2014

LIFE CYCLE ASSESSMENTS (LCAs) OF PYROLYSIS-BASED GASOLINE AND DIESEL FROM DIFFERENT REGIONAL FEEDSTOCKS: CORN STOVER, SWITCHGRASS, SUGAR CANE BAGASSE, WASTE WOOD, GUINEA GRASS, ALGAE, AND ALBIZIA

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By

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A THESIS

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

In Chemical Engineering

MICHIGAN TECHNOLOGICAL UNIVERSITY

2014

This thesis has been approved in partial fulfillment of the requirements for the Degree of MASTER OF SCIENCE in Chemical Engineering

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Preface

This thesis is based on several life cycle assessments. The waste wood life cycle assessment was completed and the corresponding section was written by Edwin Maleche and myself. The guinea grass and corn stover life cycle assessment was completed and the corresponding section was written by Jiqing Fan and myself. The remaining life cycle assessments and sections of my thesis were completed and written by myself with the help of my advisor Dr. Shonnard.

Abbreviation Definition List

Pyoil – Pyrolysis Oil

Biooil – Biofuel oil

LCA- Life Cycle Assessment

LHV- Lower Heating Value

EAF- Energy Allocation Factor

EA- Energy Allocation

LA-Low Ash

Dis. - Displacement

IBR- Integrated Biorefinery

GHG- Greenhouse Gas

RFS- Renewable Fuel Standard

ILUC- indirect Land Use Change

DLUC- direct Land Use Change

BDMTD- Bone dry metric tons per day

MDT – Million dry tons

MT- Metric tons

CW-Cooling Water

BFW- Boiler Feed Water

RTP- Rapid Thermal Process

FED- Fossil Energy Demand

CED- Cumulative Energy Demand

GWP-Global Warming Potential

Abstract

Renewable hydrocarbon biofuels are being investigated as possible alternatives to conventional liquid transportation fossil fuels like gasoline, kerosene (aviation fuel), and diesel. A diverse range of biomass feedstocks such as corn stover, sugarcane bagasse, switchgrass, waste wood, and algae, are being evaluated as candidates for pyrolysis and catalytic upgrading to produce drop-in hydrocarbon fuels. This research has developed preliminary life cycle assessments (LCA) for each feedstock-specific pathway and compared the greenhouse gas (GHG) emissions of the hydrocarbon biofuels to current fossil fuels. As a comprehensive study, this analysis attempts to account for all of the GHG emissions associated with each feedstock pathway through the entire life cycle. Emissions from all stages including feedstock production, land use change, pyrolysis, stabilizing the pyrolysis oil for transport and storage, and upgrading the stabilized pyrolysis oil to a hydrocarbon fuel are included. In addition to GHG emissions, the energy requirements and water use have been evaluated over the entire life cycle. The goal of this research is to help understand the relative advantages and disadvantages of the feedstocks and the resultant hydrocarbon biofuels based on three environmental indicators; GHG emissions, energy demand, and water utilization. Results indicate that liquid hydrocarbon biofuels produced through this pyrolysis-based pathway can achieve greenhouse gas emission savings of greater than 50% compared to petroleum fuels, thus potentially qualifying these biofuels under the US EPA RFS2 program. GHG emissions from biofuels ranged from 10.7-74.3 g/MJ from biofuels derived from sugarcane bagasse and wild algae at the extremes of this range, respectively. The cumulative energy demand (CED) shows that energy in every biofuel process is primarily from renewable biomass and the remaining energy demand is mostly from fossil fuels. The CED for biofuel range from 1.25-3.25 MJ/MJ from biofuels derived from sugarcane bagasse to wild algae respectively, while the other feedstock-derived biofuels are around 2 MJ/MJ. Water utilization is primarily from cooling water use during the pyrolysis stage if irrigation is

not used during the feedstock production stage. Water use ranges from 1.7 - 17.2 gallons of water per kg of biofuel from sugarcane bagasse to open pond algae, respectively.

Chapter 1: Introduction to Pyrolysis Based Liquid Hydrocarbon Transportation Fuels

1.1 Importance of Biofuels in the United States

1.1.1Energy Security/Reduction in Imports

As of 2007, 59% of the oil in the United States was imported from foreign countries and 69% of that oil was used in the transportation sector (Global Insight 2008). Since the U.S. relies heavy on oil imports, certain countries could cripple the U.S. economy if an oil embargo was placed on the U.S. from oil producing countries such as the oil embargo of 1973 by the Organization of the Petroleum Exporting Countries (OPEC). To improve energy security, the U.S. needs to supply its own transportation energy by producing alternatives to imported petroleum, such as biofuels. Creating biofuels in the U.S. is important because much of the economy is tied to the price of oil. If the U.S. produced its own transportation fuels, conflict in the Middle East and other oil-producing regions would not affect the U.S. economy as much. Relying heavily on oil imports could weaken the U.S. economy and strengthen foreign economies; while use of locally produced biofuels may help stabilize transportation fuel prices, create rural jobs, decrease national expenditures on imported petroleum, and generally help the U.S. economy (Global Insight 2008).

1.1.2 Water Quality

Fertilizer use contributes to eutrophication of surface water and dead zones in lakes and oceans, such as in the Gulf of Mexico starting at the Mississippi River delta. Nutrient run off causes algae blooms, which leaves the water with little oxygen. Many marine animals can’t live without this oxygen and therefore the nutrient run off creates these dead zones.

Different feedstocks require different amounts of nutrients. Feedstocks that use large amounts of nitrogen and phosphorus fertilizers could potential contribute significantly to these dead zones.

Another concern with water quality is tillage on marginal land, which moves sediments, fertilizers, and herbicides into river and lakes. Native grasses like switchgrass reduce erosion on marginal lands, which will improve water quality by reducing erosion.

1.1.3 Land Use Change

Indirect land use change (iLUC) and direct land use change (dLUC) can contribute a large amount of GHG emissions to the overall life cycle of pyrolysis based biofuels. dLUC emissions are due to changes in GHG emissions when land is converted to biofuel production; from carbon stock changes and net changes in emission of all greenhouse gases. Carbon stock changes are proportional to changes in net uptake or release of CO_2 from the atmosphere. For example, crops such as switchgrass take in CO_2 from the atmosphere as well as nutrients from the soil to grow. When switchgrass is harvested the roots are left in the soil and carbon is stored in the soil. If carbon levels above ground and in the soil increase, a GHG emission credit is given to the biofuel, but if there is less carbon in the soil due to biofuels production than the GHG emissions in the biofuel life cycle increase. iLUC emissions may occur when land currently in food crop production is used for biofuel production. While this situation could incur dLUC emissions as described above, there may also be an indirect emission when natural lands elsewhere in the world are converted to food crop production to make up for the lost food production. iLUC emissions are determined using global economic models of the agricultural sector in order to understand the effects of biofuel induced food price changes on the conversion of lands. If feedstocks are not food crops like corn, or do not use farm land then iLUC is less of a concern for that feedstock (Eisentraut 2010).

1.1.4 Other Factors Affecting GHG Emissions of Biofuels

There are many other environmental factors pertaining to biofuels that may affect the GHG emissions;

1. Choice of primary energy for heat and power
2. Distance and mode of transport for feedstocks and biofuel products
3. Fertilization for feedstock production, including N_2O emissions from the land after application.
4. The allocation of emissions to co-products

Another aspect of this LCA involves the carbon dioxide used in photosynthesis when the plant grows. This carbon dioxide could be taken as a credit but this carbon dioxide is then release when the final transportation fuel is processed and combusted. In this study this "biogenic" carbon dioxide is not accounted for during feedstock production, conversion to biofuels, or combustion, but rather a focus is taken on fossil fuels and emissions of fossil CO_2. This LCA also looks at the types of energy used to produce each biofuel (fossil and renewable) to understand how important fossil fuels are to the processing of the biofuels.

1.1.5 Jobs/Rural Development

Millions of new jobs relating to renewable transportation fuels are expected in the next several decades. Many jobs in engineering, legal, and research & consulting will also be added as a result of increasing use of alternative transportation fuels (Global Insight 2008). Rural jobs will also be created by planting energy crops, used to produce biofuels, on land that is not suitable for farming food crops. Job growth is less in rural areas compared to urban areas and rural poverty is on the rise (Ellis 2011). Biofuels production would help rural families by providing more jobs that would also help insure energy security for the United States. Green jobs, some of which would be related to biofuels production and use, could contribute up to 10% of new jobs in the United States in the next several decades (Global Insight 2008). Renewable transportation fuels have the potential to create a huge industry and create jobs for a wide variety of people in the United States.

