982
CO2 (w/ C in VOC & CO)	-14.74643594	31.90952	298.382	315.5456	-3913.00027	8467.265	79176.5	83730.74
CH4	0.441939796	0.072739	0.0938	0.608479	117.2697287	19.30146	24.89	161.4612
N2O	0.000934458	0.000594	0.0007	0.002229	0.247960511	0.157654	0.18575	0.591361
GHGs	-1.240610723	34.24914	301.382	334.3905	-329.198873	9088.087	79972.4	88731.28
VOC: Total	0.020135841	0.014992	0.075	0.110128	5.343091141	3.978191	19.9014	29.2227
CO: Total	0.049696332	0.025333	2.7274	2.80243	13.18703457	6.722282	723.722	743.6311
NOx: Total	0.123493685	0.048535	0.2339	0.405929	32.7693299	12.87896	62.0659	107.7142
PM10: Total	0.010096692	0.005385	0.0231	0.038582	2.679180181	1.428897	6.12964	10.23771
PM2.5: Total	0.008018537	0.004229	0.0095	0.021747	2.127736945	1.122059	2.52085	5.770642
SOx: Total	0.085283398	0.044746	0.00167	0.131697	22.63014345	11.87348	0.44255	34.94618
BC Total	0.010134327	0.002092	0.00163	0.013852	2.689166634	0.555225	0.43129	3.675678
OC Total	0.002132547	0.000707	0.0045	0.007342	0.565876247	0.187605	1.19467	1.948152
VOC: Urban	0.00260767	0.007771	0.05175	0.062129	0.691951169	2.062171	13.732	16.4861
CO: Urban	0.003101422	0.010043	1.88191	1.895051	0.82296925	2.665017	499.368	502.856
NOx: Urban	0.010267583	0.017119	0.16139	0.188777	2.724526537	4.542476	42.8255	50.09247
PM10: Urban	0.001432508	0.00236	0.01594	0.019732	0.380119301	0.626336	4.22945	5.235906
PM2.5: Urban	0.001065977	0.001798	0.00656	0.009419	0.282859339	0.476996	1.73938	2.49924
SOx: Urban	0.014485189	0.023997	0.00115	0.039633	3.843677904	6.367749	0.30536	10.51679
BC: Urban	0.000259787	0.000154	0.00112	0.001535	0.068935068	0.04079	0.29759	0.407312
OC: Urban	0.000156344	0.000302	0.00311	0.003565	0.041486168	0.080155	0.82432	0.945965

Table A7 Flash Hydrolysis Model Renewable Diesel II GREET Raw Data Output

CIDI Vehicle: Algae-based RDII 100 flash process								
	Btu/mile or Gallon/mile or g/mile				Btu/mmBtu or Gallon/mmBtu or g/mmBtu			
Item	Feedstock	Fuel	Vehicle (	Total	Feedstock	Fuel	Vehicle (	Total
Total Energy	855.98618	339.7856	3768.58	4964.347	227137.878	90162.89	1000000	1317301
Fossil Fuels	2143.9932	561.2584	0	2705.252	568913.472	148931.2	0	717844.7
Coal	292.05967	34.96693	0	327.0266	77498.6956	9278.555	0	86777.25
Natural Gas	1559.7047	501.073	0	2060.778	413871.193	132960.9	0	546832.1
Petroleum	292.22883	25.21842	0	317.4472	77543.5833	6691.764	0	84235.35
Water Consumption	0.1431835	0.031915	0	0.175099	37.9940692	8.468725	0	46.46279
CO2 (w/ C in VOC & CO)	-161.5714	35.51237	288.47	162.4106	-42873.338	9423.288	76546.1	43096.03
CH4	0.3578764	0.068093	0.0938	0.51977	94.9633062	18.06873	24.89	137.9221
N2O	0.0031655	0.000342	0.0007	0.004207	0.83997066	0.090715	0.18575	1.116432
GHGs	-149.99625	37.64577	291.469	179.1187	-39801.847	9989.39	77342	47529.55
VOC: Total	0.0353865	0.009544	0.075	0.11993	9.38988124	2.53242	19.9014	31.82372
CO: Total	0.1012406	0.017257	2.7274	2.845898	26.8644159	4.579244	723.722	755.1654
NOx: Total	0.186239	0.037593	0.2339	0.457732	49.4189469	9.975487	62.0659	121.4603
PM10: Total	0.020032	0.005974	0.0231	0.049106	5.31552979	1.585251	6.12964	13.03042
PM2.5: Total	0.0145854	0.005356	0.0095	0.029442	3.87027674	1.421278	2.52085	7.812401
SOx: Total	0.2067545	0.018389	0	0.225143	54.8627791	4.879447	0	59.74223
BC Total	0.008998	0.002401	0.00163	0.013025	2.38763268	0.637209	0.43129	3.456128
OC Total	0.0027642	0.000489	0.0045	0.007756	0.73347931	0.129884	1.19467	2.058034
VOC: Urban	0.0020931	0.001425	0.05175	0.055268	0.55541643	0.37805	13.732	14.66545
CO: Urban	0.0085458	0.00246	1.88191	1.892912	2.26764985	0.652687	499.368	502.2884
NOx: Urban	0.0240945	0.006208	0.16139	0.191694	6.39352849	1.64732	42.8255	50.86632
PM10: Urban	0.0038383	0.001447	0.01594	0.021224	1.01851034	0.383865	4.22945	5.631825
PM2.5: Urban	0.0027541	0.001321	0.00656	0.01063	0.73081446	0.350495	1.73938	2.820694
SOx: Urban	0.040592	0.004692	0	0.045284	10.7711773	1.245113	0	12.01629
BC: Urban	0.0002967	6.22E-05	0.00112	0.00148	0.07872761	0.01651	0.29759	0.392825
OC: Urban	0.000292	8.03E-05	0.00311	0.003479	0.07747007	0.021302	0.82432	0.923095

Table A8 Flash Hydrolysis Model Renewable Gasoline GREET Raw Data Output

SI Vehicle: Algae-based RG100 flash process								
	Btu/mile or Gallon/mile or g/mile				Btu/mmBtu or Gallon/mmBtu or g/mmBtu			
Item	Feedstock	Fuel	Vehicle (	Total	Feedstock	Fuel	Vehicle (	Total
Total Energy	1116.21497	182.5396	4522.29	5821.045	246825.15	40364.4	1000000	1287189.55
Fossil Fuels	2795.78968	94.66625	0	2890.456	618224.28	20933.25	0	639157.539
Coal	380.848871	47.13058	0	427.9795	84215.927	10421.84	0	94637.7661
Natural Gas	2033.87135	26.62741	0	2060.499	449743.65	5888.036	0	455631.688
Petroleum	381.06946	20.90826	0	401.9777	84264.706	4623.379	0	88888.0851
Water Consumption	0.1867128	0.019832	0	0.206545	41.287221	4.385358	0	45.6725787
CO2 (w/ C in VOC & CO)	-174.04791	10.04793	339.832	175.8318	-38486.67	2221.868	75145.9	38881.1428
CH4	0.46667454	0.013309	0.0106	0.490583	103.19429	2.942966	2.34395	108.481201
N2O	0.00412784	0.000135	0.0067	0.010963	0.9127755	0.029796	1.48155	2.42412143
GHGs	-158.95379	10.48291	341.925	193.4544	-35148.96	2318.053	75608.9	42777.971
VOC: Total	0.04614433	0.006398	0.1701	0.222642	10.203753	1.414801	37.6137	49.2322384
CO: Total	0.13201877	1.318953	2.8656	4.316572	29.1929	291.6561	633.661	954.510191
NOx: Total	0.24285764	2.100438	0.1205	2.463796	53.702355	464.4634	26.6458	544.811556
PM10: Total	0.0261219	0.002377	0.0257	0.054199	5.7762556	0.525664	5.68296	11.9848802
PM2.5: Total	0.01901955	0.00157	0.0117	0.03229	4.2057346	0.347214	2.58718	7.14013349
SOx: Total	0.26961005	0.017754	0	0.287364	59.618033	3.925939	0	63.5439722
BC Total	0.01173345	0.000315	0.00215	0.014198	2.5945817	0.069725	0.47523	3.13953424
OC Total	0.00360451	0.000374	0.00636	0.010339	0.7970539	0.08265	1.40655	2.28625687
VOC: Urban	0.00272946	0.001343	0.11737	0.121441	0.6035574	0.296883	25.9534	26.8538828
CO: Urban	0.01114382	0.001144	1.97726	1.989552	2.4641993	0.252898	437.226	439.943342
NOx: Urban	0.03141947	0.004826	0.08315	0.119391	6.9476902	1.067235	18.3856	26.4005204
PM10: Urban	0.00500523	0.000616	0.01773	0.023355	1.1067902	0.136281	3.92124	5.16431413
PM2.5: Urban	0.00359141	0.000449	0.00807	0.012114	0.7941581	0.099316	1.78516	2.67863185
SOx: Urban	0.05293238	0.006142	0	0.059075	11.704774	1.3582	0	13.0629739
BC: Urban	0.00038689	3.93E-05	0.00148	0.001909	0.0855514	0.008696	0.32791	0.42215429
OC: Urban	0.00038071	6.45E-05	0.00439	0.004834	0.0841848	0.014259	0.97052	1.06896527

APPENDIX B: PUBLISHERS APPROVAL OF MATERIAL

Argonne National Laboratory Approval for use of figure X in this work

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June 4, 2015

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Permission is hereby granted for the use of the requested materials — **FIGURE 4 "Carbon Flows in the Pathway" of "Life-cycle analysis of algal lipid fuels with the GREET model" (ANL/EVS-11/5)** — to be included in **Andy Bessette's** with the following stipulations:

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Sincerely,

Yvette Woell

CIS-360 (08/05/2014)