1.2 Background on Rapid Thermal Processing of Biofuels

1.2.1 Feedstock Production

In this study, many feedstocks are being modeled from data provided by several companies and individuals as shown in table 1.2. These feedstocks are being modeled to better understand the effect of feedstock type on the environmental impacts of pyrolysis-based biofuels. Figure 1.1 shows representative locations for cultivation of the various biomass feedstocks used in this study based on information from feedstock providers in this study. Waste wood includes all the tree branches and some stumps and roots produced during lumber harvesting, assuming a location in Washington State. Corn Stover is the stalk and leaves of corn that is left in the field after corn grain harvest, and it is assumed to be cultivated in the Midwest of the U.S. Switchgrass can be grown in much of the United States as shown in Figure 1.1, especially in the Southeast and in Mid-Atlantic states. Sugarcane bagasse is a lignocellulosic waste product from sugar cane processing assuming sugar cane grown in the southern states of the U.S. and in Brazil, among other countries. Algae can be grown in regions with ample sun year-round, abundant water supplies, and where nutrient runoff causes blooms in rivers and lakes. One promising region is in the southwestern part of the United States, where land is not suitable for food crops and where sun shines most of the year, and where deep saline aquifers may provide a water resource. Guinea grass and albizia, which are invasive grass and tree species, respectively, grow wild in Hawaii. These feedstocks are being studied as possible energy crops to produce renewable hydrocarbon transportation biofuels.

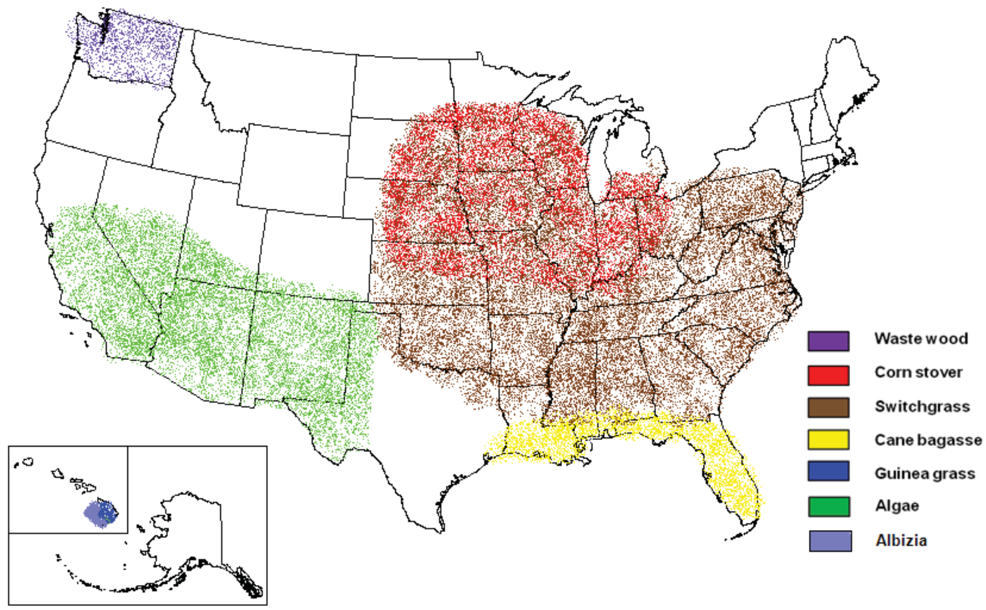

Figure 1.1: Map with locations of each feedstock in the United States

1.2.2 Land Requirements

The calculations of land required are based on an upgrading facility processing 2,800 bone dry metric tons per day (BDMTD) of biomass feedstock, which equates to 96.7 million gallons of biofuel per year based on switchgrass yields provided by Ceres. For reasons of economy of scale, a high biomass input rate is preferred for a commercial-scale advanced biofuel production facility. Multiple satellite pyrolysis facilities would provide the liquid feedstock to the upgrading facility. Using the data inputs from each feedstock provider and the assumed 2,800 BDMTD facility input rate, the amount of land that is required was calculated and is shown in the Table 1.1 below. The land required for wild algae could not be calculated because the yield, or concentration, was given in terms of a volume (m^3). The energy per unit area is also calculated using the yield and lower heating value (LHV) and is shown in the table below.

Table 1.1: Land and Energy Requirements for a 2,800 BDMTD for each Feedstock

Feedstocks	Yields (MT/ha /yr)	LHV (MJ/kg)	Hectares	acres	mi^2	Energy (GJ/ha)
Switchgrass	13.6	16.4	75,400	186,200	291	222
Guinea grass (managed)	19.4	14.8	52,700	130,100	203	287
Guinea grass (unmanaged)	9.7	14.8	105,000	260,200	407	143
Wild Algae		16.4				
Open pond Algae	91	20	11,200	27,700	43.4	1,820
Waste wood	2.5	20	409,000	1,010,000	1578	50
Corn stover	6.3	16.7	162,000	401,000	626	105
Cane bagasse	24.6	13.7	41,500	103,000	160	336
Albizia	22.4	20	45,600	112,700	176	448

Table 1.1 shows that the open pond algae has the highest yield and therefore requires the least amount of area while waste wood has the lowest yield and therefore requires the most land. Open pond algae has the highest yield and highest LHV and therefore the highest energy per unit area. Waste wood has the lowest yield and highest LHV, but because the yield is so low the energy per unit area is the lowest out of all the feedstocks. The sources and references for the yields and LHV data are shown in Table 1.2 below.

Table 1.2: Yield and LHV references for each feedstock

Feedstocks	Yield sources and references	LHV sources and references
Switchgrass	Ceres [(1)]	UOP[(Inc.)]
Guinea grass (managed)	David Ringuette [(3)]	UOP
Guinea grass (unmanaged)	David Ringuette	UOP
Wild Algae	No data	UOP
Open pond Algae	(Stratton et al. 2010)	Assumption
Waste wood	U.P. Survey	Grays Harbor [(4)]
Corn stover	(Morey et al. 2010)	(Morey et al. 2010)
Cane bagasse	(U.S. Department of Energy 2011)	(CARB 2009a)
Albizia	(Tenbruggencate 2008)	Assumption

(1) Contact Sam Harris and Spencer Swayze

(2) Contact Tom Kalnes

(3) University of Hawaii consultant to Imperium

(4) Contact Bruce McComas

1.2.3 Feedstock Availability

It is important to know how much of each feedstock is available. If it is not possible to obtain large amounts of each feedstock it will not be possible to make large quantities of biofuels. Also, the feedstock must be harvested in a sustainable manner to insure economic, social, and environmental sustainability. Table 1.3 below shows the amount of feedstock that can be sustainable harvested in the United States according to a recent national study.

Table 1.3: The amount of feedstock that is available annually and can be sustainably harvested in million dry metric tons per year (MDT) (U.S. Department of Energy 2011)

	Feedstock Availability (MDT/yr)
Waste wood	45
Corn Stover	20
Sugarcane bagasse	1.1

This study assumed that seven 400 BDMTD RTP satellite units, which would produce stabilized pyrolysis biooil feedstock for a central upgrading unit, and this approximately equates to 1 million dry metric tons/yr. This shows that even sugarcane bagasse, could still produce enough biomass for a central upgrading unit. Therefore, the available waste wood and stover feedstocks could produce stabilized pyrolysis biooil for approximately 45 and 20 commercial-scale upgrading units around the United States, respectively. Other feedstocks such as algae, albizia, switchgrass, and guinea grass are not currently commercially available and the current potential feedstock amount has not been estimated. Of course, the optimum scale of a commercial advanced biofuels production facility will be a complex function of the overall biofuel economic viability, but this high level analysis provides preliminary estimates of magnitude of the number of commercial scale facilities needed to utilize the entire sustainable feedstock supply for the types listed in Table 1.3.

1.2.4 Integrated Biorefinery for Production of Biofuel

Figure 1.2 provides a simplified block flow diagram of the Integrated Bio-Refinery (IBR) concept as defined by UOP LLC, focusing only on this life cycle stage and showing some “upstream” and “downstream” inputs and outputs, as well as some products and co-products (steam and filter cake). The final products are gasoline, kerosene, and diesel, which are combined and for the purpose of this study into a functional unit called “biofuel”.

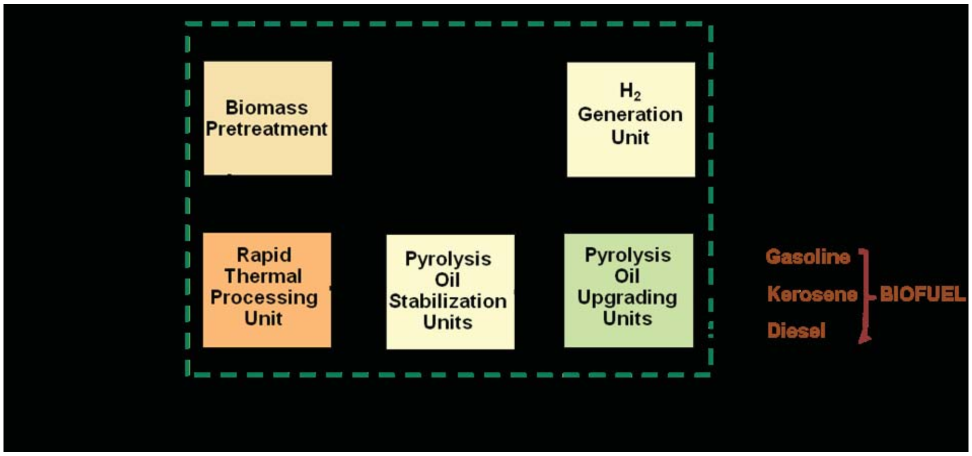

Figure 1.2: Overall process pathway configuration the IBR process. Dashed arrows indicate recycle of material and energy between processing steps. Solid arrows indicate important material flows.

1.2.5 Rapid Thermal Processing (Fast Pyrolysis)

After the biomass has been produced and transported to a pyrolysis facility, it is then converted to pyrolysis bio-oil. For this study, we assume that this pyrolysis step is done by the Ensyn (http://www.ensyn.com) Rapid Thermal Process (RTP™) technology, which is a commercially practiced fast pyrolysis process. This process feedstock is small (<6 mm) particles of dried biomass (5-6% moisture) that are rapidly heated up to 500°C by hot sand in an oxygen free atmosphere. The resultant vapors are separated from sand and char and then rapidly cooled to condense the bio-oil. This process produces by-products of char and fuel gas, which are combusted to provide process heat to dry the original biomass, and in some cases to produce a steam co-product. The main product that is produced is called pyrolysis oil or RTP™ green fuel, which is a liquid oxygenated organics (hydroxyl, carbonyl, and carboxyl group components) - based fuel. This product must be stabilized before it is stored because otherwise the oil will become too viscous due to the polymerization reactions and therefore will not be suitable for transportation fuel (Diebold and Czernik 1997).

1.2.6 Stabilization

Stabilization involves two steps. The first step filters solid char from the pyrolysis oil. This char is considered a co-product, which could be used as a stand-alone solid fuel or used to co-fire with coal. After the pyrolysis oil is filtered it is transported to the upgrading facility, where stabilization is completed. The second step in stabilization uses ion exchange to remove metals coming from the ash portion of the biomass, which are catalyst poisons. This stage also uses ethanol as a flush solvent in the ion exchange unit, which becomes part of the demetallized liquid and is later converted to ethane in the upgrading step.

1.2.7 Upgrading

After the pyrolysis oil is stabilized it is then hydroprocessed to produce three grades of hydrocarbon biofuels, which include gasoline, kerosene, and diesel. Stabilized pyrolysis oil is almost completely deoxygenated by hydrodeoxgenation and decarboxylation reactions. The required hydrogen is produced in the hydrogen generation unit (steam reforming) using the co-products, which are C1-C4 hydrocarbons generated in the upgrader and ethane from the ethanol used in the stabilization stage, as well as supplemental amounts of natural gas for feedstock and fuel. Steam is generated during both the upgrading and hydrogen generation steps and a portion of this steam is exported from the process as a co-product.

1.3 Sustainability Issues of Biomass and Biofuels

1.3.1 Sustainability Background

The production of pyrolysis based biofuels has the potential to be economically, socially, and environmentally sustainable, depending on which feedstock is used to produce the biofuel. For example, the commercial implementation of cellulosic biofuel technology will stimulate the market for agricultural by-products like sugar cane bagasse, corn stover, and forest residues and provide the opportunity for farmers or woody biomass producers to increase the amount of revenue per unit area. Additional rural jobs will be created to harvest and transport these residual feedstocks, and engineers and operators will be employed to convert these feedstocks into biofuels. Finally, biofuels are good for the environment because they would replace fossil fuels, which in most cases emit higher levels of GHG emissions (Eisentraut 2010).

When looking at the environmental acceptability of pyrolysis based biofuels, the feedstock used to produce these biofuels needs to be cultivated and harvested in a sustainable manner. There are many sustainability criteria that could be used to evaluate biofuels, including GHG emissions and savings, which will be discussed thoroughly in other sections of this thesis, soil erosion, nutrient runoff and leaching, land use change, water use, and biomass yield. Erosion must be minimized so valuable soil and nutrients are not lost. Fertilizer use should be controlled and reduced because fertilizers are derived from fossil fuels, and runoff / leaching cause water pollution and surface water eutrophication (excess algae growth and then oxygen depletion). Feedstocks should not compete with food crops because of the potential to increase global food prices and impact from iLUC GHG emissions. Minimal or no irrigation should be used to conserved fresh water, which will be discussed in another section. Lastly, the biomass yield needs to be considered because higher yields would require less land for any given biofuels production target.

1.3.2 Switchgrass/Guinea Grass Sustainability Issues

Switchgrass and guinea grass show potential as a feedstock for biofuels production because many aspects associated with these feedstocks are sustainable. As energy crops they have several attributes including high yields, relatively small nutrient inputs, and the ability to grow on marginal lands. Because these crops can be grown on marginal lands, they would not directly compete with food crops, thereby avoiding food price inflation and iLUC effects. Since the yields are high compared to other biomass resources (corn stover for example), less land would be devoted to feedstock production if they were used as a biofuel feedstock. Finally, according to the feedstock suppliers in our study, neither of these crops require irrigation which is beneficial for water conservation.

Guinea grass currently grows wild on the Hawaiian Islands and is concentrated on abandoned pineapple plantations. Guinea grass could be harvested now on unmanaged land, which would result in far less inputs but the yield would be reduced by half of what is possible with managed land (Table 1.1). With no inputs from fertilizers, less fossil fuels would be required, because fossil fuels are used to produce fertilizers. However, more fuel would be used in the harvest stage because twice as much land would be required than if the land was managed.

Growing exclusively switchgrass would limit biodiversity, which could lead to a greater risk of plant disease and reduced wildlife diversity. However, if other native grasses were grown with switchgrass this would increase the biodiversity of the plantations and decrease these negative effects. Switchgrass is also native to North America so there is little threat that this feedstock will become invasive like other potential feedstocks (U.S. Department of Energy 2011).

1.3.3 Waste Wood Sustainability Issues

Waste wood has no fertilizer requirements, does not require irrigation, and does not compete with food crops. However, waste wood exhibits the lowest yield compared to other feedstocks in this study, which means that waste wood derived biofuels require more land to produce the same amount of biofuels when compared to other feedstocks. Less inputs like fertilizers result in lower GHG emissions and decreased fossil fuel use, but relatively longer transportation distances for waste wood would be a disadvantage. There are also no water inputs for irrigation, which is beneficial to water conservation. Finally, waste wood does not compete with food production and as a result would have no iLUC emissions associated with a biofuels produced from this feedstock.

Waste wood serves many purposes in the forests of the United States. These branches serve as natural habits for wild life and some plants grow in rotten and decaying wood. Also, once the wood decays it returns nutrients to the soils that are essential to the forest. Waste wood also helps reduce erosion, which could remove a lot of soil and nutrients that are needed for a healthy forest. When using waste wood as a biofuel feedstock, the natural processes should be considered when deciding on at how much waste can be sustainably removed (U.S. Department of Energy 2011).

1.3.4 Crop Residues Sustainability Issues

Crop residues like corn stover and sugar cane bagasse provide many environmental benefits to the ecosystem. Harvesting too much corn stover could result in an increase in agricultural soil erosion, which could result in a large amount of soil and nutrient contamination in local water systems. Also, residues trap moisture in the soil and replenish the soil with nutrients. Only a certain percent of residues can sustainably be harvested. Sustainable harvest is based on two criteria, the soil loss limit cannot be exceeded, and there can be no long-term loss of soil organic matter (U.S. Department of

Energy 2011). By meeting these two criteria crop residues can be harvested for biofuel production. Sugar cane residues can also be harvest but most of the residue called bagasse is currently being used as a fuel and only a portion of the residue called waste is recommended by the billion ton study to be used as a feedstock (U.S. Department of Energy 2011).

The use of corn stover as a biofuel feedstock does require fertilizers to be returned to corn fields to replace the nutrients lost from corn stover collection. Reliance on fertilizers and fossil fuels is a disadvantage compared to other feedstocks like sugarcane bagasse, which do not require fertilizers. Corn stover is viewed as a waste product in this study and therefore does not carry any burden from corn cultivation and harvesting. One of the scenarios in this thesis looks at stover as a co-product, where these corn-related burdens are accounted for. Unlike corn stover, sugarcane bagasse is collected from a sugar production facility and therefore no fertilizer losses are associated with bagasse use as a biofuel feedstock because bagasse is removed from the land as a normal part of cane processing. Sugarcane is not produced as much as corn in the United States so much more corn stover is available domestically and therefore more domestic biofuel could be produced.