APPENDIX C: CHAPTER 3 COST DATA

Table C1. Cost Data Pertains to Initial Outlays for Open Pond System Generating RDII and Utilizing HTM or AP for Co-product Generation

Item	Unit Price	Total Outlay – HTM	Total Outlay – AP	Notes
INFRASTRUCTURE				
Buildings, roads, drainage	$3,139/ha	$1,047,850	$1,047,850	
Distribution system - electricity	$3,1399/ha	$1,047,850	$1,047,850	
Distribution system - water	$8.90/linear m	$90,988	$90,988	A
Distribution system - gases	$15.60/linear m	$4,163,625	$4,163,625	B
Distribution system - nutrients	$8.90/linear m	$54,593	$54,593	C
Flash hydrolysis system	$19,481/ha	$6,503,545	$6,503,545	D
Flash hydrolysis heat exchanger	$1,248/ha	$416,627	$416,627	E
Harvesting system	$12,517/ha	$4,178,626	$4,178,626	F
HTL and catalytic upgrade system	$18,531/ha	$6,188,086	$6,188,086	G
HTL heat exchanger	$1,248/ha	$416,627	$416,627	E
HTM system	$81,938/reactor	$1,139,744		H
HTM heat exchanger	$1,248/ha	$416,627		E
AP system	$81,938/reactor		$1,139,744	H
Oil storage (1 yr)	$50/barrel	$16,692	$16,692	
Intermediate product storage (30 days)	$50/barrel	$16,692	$16,692	
Fuel storage (30 days)	$50/barrel	$16,692	$16,692	
Miscellaneous infrastructure costs	$342/ha	$114,238	$114,238	I
Land (total = pond area + peripherals)	$1,590/ha	$530,799	$663,499	
Waste treatment (blow down)	$1,146/ha	$663,499	$382,706	
TOTAL INFRASTRUCTURE COST		$26,875,309	$26,458,681	
CONSTRUCTION AND MAJOR EQUIPMENT COSTS				
Clearing and grubbing	$8,713/ha	$2,908,564	$2,908,564	
Excavation	$9.50/bank m^3	$1,713,519	$1,713,519	J
Fine grading – lagoon bottoms (@ 90%)	$3.80/$m^2$	$775,934	$775,934	K
Fine grading – lagoon tops (@ 10%)	$0.5/$m^2$	$11,426	$11,426	
Fine grading – slopes (gentle finish)	$0.2/$m^2$	$34,753	$34,753	
Gas sumps, aerators (for CO_2 delivery)	$2,288/piece	$1,251,858	$1,251,858	L
Geotextile	$3/$m^2$	$508,625	$508,625	M
Gravel	$0.02/kg	$434,548	$434,548	N
Paddle wheels	$573/piece	$1,914,394	$1,914,394	
Steel – tanks	$0.28/kg	$6,120	$6,120	
Settling ponds (for algae harvest)	$2,293/ha	$408,847	$408,847	
Water pumps	$716/piece	$95,038	$95,038	O
TOTAL COST FOR CONSTRUCTION AND MAJOR EQUIPMENT		$10,063,627	$10,063,627	
MISCELLANEOUS COSTS				
Start-up		$1,843,846	$1,823,014	P
Engineering and contingencies		$5,531,537	$5,469,043	Q
Working capital		$11,063,074	$10,938,086	R
TOTAL MISCELLANEOUS COSTS		$18,469,468	$18,261,154	S
TOTAL INITIAL OUTLAY		$55,408,404	$54,783,463	

A. Assume 100 ft/ha (30.5 m/ha) for algae media, water supply; PVC Class 150, 3”-diameter; excludes excavation or backfill.

B. Assume 800 m/ha; polyethelyene, 60 PSI, 1.25"-diameter, @100' ft, coupling, SDR 11, excludes excavation or backfill.
C. Assume 60 ft/ha (18.3 m/ha) for inflows of nutrient solution.
D. $52,000,000 HTL system cost per 221,920 Mg LEA processed/year. Our incoming biomass is 83.14 Mg/year. Assume linearity.
E. 4 heat exchangers for a 200 Mg/d system = $8,789,880 installed 2012 price, 2017 price = $10,953,790 2017, we need 41.6 Mg DS/year. Use 2 heat exchangers per system. Assume linearity.
F. $41,000,000 harvesting cost per 136,260 Mg DS produced/year. Our DS yield is 41.6 Mg DS/year. Assume linearity.
G. $117,800,000 HTL system plus hydrocracking and hydrotreating per 221,920 Mg LEA processed/year. Our FH BI incoming is 34.92 Mg/year. Assume linearity.
H. Volumetric flow rate = $0.56m^3/d$. $C = a + b*S^n$. $C = 61{,}500 + 32{,}500\ (0.56)^{0.8}$. Residence time of 1 hr. Assume linearity.
I. Assumed price per hectare includes service facilities, instrumentation, and machinery.
J. Excavated areas are as follows: long ends, cones, divider levees, interior levees, top circles, bottom circles. Total excavated volume is 47.7 m^3 per 1-ha. Total area to be excavated is 481 m^2 per ha. Price assumes trench or continuous footing, common earth, 3/8 CY excavator, 1-4' deep; excludes sheeting or dewatering.
K. Lagoon bottoms to be graded for paving with grader; lagoon tops to be graded for compaction.
L. Lake aeration system, 110/220-volt motor, 9.2 amp @ (110v), 4.8amp @ (220v), 10psi-10.0 cfm open air flow (pumps air to 20' depth).
M. Geotextile dimensions are calculated as twice the walkway area to account for the slopes: (2*4658*x ha/FU*0.05) = 41 m^2/ha @ 5%.
N. Compacted gravel layer is 4'-deep, covering 10% of pond area, mostly near paddlewheels and other erosion-prone areas.
O. Price based on *Pentair Whisperflo* pool pump: controllable, single phase, 2 HP.
P. 5% of total infrastructure cost AND total cost for construction and major equipment.
Q. 15% of total infrastructure cost AND total cost for construction and major equipment.
R. 25% of total direct capital.
S. Sum of total infrastructure cost, total cost for construction and major equipment, start-up, and engineering and contingencies.