1.3.5 Algae Sustainability Issues

In this study both wild algae and open pond algae are investigated as possible feedstocks. Wild algae has many sustainable benefits including no inputs to cultivate because nutrients are from runoff from agriculture and other lands and for cases where algae is grown using nutrients in wastewater. This latter case can potentially realize a credit for avoided emissions during wastewater treatment. Open pond algae is cultivated in efficient engineered systems. Both types of algae have high yields, high energy densities, and do not directly compete with food production. Because wild algae grows naturally in water from the nutrients available, no inputs for wild algae cultivation is required. In contrast, open pond algae requires inputs such as fertilizers and carbon dioxide but requires less electricity to harvest than wild algae because raceway algae grows to higher density. Algae grown in wastewater helps eliminate nutrients in effluents that may need to be removed during secondary wastewater treatment. Both types of algae have no iLUC impacts because open pond algae can be grown in raceway ponds where agriculture is not suitable, and wild algae grows naturally and does not use land where food crops can be produced. Another benefit is that a large amount of biomass energy can be harvested from algae in a small area because of the high biomass yields.

1.3.6 Albizia Sustainability Issues

Albizia is an invasive tree that grows on the Hawaiian Islands. This tree has many sustainable qualities that could make this a good feedstock. Albizia is a nitrogen-fixing plant, and therefore requires no N fertilizer inputs, it grows 60 feet after ten years, and sequesters carbon in the soil on abandoned pineapple plantation. Albizia can be grown in low nutrient soils and this tree grows rapidly which would increase the yield compared to other biomass feedstocks.

1.4 A Review of LCA of Pyrolysis-Based Biofuels and Bioenergy

There are several published reports that address LCA of pyrolysis based fuels and power. The Kauffman et al. study (Kauffman et al. 2011) was based on a similar pyrolysis process (similar to the Envergent process). This study was based on corn stover as the feedstock. The biofuel pathway included feedstock production, pyrolysis, upgrading and biofuel use in vehicles, but did not include stabilization prior to upgrading. Kauffman et al. (2011) apply large displacement credits to the diesel product for co-products gasoline and biochar. Credits were also applied for sequestering atmospheric C in the biochar. The study assumed that the pyrolysis stage was fully integrated so there were no other process inputs, such as heat and electricity, downstream of the biomass pretreatment. The last difference compared to this study is that Kauffman et al. (2011) used the LCA model

GREET, which is a tool developed by the Department of Energy to estimate GHG emissions of alternative-fuel vehicle transportation pathways, while this study (UOP-MTU) used SimaPro software to determine the GHG emissions. In this study gasoline is one of the main components of the final product called a mixed biofuel. This mixed biofuel includes gasoline, kerosene, and diesel. Also, in the UOP-MTU LCA study biochar is combusted and the resultant heat is used internally to displace fossil fuels and therefore no excess char or sequestration of C in the char is taken into account. The UOP-MTU study considers other co-products, steam from several of the processing stages as well as filter cake (a solid fuel) from the stabilization process. There are also many inputs in pyrolysis including electricity that Kauffman et al. (2011) does not consider based on integration of the process within an existing facility.

The Hsu report (Hsu 2011) used mass and energy balance inputs from a PNNL report (Jones et al. 2009) for the pyrolysis and upgrading inputs, which are similar to UOP-MTU study inputs. The PNNL study considered forest residues as the feedstock. The Hsu report however had 27% of the net GHG emissions come from electricity production and only 6% of the GHG emissions came from hydrogen production. The Hsu report chose the ecoprofile "Natural gas, high pressure, at consumer/RER" and replaced the electricity usage with US grid electricity. This selection of natural gas as source of hydrogen does not account for all of the CO_2 emissions generated during the steam methane reforming process to produce hydrogen. There is an emission of CO_2 in the Hsu report for upgrading but it does not agree stoichiometrically to the amount that would be produced by the natural gas that was used to produce the hydrogen through steam reforming. Also, in this report stabilization was not considered nor were there any credits for steam co-production. (Jones et al. 2009).

The Fan et al. report (Fan et al. 2011) modeled the life cycle impacts of producing pyrolysis oil from several woody feedstocks, and with the pyrolysis oil being combusted to produce electricity. The inputs for feedstock production, pretreatment, and pyrolysis are similar to this current UOP-MTU study except there was no steam generated during pyrolysis and less electricity was used in the pyrolysis step in the Fan et al. study (2011). Also, the transportation distance is higher for forest residues in the Fan et al. (2011) study. For this UOP-MTU study the transportation distances for forest residues are similar to the poplar and willow transportation distances in the Fan et al. (2011) report.

Although there are prior studies and reports on the LCA of pyrolysis-based liquid transportation biofuels, there are also limitations to these prior studies. There is a relative lack of focus on different biomass feedstocks and what effects that feedstocks have on the LCA results, particularly the impact of feedstock on greenhouse gas emissions is not well understood. Pyrolysis-based biofuel production is a fast evolving technology and there is a continued need to update prior LCAs with new inputs, such as inputs for stabilization. Based on these limitations, the following research objectives are identified.

1.5 Research Objectives

1. Develop complete LCA analyses for the production of each feedstock on the basis of 1 dry metric ton of feedstock.
2. Develop complete LCA analyses for stabilized pyrolysis oils from each feedstock on the basis of 1 MJ of stabilized pyrolysis oil.
3. Develop complete LCA analyses for each pyrolysis-based biofuels on the basis of 1 MJ of total transportation fuel produced (gasoline+diesel+kerosene).
4. To gain an understanding of the relative importance of biofuel pathway stages by organizing LCA results for each feedstock-specific pyrolysis-based biofuel around each stage.
5. To investigate the relative importance of key LCA inputs through scenario analyses
6. Make recommendations on ways to reduce environmental impacts of pyrolysis-based biofuels produced from select biomass feedstocks.

Chapter 2: Life Cycle Assessment: Background and Assumptions

2.1 Goal and Scope

The main goal of this life cycle assessment (LCA) is to help the research sponsor, UOP LLC (a Honeywell Company), to understand the environmental impacts of producing and using pyrolysis-based liquid transportation fuels from a range of biomass feedstocks. Results from this research will be used by the sponsor to help make engineering design decisions with regard to unit operations choices and operating conditions. The scope of the study is limited to four impacts; the GHG emissions, cumulative energy demand (CED), fossil energy demand (FED), and water use for the entire life cycle of each pyrolysis-based biofuel.

2.2 Target Audience

Many people may read this thesis, including the DOE, UOP, facility, staff, and students from MTU and other university, and other LCA experts. This thesis is intended to give detailed information on inputs and a scientific discussion on the results. Background information will also be provided on the IBR processing stages, including pyrolysis, stabilization, and upgrading, as well as feedstock production.

2.3 Functional Unit

This thesis is organized into three sections. Each section utilizes a different functional unit. The first section is feedstock production and the functional unit is one dry metric ton of biomass feedstock. The next section includes feedstock pretreatment, pyrolysis, and stabilization and the functional units examined are 1 MJ of stabilized pyoil and 1 metric ton of stabilized pyoil. The last section covers upgrading of stabilized pyrolysis oil to drop-in hydrocarbon biofuels and includes the entire life cycle. The functional unit considered in this section are 1 MJ of biofuel and 1 metric ton of biofuel.

2.4 System Boundaries and Description of Product System

The system boundary is the complete life cycle from cradle-to-grave. Figure 2.1 shows each stage in the life cycle, including major inputs and outputs, from feedstock production to biofuel combustion in an engine. In the feedstock production stage, this study includes inputs such as fertilizer requirements, fuel (including electricity) for harvesting or collecting each feedstock, and transporting feedstock to the RTP facility After feedstock production, each feedstock has electricity inputs to reduce the size of the feedstock in preparation for pyrolysis, in a stage called pretreatment. Pyrolysis has inputs like natural gas and electricity used to and dry heat the biomass up to approximately 500°C. The pyrolysis oil needs to be stabilized, which has electricity inputs, chemicals for ion exchange, and ethanol as a rinse solvent. The last stage is upgrading to hydrocarbon biofuels and the main input is natural gas used for fuel and to produce hydrogen to hyrdoprocess the stabilized pyoil. Most of these stages also require either cooling water, boiler feed water, or rinse water or some combination of water resources.

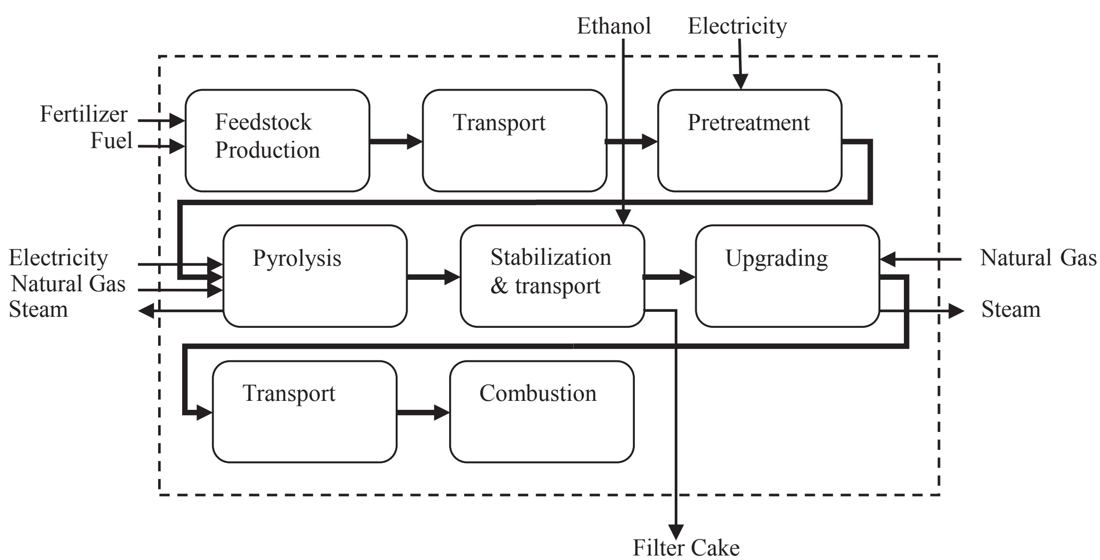

Figure 2.1: System boundary for the LCA with some inputs and co-products

2.5 Allocation

In nearly every LCA of a specific product, there can be many co-products created within the same product system. Co-products are allocated a portion of the environmental burdens from the product life cycle by using different methodologies, such as energy or displacement allocation. In this LCA there are multiple co-products, which are shown in Figure 2.1 and will be discussed in detail in chapters 4 and 5. Other product system outputs were considered waste and therefore did not carry any environmental burdens. The filter cake and steam, has a high energy content and could be used as fuel were considered co-products and therefore shared a portion of the environmental burdens. This study looked at two ways of allocating life cycle impacts to the co-products. The first is displacement, which assigns all environmental burdens to the transportation biofuels and then takes an emissions credit for the avoided products in the market displaced by the co-product. For example, steam is produced in more than one stage of the product life cycle as shown in Figure 2.1. Steam is exported from the product system and is available for use in the industrial sphere where it may displace steam generated by natural gas, fuel oil, or coal. When displacement occurs, an environmental credit equal to the impact avoided can be claimed by the main product. In the results this credit will show up as a negative emission and helps offset the other emissions in the process. Displacement allocation (also referred to as system expansion) is used by the U.S. Environmental Protection Agency to evaluate biofuels and determine whether they count toward the Renewable Fuels Standard production targets.

The other type of allocation used in this study was energy allocation. This methodology attributes part of the burden to the co-products and only a fraction of the total emissions are assigned to the main product. This allocation approach ratios the output energy that is carried with the main product to the total output energy. This energy allocation calculation occurs at each life cycle stage for which one or more co-products are produced. The fraction of emissions applied to the main product is called the energy allocation factor (EAF). The energy allocation factor is applied not only to this stage but also to all upstream stages. The calculation below shows how to calculate the EAF for the pyrolysis stage in Figure 2.1 for which the main product is pyrolysis oil (pyoil) and the co-product is steam (in this example for albizia as a feedstock). The numerator is the energy of the pyoil (pyoil mass multiplied by the lower heating value (LHV) of pyoil) and the denominator is the total output energy. Table 2.1 summarizes all the EAFs for each stage and each feedstock. Energy content of steam was taken to be 3.2 MJ/kg of steam, obtained from a steam ecoprofile in the LCA software SimaPro, which represents the total primary energy required to produce 1 kg of average chemical process industry steam.

$$\mathrm{EAF} = \frac{1\frac{kg\ of\ pyoil}{kg\ of\ pyoil}*16.6\ \frac{MJ\ of\ pyoil}{kg\ of\ pyoil}}{1\frac{kg\ of\ pyoil}{kg\ of\ pyoil}*16.6\ \frac{MJ\ of\ pyoil}{kg\ of\ pyoil}+0.78\ \frac{kg\ of\ steam}{kg\ of\ pyoil}*3.2\ \frac{MJ\ of\ steam}{kg\ of\ steam}} = 0.87 \qquad (2.1)$$

Table 2.1: EAFs for each feedstock at each stage. Calculations are shown for each EAF in the Appendix 2.

	Pyrolysis	Stabilization	Upgrading
Albizia	0.87	0.95	0.80
Corn Stover	0.88	0.93	0.83
Corn Stover Low Ash	0.77	0.94	0.82
Switchgrass	0.89	0.95	0.81
Guinea Grass	0.97	0.96	0.82
Sugarcane Bagasse	0.93	0.96	0.85
Waste Wood	0.83	0.95	0.83
Wild Algae	0.97	0.92	0.84
Open Pond Algae	0.91	0.95	0.85

Chapter 3: Inputs and Results for Feedstock Production

3.1 Feedstock Production Inputs

3.1.1 Albizia

The goal of this analysis is to estimate GHG emissions from the albizia supply chain in the context of a Hawaiian location. No data was available from albizia growers, so inputs were assumed similar to a study conducted in the Upper Peninsula of Michigan, which had inputs for mixed hardwood logging residue collection and transport from natural regeneration hardwood site near Trenary, MI, and Grays Harbor’s inputs for chipping and grinding as shown in Table A3.1 in Appendix 3. Figure 3.1 shows the albizia supply chain for feedstock production.

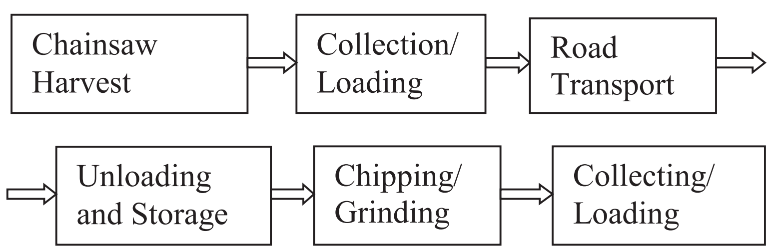

Figure 3.1: Stages for albizia production used in this LCA

Albizia inputs were assumed to be similar to waste wood with the exception of a harvesting step. This process assumes most of the harvesting of albizia will be selective harvesting. Albizia is considered an invasive species in Hawaii and plantations in Hawaii may not be acceptable. Chainsaw harvesting was selected because the trees might grow in hard to reach places where large machines cannot go. When power from the grid is required, this analysis assumes a Hawaiian electricity average as shown in appendix 3. The rest of the inputs are diesel for the machines and electricity for chipping.

The truck input takes into account the road infrastructure, operation and vehicle maintenance, expenditures, and environmental interventions due to road construction. The ecoprofile “Building machine” in the ecoinvent database, a surrogate for loading and unloading equipment, was taken into consideration for the unloading and storage stage and the collecting and loading stage, which includes the transportation of the parts to the assembly plant and building the machine.

3.1.2 Switchgrass

The goal of the switchgrass analysis is to determine the greenhouse gas (GHG) emissions for planting, cultivation, harvesting, and transportation steps, and to compare GHG results from Ceres input data with GHG results from the literature. Input data upstream of the pyrolysis oil production step was provided by Ceres for various process stages of switchgrass production. Three scenarios with different transportation distances were taken into consideration for switchgrass as well as geographic location scenarios each requiring different amounts of nitrogen fertilizer. Figure 3.2 below shows key stages in the switchgrass production life cycle.

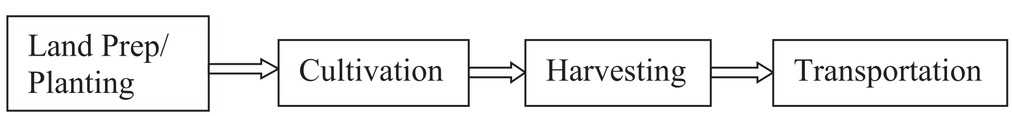

Figure 3.2: Stages for switchgrass production used in this LCA.

The switchgrass feedstock supply chain inputs provided by Ceres are summarized in Table A3.2 for switchgrass. Ceres does not believe that soybean and corn acres will be converted to switchgrass, especially at current corn and soybean prices. More likely, pasture lands and marginal lands no longer profitable for food production will be converted. In this initial scenario the stand was established on existing row crop land without any supplemental irrigation. Soil was assumed to have low potassium and phosphorus content with pH less than 5 therefor lime, potassium, and phosphorus were added. There was no use of pesticides for crop protection and herbicide data was not available, and therefore not input into the analysis. According to Ceres Electricity and natural gas were also not used in the cultivation according to Ceres input data.

Table A3.2 also compares input data from Ceres on switchgrass production to literature data (Cherubini and Jungmeier 2010). Herbicide and switchgrass seed data are not included in this analysis because Ceres did not have inputs and was assumed to have negligible effect on the results, as shown in (Cherubini and Jungmeier 2010). Any inputs that were missing from Ceres were either taken from Ecoinvent database in SimaPro or estimated as shown later in the report. Any input data that was not in the literature was assumed to be the same as the data from the Ceres or the SimaPro inputs were used.