Table C2. Cost Data Pertains to Initial Outlays for Open Pond System Generating RG and Utilizing HTM or AP for Co-product Generation

Item	Unit Price	Total Outlay – HTM	Total Outlay – AP	Notes
INFRASTRUCTURE				
Buildings, roads, drainage	$3,139/ha	$561,815	$561,815	
Distribution system - electricity	$3,1399/ha	$561,815	$561,815	
Distribution system - water	$8.90/linear m	$48,784	$48,784	A
Distribution system - gases	$15.60/linear m	$2,232,367	$2,232,367	B
Distribution system - nutrients	$8.90/linear m	$29,271	$29,271	C
Flash hydrolysis system	$19,481/ha	$3,486,938	$3,486,938	D
Flash hydrolysis heat exchanger	$1,248/ha	$223,379	$223,379	E
Harvesting system	$12,517/ha	$2,240,410	$2,240,410	F
HTL and catalytic upgrade system	$18,531/ha	$3,317,801	$3,317,801	G
HTL heat exchanger	$1,248/ha	$223,379	$223,379	E
HTM system	$81,938/reactor	$611,085		H
HTM heat exchanger	$1,248/ha	223,379		E
AP system	$81,938/reactor		$611,085	H
Oil storage (1 yr)	$50/barrel	$8,949	$8,949	
Intermediate product storage (30 days)	$50/barrel	$8,949	$8,949	
Fuel storage (30 days)	$50/barrel	$8,949	$8,949	
Miscellaneous infrastructure costs	$342/ha	$61,250	$61,250	I
Land (total = pond area + peripherals)	$1,590/ha	$355,741	$355,741	
Waste treatment (blow down)	$1,146/ha	$205,191	$205,191	
TOTAL INFRASTRUCTURE COST		$14,409,451	$14,186,703	
CONSTRUCTION AND MAJOR EQUIPMENT COSTS				
Clearing and grubbing	$8,713/ha	$1,559,454	$1,559,454	
Excavation	$9.50/bank m^3	$918,719	$918,719	J
Fine grading – lagoon bottoms (@ 90%)	$3.80/$m^2$	$416,024	$416,024	K
Fine grading – lagoon tops (@ 10%)	$0.5/$m^2$	$6,126	$6,126	
Fine grading – slopes (gentle finish)	$0.2/$m^2$	$18,633	$18,633	
Gas sumps, aerators (for CO_2 delivery)	$2,288/piece	$671,196	$671,196	L
Geotextile	$3/$m^2$	$272,704	$272,704	M
Gravel	$0.02/kg	$232,987	$232,987	N
Paddle wheels	$573/piece	$1,026,420	$1,026,420	
Steel – tanks	$0.28/kg	$3,281	$3,281	
Settling ponds (for algae harvest)	$2,293/ha	$219,207	$219,207	
Water pumps	$716/piece	$50,956	$50,956	O
TOTAL COST FOR CONSTRUCTION AND MAJOR EQUIPMENT		$5,395,709	$5,395,709	
MISCELLANEOUS COSTS				
Start-up		$979,258	$979,089	P
Engineering and contingencies		$2,970,774	$2,937,267	Q
Working capital		$5,941,548	$5,874,535	R
TOTAL MISCELLANEOUS COSTS		$9,902,580	$9,790,891	S
TOTAL INITIAL OUTLAY		$29,707,741	$29,372,673	

A. Assume 100 ft/ha (30.5 m/ha) for algae media, water supply; PVC Class 150, 3”-diameter; excludes excavation or backfill.
B. Assume 800 m/ha; polyethelyene, 60 PSI, 1.25”-diameter, @100’ ft, coupling, SDR 11, excludes excavation or backfill.
C. Assume 60 ft/ha (18.3 m/ha) for inflows of nutrient solution.

D. $52,000,000 HTL system cost per 221,920 Mg LEA processed/year. Our incoming biomass is 83.14 Mg/year. Assume linearity.
E. 4 heat exchangers for a 200 Mg/d system = $8,789,880 installed 2012 price, 2017 price = $10,953,790 2017, we need 41.6 Mg DS/year. Use two heat exchangers per system. Assume linearity.
F. $41,000,000 harvesting cost per 136,260 Mg DS produced/year. Our DS yield is 41.6 Mg DS/year. Assume linearity.
G. $117,800,000 HTL system plus hydrocracking and hydrotreating per 221,920 Mg LEA processed/year. Our FH BI incoming is 34.92 Mg/year. Assume linearity.
H. Volumetric flow rate = 0.56m3/d. C= a + b*Sn. C = 61,500 + 32,500 (0.56)0.8. Residence time of 1 hr. Assume linearity.
I. Assumed price per hectare includes service facilities, instrumentation, and machinery.
J. Excavated areas are as follows: long ends, cones, divider levees, interior levees, top circles, bottom circles. Total excavated volume is 47.7 m3 per 1-ha. Total area to be excavated is 481 m2 per ha. Price assumes trench or continuous footing, common earth, 3/8 CY excavator, 1-4' deep; excludes sheeting or dewatering.
K. Lagoon bottoms to be graded for paving with grader; lagoon tops to be graded for compaction.
L. Lake aeration system, 110/220-volt motor, 9.2 amp @ (110v), 4.8amp @ (220v), 10psi-10.0 cfm open air flow (pumps air to 20’ depth).
M. Geotextile dimensions are calculated as twice the walkway area to account for the slopes: (2*4658*x ha/FU*0.05) = 41 m2/ha @ 5%.
N. Compacted gravel layer is 4’-deep, covering 10% of pond area, mostly near paddlewheels and other erosion-prone areas.
O. Price based on *Pentair Whisperflo* pool pump: controllable, single phase, 2 HP.
P. 5% of total infrastructure cost AND total cost for construction and major equipment.
Q. 15% of total infrastructure cost AND total cost for construction and major equipment.
R. 25% of total direct capital.
S. Sum of total infrastructure cost, total cost for construction and major equipment, start-up, and engineering and contingencies.

Table C3. Cost Data Pertains to Initial Outlays for Open Pond System Generating HRJ and Utilizing HTM or AP for Co-product Generation

Item	Unit Price	Total Outlay – HTM	Total Outlay – AP	Notes
INFRASTRUCTURE				
Buildings, roads, drainage	$3,139/ha	$869,534	$869,534	
Distribution system - electricity	$3,1399/ha	$869,534	$869,534	
Distribution system - water	$8.90/linear m	$75,505	$75,505	A
Distribution system - gases	$15.60/linear m	$3,455,089	$3,455,089	B
Distribution system - nutrients	$8.90/linear m	$45,303	$45,303	C
Flash hydrolysis system	$19,481/ha	$5,396,818	$5,396,818	D
Flash hydrolysis heat exchanger	$1,248/ha	$345,729	$345,729	E
Harvesting system	$12,517/ha	$3,467,537	$3,467,537	F
HTL and catalytic upgrade system	$18,531/ha	$5,135,041	$5,135,041	G
HTL heat exchanger	$1,248/ha	$345,729	$345,729	E
HTM system	$81,938/reactor	$945,791		H
HTM heat exchanger	$1,248/ha	$345,729		E
AP system	$81,938/reactor		$945,791	H
Oil storage (1 yr)	$50/barrel	$13,851	$13,851	
Intermediate product storage (30 days)	$50/barrel	$13,851	$13,851	
Fuel storage (30 days)	$50/barrel	$13,851	$13,851	
Miscellaneous infrastructure costs	$342/ha	$94,798	$94,798	I
Land (total = pond area + peripherals)	$1,590/ha	$550,590	$550,590	
Waste treatment (blow down)	$1,146/ha	$317,580	$317,580	
TOTAL INFRASTRUCTURE COST		$22,301,859	$21,956,131	
CONSTRUCTION AND MAJOR EQUIPMENT COSTS				
Clearing and grubbing	$8,713/ha	$2,413,605	$2,413,605	
Excavation	$9.50/bank m^3	$1,421,925	$1,421,925	J
Fine grading – lagoon bottoms (@ 90%)	$3.80/$m^2$	$643,891	$643,891	K
Fine grading – lagoon tops (@ 10%)	$0.5/$m^2$	$9,482	$9,482	
Fine grading – slopes (gentle finish)	$0.2/$m^2$	$28,839	$28,839	
Gas sumps, aerators (for CO_2 delivery)	$2,288/piece	$1,038,826	$1,038,826	L
Geotextile	$3/$m^2$	$422,071	$422,071	M
Gravel	$0.02/kg	$360,600	$360,600	N
Paddle wheels	$573/piece	$1,588,616	$1,588,616	
Steel – tanks	$0.28/kg	$5,078	$5,078	
Settling ponds (for algae harvest)	$2,293/ha	$339,273	$339,273	
Water pumps	$716/piece	$78,865	$78,865	O
TOTAL COST FOR CONSTRUCTION AND MAJOR EQUIPMENT		$8,351,071	$8,351,071	
MISCELLANEOUS COSTS				
Start-up		$1,532,646	$1,515,360	P
Engineering and contingencies		$4,597,939	$4,546,080	Q
Working capital		$9,195,879	$9,092,160	R
TOTAL MISCELLANEOUS COSTS		$15,326,465	$15,153,601	S
TOTAL INITIAL OUTLAY		$45,979,395	$45,460,802	