The inputs associated with nitrogen fertilizer for 10 location scenarios are shown in Table A3.3, and annual productivities on the basis of dry mass as listed below.

1. Southeast with low nitrogen input (17.61 MT/ha), where MT is dry metric tons
2. Southeast with high nitrogen input (17.61 MT/ha)
3. Northern plains with low nitrogen input (11.62 MT/ha)
4. Northern plains with high nitrogen input (11.62 MT/ha)
5. Mid-Latitude with low nitrogen input (17.44 MT/ha)
6. Mid-Latitude with high nitrogen input (17.44 MT/ha)
7. Southern plains with low nitrogen input (15.5 MT/ha)
8. Southern plains with high nitrogen input (15.5 MT/ha)
9. Nitrogen balance (inputs to meet the N taken up during growth)
10. Literature (16 MT/ha)

Scenario #9 was named the nitrogen balance scenario. This scenario was calculated using data given from an elemental analysis of dry switchgrass, which was found to contain 0.44% nitrogen. This means that for every dry metric ton of switchgrass 4.4 kg of nitrogen are required, assuming all nitrogen is taken up into switchgrass. This assumption is of course an idealization because some N is lost due to volatilization and leaching, but this scenario provides a benchmark for N addition. This would seem to represent the minimum amount of nitrogen fertilizer required but input of N is actually on the high side when comparing to the other eight scenarios, which implies some natural sources of nitrogen.

A switchgrass plot life of seven years was considered in this study and input data was averaged over this time period since the inputs provided by Ceres varied year-to-year according to a cultivation schedule. The fertilizers for potassium and phosphorus were assumed to be potassium sulfate, and monoammonium phosphate. Urea (50% of N in fertilizer), ammonium nitrate (50% of N in fertilizer), and limestone were identified as inputs and were provide by Ceres. The inputs were all converted to have the same basis; 1 dry metric ton switchgrass. An example of how the input data was calculated for location scenario 1 is given in equation 3.1

$$\frac{58.28\ kg\ of\ N\ in\ fertilizer}{1Ha} * \frac{1Ha}{17.61\ dry\ MT} * \frac{0.5\ kg\ of\ N\ in\ urea}{1\ kg\ of\ N\ in\ fertilizer} = 1.65\ \frac{kg\ of\ N\ in\ urea}{dry\ MT} \tag{3.1}$$

where, 58.28, 17.61 and 0.5 were provided by Ceres. The truck transport inputs during the transportation stages included road infrastructure, expenditures and environmental interventions due to construction, renewal and disposal of roads have been allocated based on ton kilometers, which is provided by the Ecoinvent database of SimaPro7.2. The distance between the bio-refinery and the switchgrass plantations varies so several different scenarios were developed. The scenarios included one way transportation distances of 15, 25, and 50 miles.

For all of the switchgrass scenarios' harvesting stage and other stages with machinery, 0.006 kg lubricating oil/kg diesel was assumed (from Ecoinvent database of SimaPro7.2) and calculated as

$$\frac{43.14\ gal\ of\ diesel}{1\ Ha} * \frac{3.785\ L}{1\ gal} * \frac{0.85\ kg\ diesel}{1\ L\ of\ diesel} * \frac{0.006\ kg\ lubricating\ oil}{kg\ diesel}$$

$$= 0.83\ \frac{kg\ lubricating\ oil}{ha\ of\ Switchgrass} \quad (3.2)$$

where, 43.14 gallons diesel/ha is input data from Ceres and the rest are conversion factors. Hydraulic oil and grease inputs were assumed to be in the same ratio to the diesel fuel consumption as the data provided in published data (ecoinvent data). GHG emissions associated with building the machinery used in the cultivation and harvest stages were calculated using input data available in SimaPro (ecoinvent data).

Direct land use change (dLUC) emissions of CO_2 for switchgrass varied greatly depending on location. The dLUC inputs for switchgrass are summarized in Table A3.4 in the appendix. The dLUC emissions of CO_2 ranged between -248 (sequestration of CO_2) to +37 (emission) kg CO_2 / dry MT of switchgrass depending on location. Indirect land use change (iLUC) emissions of CO_2 were not included because it is assumed that switchgrass will be grown on marginal land, which would not compete with food crops.

3.1.3 Wild Algae

Wild algae is cultivated and harvested using electric pump motors to recover algae-containing water existing waterways of treatment facilities and process it through equipment that separates the biomass from the water using chemical agents to aid in the separation. Table A3.5 in the appendix shows the wild algae production inputs provided by Aquaflow Bionomic Corporation, while Figure 3.3 shows the main stages including pumping to harvester, harvesting, dewatering, and transport. The transportation distance for shipping the dewatered algae to the IBR facility is assumed to be 100 km one way.

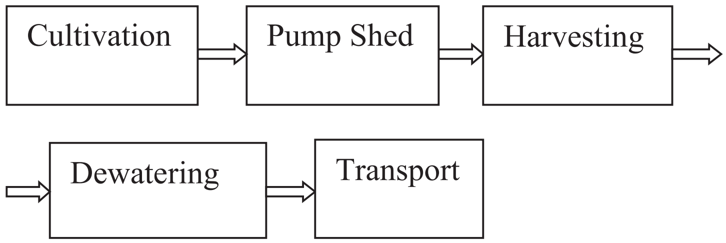

Figure 3.3: System boundaries for wild algae production

A basis of 1 dry metric ton of Algae was used for the data listed in Table A3.5. The main category of inputs for the LCA was the electricity used by the motors. In this analysis it is assumed that the inventory of emissions for the electricity inputs are from US average grid using an ecoprofile from the ecoinvent database in SimaPro and the chemical agents are assumed to be generic organic chemicals (because of lack of data from the biomass supplier). It is assumed that using wastewater treatment nutrients avoids the large emissions associated with the normal wastewater treatment biological nitrogen removal process.

3.1.4 Open Pond Algae

Another algae case investigated was open pond algae, and the system boundary for this analysis is shown in Figure 3.4. This algae was assumed to be grown in desert regions in the southwest of the United States. This would avoid any iLUC because it would be grown on land not suitable for farming, however this cultivation method may incur dLUC emissions of CO_2 depending on the carbon stocks on the land used prior to algae pond construction (not considered in this thesis).

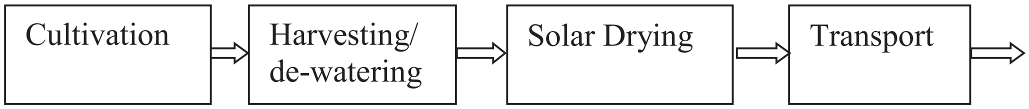

Figure 3.4: System boundaries for open pond algae production

In our study of cultivation of open pond algae, injections of CO_2 as well as nutrients like nitrogen, phosphate, and potassium were included. Cultivation also requires water consumption due to water losses in evaporation and electricity for motor-driven equipment used to move water around the system. Harvesting / de-watering require electric pumps to pump solution through a vacuum filter (0.1-3.5% solids) and into a centrifuge (5-40% solids) to de-water the algae solution. Solar drying then concentrates the moist mat of algae to 90% solids. For all electricity inputs US electricity mix was assumed. These inputs are summarized in Table 3.1.

Table 3.1: Inventory data from the report by (Stratton et al. 2010) for open pond algae cultivation, harvesting, drying and transport with a basis of one dry metric ton algae

Item	Inputs	Units
Cultivation		
CO_2 requirements	2180	kg
Direct injection of CO_2	50	kWh
Nitrogen fertilizer as N (NH_4NO_3)	53	kg
Superphosphate (as P_2O_5)	29	kg
Potassium sulfate (as K_2O)	30	kg
Nutrient supply	4.75	kWh
Mixing	85.6	kWh
Water supply	67.4	kWh
Harvesting/de-watering		
Vacuum belt filter	14.0	kWh
Dewater 5 – 40% solids	120	kWh
Drying Scenario		
Natural gas	7380	MJ
Transportation	100	tkm

3.1.5 Cane Bagasse and Corn Stover

Two scenarios were investigated to calculate GHG emissions for sugar cane bagasse and corn stover as biomass feedstocks for PyGasoline and PyDiesel production. In the first scenario, sugar cane bagasse was considered as a co-product of sugarcane ethanol production, and corn stover as a co-product of corn grain harvesting and collection. The second scenario considered both sugarcane bagasse and corn stover as waste products from their original production systems. An energy allocation (Spatari et al.) method was used to determine GHG emissions of production of bagasse and corn stover when these feedstocks were considered as co-products. Other allocation methods may be used in future studies. The EA method involves an energy balance utilizing material flows and lower heating values (LHV) for each material. For bagasse, the system boundary for EA calculation encompasses the entire production chain up to conversion to ethanol, whereas for corn stover the production chain ends with corn harvesting. The EA factor was calculated using the following equations, where the denominator represents the total energy content of all products and numerator is energy content of the co-product only.

$$EA_{bagasse} = \frac{LHV_{bagasse} \times Mass_{bagasse}}{LHV_{bagasse} \times Mass_{bagasse} + LHV_{ethanol} \times Volume_{ethanol}} \tag{3.3}$$

$$EA_{stover} = \frac{LHV_{stover} \times Mass_{stover}}{LHV_{stover} \times Mass_{stover} + LHV_{grain} \times Mass_{grain}} \tag{3.4}$$

The LHVs of ethanol and sugarcane bagasse, as well as the ethanol yield from sugarcane and corn were obtained from the CARB reports (CARB 2009a; 2009b); and the LHV of bagasse and stover are obtained from the literature (Table 1.2).

The environmental burden of sugarcane bagasse was calculated by multiplying GHG emissions from sugarcane ethanol production (1.9 g CO eq. /MJ ethanol produced) by the allocation factor of bagasse (eqn. 3.5). According to the CARB report (CARB 2009a), one tonne of sugarcane (assuming 70% moisture) can produce 24 gallons of ethanol with 180 kg dry bagasse as co-product; 154.08 kg of which are burned to provide heat and electricity for ethanol production and with the remainder available for use as biomass feedstock for PyGasoline and PyDiesel production. Therefore, the energy allocation factor of sugar cane bagasse can be calculated as:

$$EA\ factor = \frac{(180-154.08)kg \times 13.66MJ/kg}{24\ gal \times 80.53MJ/gal + (180-154.08)kg \times 13.66MJ/kg} = 0.1548 \qquad (3.5)$$

This method of estimating the EA factor for bagasse is an over-estimate because bagasse is a co-product from the sugar solution extraction step in the ethanol process, and therefore the emissions from fermentation and distillation to recover ethanol should not be allocated to bagasse.

Similarly, the environmental burden of corn stover was calculated by multiplying GHG emissions of corn farming and harvesting (5.65 g of CO_2 eq. / MJ of corn ethanol) by the allocation factor of corn stover (eqn. 3.6). According to the CARB report (CARB 2009b), one bushel (56 lb) of corn can produce 2.72/2.62 gallons of ethanol (dry mill/wet mill, respectively). It was assumed that 50% of the corn consists of corn grain and the remainder is corn stover (from CARB report). The LHVs of corn grain and corn stover are 15.5 and 16.5 MJ/kg, respectively. Therefore, the energy allocation factor of corn stover is calculated as:

$$EA\ factor = \frac{56\ lb * 0.454\frac{kg}{lb} * 50\% * 16.5\ MJ/kg}{56\ lb * 0.454\frac{kg}{lb} * 50\% * 15.5\frac{MJ}{kg} + 56\ lb * 0.454\frac{kg}{lb} * 50\% * 16.5\frac{MJ}{kg}} = 51.56\% \qquad (3.6)$$

Corn stover and cane bagasse LCAs were also developed assuming these feedstocks as waste products that come without environmental burden. The inputs are shown in the Table 3.2 for corn stover waste and when considered a co-product and Table 3.3 for cane bagasse waste and when considered a co-product. Another feedstock is low ash corn stover, which is assumed to have the same inputs for feedstock production. This scenario differs from corn stover because low ash corn stover is collected when corn is being processed and so the stover never touches the ground. The inputs for the feedstock production stage for low ash stover are assumed to be the same as for normal stover (lack of data on low ash stover). However, inputs for low ash stover will be different compared to normal stover for pyrolysis, stabilization, and upgrading (see chapters 4&5).

Table 3.2: Inputs for corn stover as a waste and also for low ash corn stover with a basis of one dry metric ton of feedstock (Morey et al. 2010)

Life Cycle Stage	Inputs	Units
Collection		
Stalk Shredding		
Lubricating oil	1.29E-03	gallons
Diesel fuel	0.222	gallons
Raking		
Lubricating oil	3.53E-04	gallons
Diesel fuel	0.053	gallons
Baling		
Lubricating oil	1.29E-03	gallons
Diesel fuel	0.225	gallons
Bale moving		
Lubricating oil	2.35E-03	gallons
Diesel fuel	0.424	gallons
Loading		
Diesel fuel	0.134	gallons
Lubricating oil	1.53E-03	gallons
Transportation		
Diesel	0.408	gallons
Lubricating oil	2.47E-03	gallons
Unloading		
Diesel fuel	0.134	gallons
Lubricating oil	1.53E-03	gallons
Nutrients Replacement		
Ammonia	9.42	kg
Diammonium phosphate	2.9	kg
Potassium sulphate	12.7	kg

Table 3.3: Inputs for the cane bagasse as a waste with a basis of one dry metric ton of feedstock

	Inputs	Units
Loading		
Diesel	0.134	gallons
Lubricating oil	1.53E-03	gallons
Transport		
Truck	100	tkm
Unloading		
Diesel	0.134	gallons
Lubricating oil	1.53E-03	gallons
Loading		
Diesel	0.134	gallons
Lubricating oil	1.53E-03	gallons

3.1.6 Waste Wood

The goal of this analysis is to estimate GHG emissions from the waste wood supply chain in the context of a Washington state location. The data was collected from Grays Harbor who provides forest feedstock to the Grays Harbor Paper facility. As shown in Figure 3.5, the waste wood supply chain has several stages.

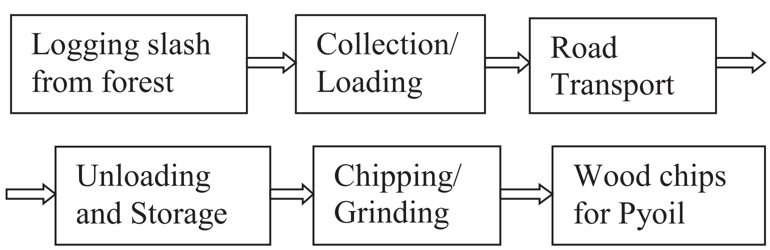

Figure 3.5: Stages for production of waste wood in Washington State.

Some of the inputs in the Table A3.6 in the Appendix were obtained from a UP survey of logging residue collection and transport from a natural regeneration hardwood site near Trenary, MI similar to the Grays Harbor site. Grays Harbor did supply chipping/grinding and road transportation inputs for this LCA.

The Grays Harbor waste wood analysis used machinery, diesel and electricity for the chipping stage. GHG emissions emitted during the chipping of the waste wood with electric driven equipment assumed a Washington state (U.S. EPA 2005) electrical grid mix, which include the GHG gases of CO_2, CH_4, and N_2O. Chipping requires two 450 hp chippers that process 60 green MT every hour. There is also a transmission loss factor of 1.1 (from Ecoinvent database of SimaPro7.2) and 95% of the biomass is chipped using electric-powered motors, while the rest requires diesel grinding. Using these inputs the required electricity can be calculated using equation 3.7

$$2 * 450hp * \frac{0.746KW}{1hp} * \frac{1\ hr}{60\ green\ MT} * \frac{2\ green\ MT}{1\ dry\ MT} * 1.1 * 0.95 = 23.4KWh \tag{3.7}$$

The truck inputs take into account the road infrastructure, operation and vehicle maintenance, expenditures, and environmental interventions due to road construction. Building machine was taken into consideration for unloading and storage stage which includes the transportation of the parts to the assembly plant and building the machine.

3.1.7 Guinea Grass

Guinea grass (Tenbruggencate) grows wild on the Hawaiian Islands and is concentrated on abandoned pineapple and sugar cane plantations. Currently no fertilizers are being used in GG cultivation but are assumed to be needed once the current nutrients left over from prior crop use are consumed during harvesting. An elemental analysis of a guinea grass sample was performed by Ensyn Technologies and the data was used to estimate future fertilizer needs. Figure 3.6 shows key stages in the guinea grass production life cycle which greenhouse gas emissions will be calculated.

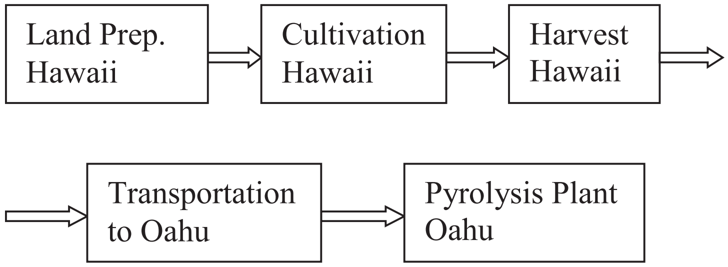

Figure 3.6: Process stages for guinea grass in the Hawaiian Islands.