A. Assume 100 ft/ha (30.5 m/ha) for algae media, water supply; PVC Class 150, 3”-diameter; excludes excavation or backfill.
B. Assume 800 m/ha; polyethelyene, 60 PSI, 1.25”-diameter, @100’ ft, coupling, SDR 11, excludes excavation or backfill.
C. Assume 60 ft/ha (18.3 m/ha) for inflows of nutrient solution.
D. $52,000,000 HTL system cost per 221,920 Mg LEA processed/year. Our incoming biomass is 83.14 Mg/year. Assume linearity.

E. 4 heat exchangers for a 200 Mg/d system = $8,789,880 installed 2012 price, 2017 price = $10,953,790 2017, we need 41.6 Mg DS/year. Use 2 heat exchangers per system. Assume linearity.
F. $41,000,000 harvesting cost per 136,260 Mg DS produced/year. Our DS yield is 41.6 Mg DS/year. Assume linearity.
G. $117,800,000 HTL system plus hydrocracking and hydrotreating per 221,920 Mg LEA processed/year. Our FH BI incoming is 34.92 Mg/year. Assume linearity.
H. Volumetric flow rate = 0.56m3/d. C= a + b*Sn. C = 61,500 + 32,500 (0.56)0.8. Residence time of 1 hr. Assume linearity.
I. Assumed price per hectare includes service facilities, instrumentation, and machinery.
J. Excavated areas are as follows: long ends, cones, divider levees, interior levees, top circles, bottom circles. Total excavated volume is 47.7 m3 per 1-ha. Total area to be excavated is 481 m2 per ha. Price assumes trench or continuous footing, common earth, 3/8 CY excavator, 1-4' deep; excludes sheeting or dewatering.
K. Lagoon bottoms to be graded for paving with grader; lagoon tops to be graded for compaction.
L. Lake aeration system, 110/220-volt motor, 9.2 amp @ (110v), 4.8amp @ (220v), 10psi-10.0 cfm open air flow (pumps air to 20' depth).
M. Geotextile dimensions are calculated as twice the walkway area to account for the slopes: (2*4658*x ha/FU*0.05) = 41 m2/ha @ 5%.
N. Compacted gravel layer is 4'-deep, covering 10% of pond area, mostly near paddlewheels and other erosion-prone areas.
O. Price based on *Pentair Whisperflo* pool pump: controllable, single phase, 2 HP.
P. 5% of total infrastructure cost AND total cost for construction and major equipment.
Q. 15% of total infrastructure cost AND total cost for construction and major equipment.
R. 25% of total direct capital.
S. Sum of total infrastructure cost, total cost for construction and major equipment, start-up, and engineering and contingencies.

APPENDIX D: CHAPTER 3 ANNUAL CASH FLOWS

Table D1. Annual Cash Flows for Operation of Open Pond System Generating RDII and utilizing HTM or AP for Co-product Generation. Direct Land Use is 334 ha

Item	Annual Cash Flow – HTM	Annual Cash Flow – AP	Notes
REVENUES			
Total RD II produced @ $2.89/gallon	$6,368,280	$6,368,280	A
Propane fuel mix produced @ $0.301 per lb	$327,478	$327,478	B
Dittmarite credits @ $200/Mg		$1,433,330	
Hydroxyapatite credit @ $500/Mg	$1,815,581		
TOTAL REVENUES	$8,511,338	$8,129,087	
EXPENSES AND OPERATING COSTS			
PROCESS COSTS			
CO_2 (from recycled flue gas) @ $44/Mg CO_2	$868,360	$868,360	
Nutrients @ $463/Mg $H_{22}N_3O_4P$	$299,104	$299,104	
Mineralizer @ 100 per Mg	$2,477	$2,477	
Labor and overhead	$307,468	$307,468	C
Other miscellaneous materials	$30,747	$30,747	D
ENERGY COSTS			
Direct electricity @ $0.0856/kWh	$443,227	$468,536	
Direct natural gas @ $2.37/mmbtu	$187,002	$167,837	
Other power	$237,595	$238,278	E
INDIRECT COSTS			
Contingency	$184,695	$182,612	F
Maintenance and insurance	$64,643	$63,914	G
TOTAL EXPENSES AND OPERATING COSTS	$2,625,287	$2,629,302	
INCREMENTAL CASH FLOWS			
(-) Depreciation	$1,477,557	$1,460,892	H
Operating income	$4,408,494	$4,038,892	
(-) Tax (at 23.6%)	$1,040,405	$953,179	
Net operating profit after tax (NOPAT)	$3,368,089	$3,085,714	
(+) Depreciation	$1,477,557	$1,460,892	
GROSS ANNUAL CASH FLOW	$4,845,647	$4,546,606	

A. RDII yield (in Mg/ha) × direct land use (in ha) × 7.14 barrels/Mg RDII) × 42 gallon/barrel × $2.89/gallon.
B. Propane Fuel Mix yield (in MJ/ha)) × direct land use (in ha) × (1kg/44.02MJ) x (1lb/0.45kg) x $0.301/lb
C. $10/hr x 8 hrs/day x 330 days/yr x 1 person/50 ponds x 1 pond/ha x direct land use. Overhead assumed to be 60% of labor.
D. Assumed to be 10% of labor and overhead.
E. Assumed to be 10% of process cost and direct energy.
F. Assumed to be 10% of total infrastructure cost.
G. Annual maintenance and insurance is assumed to be 3.5% of the respective depreciable bases (Benemann and Oswald (1996).
H. Calculated assuming an 11-year MACRS depreciation schedule (*How to Depreciate Property – IRS Instructional Form CAT No. 13081F*, 2011) and a 23.6% average marginal tax rate for the US (Hassett & Mathur, 2011).

Table D2. Annual Cash Flows for Operation of Open Pond System Generating RG and utilizing HTM or AP for Co-product Generation. Direct Land Use is 179 ha

Item	Annual Cash Flow – HTM	Annual Cash Flow – AP	Notes
REVENUES			
Total RG produced @ $2.38/gallon	$1,479,549	$1,479,549	A
Product gas produced @ $0.114 per lb	$383,204	$383,204	B
LCO produced @ $0.248 per lb	$625,528	$625,528	C
CSO produced @ $0.117 per lb	$514,664	$514,664	D
Dittmarite credits @ $200/Mg		$768,493	
Hydroxyapatite credit @ $500/Mg	$973,441		
TOTAL REVENUES	$3,976,386	$3,771,439	
EXPENSES AND OPERATING COSTS			
PROCESS COSTS			
CO_2 (from recycled flue gas) @ $44/Mg CO_2	$465,580	$465,580	
Nutrients @ $463/Mg $H_{22}N_3O_4P$	$160,367	$160,367	
Mineralizer @ 100 per Mg	$1,312	$1,312	
Labor and overhead	$164,852	$164,852	E
Other miscellaneous materials	$16,485	$16,485	F
ENERGY COSTS			
Direct electricity @ $0.0856/kWh	$248,425	$261,995	
Direct natural gas @ $2.37/mmbtu	$100,263	$89,998	
Other power	$128,587	$128,953	G
INDIRECT COSTS			
Contingency	$99,026	$97,909	H
Maintenance and insurance	$34,659	$34,268	I
TOTAL EXPENSES AND OPERATING COSTS	$1,419,556	$1,421,709	
INCREMENTAL CASH FLOWS			
(-) Depreciation	$792,206	$783,271	J
Operating income	$1,764,624	$1,566,459	
(-) Tax (at 23.6%)	$416,451	$369,684	
Net operating profit after tax (NOPAT)	$1,348,173	$1,196,774	
(+) Depreciation	$792,206	$783,271	
GROSS ANNUAL CASH FLOW	$2,140,379	$1,980,046	

A. RG yield (in Mg/ha) x direct land use (in ha) x 7.14 barrels/Mg RG) x 42 gallon/barrel x $2.38/gallon.
B. Product Gas yield (in MJ/ha)) x direct land use (in ha) x (1kg/42.6MJ) x (1lb/0.45kg) x $0.114/lb.
C. LCO yield (in MJ/ha)) x direct land use (in ha) x (1kg/44.9MJ) x (1lb/0.45kg) x $0.248/lb.
D. CSO yield (in MJ/ha)) x direct land use (in ha) x (1kg/43.6MJ) x (1lb/0.45kg) x $0.177/lb.
E. $10/hr x 8 hrs/day x 330 days/yr x 1 person/50 ponds x 1 pond/ha x direct land use. Overhead assumed to be 60% of labor.
F. Assumed to be 10% of labor and overhead.
G. Assumed to be 10% of process cost and direct energy.
H. Assumed to be 10% of total infrastructure cost.
I. Annual maintenance and insurance is assumed to be 3.5% of the respective depreciable bases (Benemann and Oswald (1996).
J. Calculated assuming an 11-year MACRS depreciation schedule and a 23.6% average marginal tax rate for the US (Hassett & Mathur, 2011).

Table D3. Annual Cash Flows for Operation of Open Pond System Generating HRJ and utilizing HTM or AP for Co-product Generation. Direct Land Use is 277 ha

Item	Annual Cash Flow – HTM	Annual Cash Flow – AP	Notes
REVENUES			
Total RJF produced @ $2.24/gallon	$3,459,336	$3,459,336	A
Propane produced @ $0.301 per lb	$1,452,491	$1,452,491	B
Naphtha produced @ $0.647 per lb	$998,367	$998,367	C
Dittmarite credits @ $200/Mg	$1,506,618	$1,189,416	
Hydroxyapatite credit @ $500/Mg			
TOTAL REVENUES	$7,416,812	$7,099,610	
EXPENSES AND OPERATING COSTS			
PROCESS COSTS			
CO_2 (from recycled flue gas) @ $44/Mg CO_2	$720,589	$720,589	
Nutrients @ $463/Mg $H_{22}N_3O_4P$	$248,205	$248,205	
Mineralizer @ 100 per Mg	$2,031	$2,031	
Labor and overhead	$159,466	$159,466	D
Other miscellaneous materials	$15,947	$15,947	E
ENERGY COSTS			
Direct electricity @ $0.0856/kWh	$365,012	$386,014	
Direct natural gas @ $2.37/mmbtu	$248,205	$230,243	
Other power	$195,266	$195,833	F
INDIRECT COSTS			
Contingency	$153,265	$151,536	G
Maintenance and insurance	$53,643	$53,038	H
TOTAL EXPENSES AND OPERATING COSTS	$2,159,567	$2,162,899	
INCREMENTAL CASH FLOWS			
(-) Depreciation	$1,226,117	$1,212,288	I
Operating income	$4,031,128	$3,742,422	
(-) Tax (at 23.6%)	$951,346	$878,964	
Net operating profit after tax (NOPAT)	$3,079,782	$2,845,459	
(+) Depreciation	$1,226,117	$1,212,288	
GROSS ANNUAL CASH FLOW	$4,305,899	$4,057,747	

A. RJF yield (in Mg/ha) x direct land use (in ha) x 7.14 barrels/Mg RJF) x 42 gallon/barrel x $2.38/gallon.
B. Propane yield (in MJ/ha)) x direct land use (in ha) x (1kg/43.2MJ) x (1lb/0.45kg) x $0.643/lb.
C. Naphtha yield (in MJ/ha)) x direct land use (in ha) x (1kg/44.38MJ) x (1lb/0.45kg) x $0.647/lb.
D. $10/hr x 8 hrs/day x 330 days/yr x 1 person/50 ponds x 1 pond/ha x direct land use. Overhead assumed to be 60% of labor.
E. Assumed to be 10% of labor and overhead.
F. Assumed to be 10% of process cost and direct energy.
G. Assumed to be 10% of total infrastructure cost.
H. Annual maintenance and insurance is assumed to be 3.5% of the respective depreciable bases (Benemann and Oswald (1996).
I. Calculated assuming an 11-year MACRS depreciation schedule and a 23.6% average marginal tax rate for the US (Hassett & Mathur, 2011).

VITA

EDUCATION

Doctor of Philosophy, Civil and Environmental Engineering **May 2018**
Old Dominion University, Norfolk, VA
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Masters of Science, Environmental Engineering **August 2015**
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Masters of Science, Management **December 2010**
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Thesis: *Utilizing Employee Empowerment for Organizational Change*
Bachelors of Science, Bio-Resource Engineering **May, 2002**
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AWARDS

- ODU 2018 CEE Department Excellent Graduate Research Assistant of the Year
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JOURNAL PUBLICATIONS

- Bessette, A.; Teymouri, A.; Martin M.; Stuart, B.; Resurreccion, E.; Kumar, S., Life Cycle Impacts and Techno-economic Implications of Flash Hydrolysis in Algae Processing. *ACS Sustainable Chemistry & Engineering 2017*.

PRESENTATIONS

- Algae Biomass Summit. October 2017. Oral Presentation. “Evaluation of Flash Hydrolysis in Algae Processing: A Combined Life Cycle and Techno-Economic Approach”. Presented by: Andrew Bessette. Author list: Andrew P. Bessette, Ali Teymouri, Mason J. Martin, Ben J. Stuart, Eleazer P. Resurreccion, Sandeep Kumar.
- Algae Biomass Summit. October 2016. Oral Presentation. “Life Cycle Assessment of an Integrated Approach towards Algae Cultivation for a Sustainable Biofuels Intermediate Production and Storage”. Presented by: Andrew Bessette. Author list: Andrew P. Bessette, Ben J. Stuart, and Sandeep Kumar.
- American Society of Naval Engineers ASNE Day March 2016. Poster Presentation. “Algae Based Biofuels Life Cycle Assessment for the Great Green Fleet”. Presented by: Andrew Bessette. Author list: Andrew P. Bessette and Sandeep Kumar.
- Algae Biomass Summit. October 2015. Poster Presentation. “Life Cycle Analysis Using Argonne GREET Model of Algae Based Biofuels produced Utilizing Flash Hydrolysis Process”. Presented by: Andrew Bessette. Author list: Andrew P. Bessette, Ali Teymouri, and Sandeep Kumar.

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- LEED Green Building Associate of U.S. Green Building Council (2016)
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