The first scenario is harvesting wild guinea grass grown on abandoned pineapple and sugar cane fields without inputs of fertilizers. This requires only the harvesting and transportation steps. Two scenarios were also considered for the land preparation step, which was assumed to be needed every 20 years. The results are summarized in Table A3.7.

- Land with minimal vegetation other than guinea grass, 5 gallons diesel/acre
- Land with medium to large trees (require shredder), 15 gallons diesel/acre

Unmanaged land has a lower annual yield of 30 green metric tons as compared to managed land of 60 green metric tons because no fertilizer is added to unmanaged land. Green metric tons refer to the yields after harvesting with some moisture content associated with the yields. An example calculation for the combustion of diesel fuel for the guinea grass land preparation with medium to large trees is shown in equation 3.8

$$\frac{15\ gal}{acre} * \frac{1\ acre}{60\ green\ MT/yr} * \frac{1\ green\ MT}{0.80\ dry\ MT} * \frac{3.785\ L}{1\ gal} * \frac{0.85\ kg\ diesel}{1\ L} * \frac{1}{20\ years} = 0.0503\ \frac{kg\ of\ diesel}{1\ dry\ MT} \tag{3.8}$$

where, 15 gal per acre, 60 green MT per acre and the 20% moisture content (factor of 0.80) were given provided by Imperium, the biomass provider, and also by Professor Dave Ringuette, University of Hawaii. Land preparation was assumed to be needed every 20 years. Diesel consumption associated with guinea grass cultivation was not provided and had to be estimated. Switchgrass data was used in this step because switchgrass and guinea grass are similar crops and therefore should have similar diesel cultivation requirements. Fertilizers were assumed to be urea, potassium sulphate, and thomas meal. The elemental analysis of guinea grass sample provided to Ensyn for pyrolysis studies showed 0.7 mass% nitrogen on a dry basis. This was then converted into a dry MT basis as shown in equation 3.9

$$\frac{0.007 kg\ of\ N\ fertilizer}{1 kg\ of\ GG} * \frac{1000 kg}{1 MT} = 7.00\ \frac{kg\ of\ N\ fertilizer}{1\ dry\ MT} \tag{3.9}$$

The phosphorous fertilizer was estimated by using a ratio of six parts phosphorus per 16 parts nitrogen, which is similar in most plants. Phosphorous fertilizer was estimated this way because this element was not listed on the elemental analysis from Ensyn. This ratio was then used to calculate the emissions associated with phosphorus. Hydraulic oil and grease were assumed to be same ratio in all stages as data was only supplied for the guinea grass harvest stage. Lubricating oil was estimated by using 0.006 kg lubricating oil/kg diesel for all machinery in every stage (from Ecoinvent database of SimaPro7.2). The transportation inputs were 100 miles round trip by truck and an assumed distance of 500 miles by oceanic barge from Hawaii to Oahu. Inventory of emissions for these transport steps were obtained using ecoprofiles in the ecoinvent database in SimaPro.

3.2 Life Cycle Impact Assessment

The GHG included N_2O, CO_2, CH_4, etc. Each gas is converted to CO_2 equivalent using the global warming potential (GWP). Some of the most common GHGs and their GWP are listed below;

1. CO_2=1.0
2. N_2O=298
3. CH_4=25

This study uses the IPCC GWP 100a method, which takes the GWP over 100 years because this time period is the most common choice. The GWP is multiplied by the mass of each GHG to determine the CO_2 eq.

Cumulative energy demand (CED) describes the total amount of energy that is consumed during the life cycle inclusive of both renewable and non-renewable sources. Fossil energy is one of the types of energy that is included in the cumulative energy demand result. The ecoinvent database includes the energy demand for each process and SimaPro uses this database to calculate the cumulative and fossil energy demand for this LCA.

3.3 Results for Feedstock Production

3.3.1 Albizia

The albizia results are shown in Table 3.4.

Table 3.4: GHG emissions for albizia production in Hawaii with a basis of one MT of dry albizia (kg CO2 equivalent (eq) emissions)

Albizia	UP Survey / Grays Harbor
Chainsaw Harvest	
Lubricating Oil	0.0784
Gasoline	0.307
Diesel	0.433
Combustion-Diesel	2.63
Combustion-Gasoline	1.38
Collecting/Loading	
Diesel	1.75
Combustion-Diesel	10.6
Machinery	0.253
Transportation	
Transport truck	15.6
Transport Barge	17.3
Unloading/Storage	
Diesel	0.971
Combustion-Diesel	5.88
Machinery	0.253
Chipping and Grinding	
Diesel	0.0551
Combustion-Diesel	0.333
Electricity-Hawaiian	18.5
Chipper and Grinder	0.0315
Collecting/Loading	
Diesel	1.75
Combustion-Diesel	10.6
Machinery	0.253
Total	88.96

The largest GHG emission in this LCA is the emissions from electricity usage in the chipping and grinding stage, which accounts for 18.5 kg of CO_2 eq. out of the total GHG emissions of 88.96 kg of CO_2 eq. Other high emission inputs include transportation, and the collecting and unloading stages, which included a high amount of diesel use. The rest of the inputs contributed little to the overall GHG emissions.

The cumulative energy demand in Table 3.5 shows the types of energy that is used to produce one MJ of albizia.

Table 3.5: Cumulative energy demand of albizia production in Hawaii with a basis of one MJ of albizia

Cumulative Energy Demand	MJ/MJ
Non renewable fossil	5.12E-02
Non renewable nuclear	1.78E-03
Non renewable biomass	8.69E-08
Renewable biomass	1.00
Renewable others	2.49E-05
Renewable water	2.86E-04
Total	1.05

Most of the energy comes from renewable biomass. The next largest amount of energy is non renewable fossil energy, which comes from the diesel use in the collecting and loading stages and electricity in the chipping and grinding stage.

The fossil energy demand shown in Table 3.6, shows what inputs contributes to the non renewable fossil energy used in albizia production.

Table 3.6: Fossil energy demand of albizia production in Hawaii with a basis of one MJ of albizia

Fossil Energy Demand	MJ/MJ
Diesel	2.55E-02
Transport truck	1.23E-02
Transport barge	1.13E-02
Gasoline	1.23E-03
Remaining	8.70E-04
Total	5.12E-02

These results show that most of the fossil energy is from diesel combustion during the collecting and loading operations and for transport, with gasoline and the rest of the inputs contributing little to the overall amount of fossil energy used in this process.

3.3.2 Switchgrass

The switchgrass production results for GHG emissions are shown in the Table 3.7 for all stages, except N fertilizer application and transport. Table 3.8 displays GHG emissions inclusive of these missing steps from Table 3.7. The average nitrogen location scenario and 50 mile transport scenario will be used for the remaining life cycle.

Table 3.7: Switchgrass GHG emissions for three scenarios at different transportation distances (15, 25, and 50 miles) with a basis of one dry metric ton and comparison to literature (Cherubini and Jungmeier 2010).

Switchgrass Process	Ceres (kg CO_2 eq.)	Literature (kg CO_2 eq.)
Land prep/planting	0.20	0.23
Cultivation	37.1*	108
Harvest	37.2	40.9
Transport 15 miles	5.32	---
Transport 25 miles	8.86	---
Transport 50 miles	17.7	---
Transport	---	20.4
Total	See table 3.8	169.5

*The emission related to nitrogen fertilizer are shown in table 3.8

The nitrogen fertilizer emissions for the nine location scenarios and the total emissions associated with the three distance scenarios are shown in the Table 3.8.

Table 3.8: Total GHG emissions for Switchgrass including nitrogen fertilizer for all locations and nitrogen balance (#9) and at varying transportation distances with a basis of one dry metric ton. (kg CO2 eq emissions)

	#1	#2	#3	#4	#5
Nitrogen Fertilizer	42.6	61.1	30.7	43.0	43.0
Total (15 miles)	122.4	140.9	110.5	122.8	122.8
Total (25 miles)	126.0	144.5	114.1	126.4	126.4
Total (50 miles)	134.2	152.7	122.3	134.6	134.6

	#6	#7	#8	#9
Nitrogen Fertilizer	61.4	30.7	43.0	56.8
Total (15 miles)	141.2	110.5	122.8	136.6
Total (25 miles)	144.8	114.1	126.4	140.2
Total (50 miles)	153.0	122.3	134.6	148.4

Equation 3.10 shows effects of field N_2O emissions, which is nearly 1/3 of total GHG emissions for switchgrass (Ceres).

$$\frac{58.28\ kg\ of\ N\ Fertilizer}{1Ha} * \frac{1Ha}{17.61\ dry\ MT} * 1\ dry\ MT\ (basis) * \frac{0.01325\ kg\ of\ N\ in\ N_2O}{1\ kg\ of\ N\ fertilizer} * \frac{(2*14+16) kg\ N_2O}{(2*14)\ kg\ of\ N\ in\ N_2O} * 298(GWP\ of\ N_2O) = 20.53\ kg\ CO_2\ \text{eq.} \tag{3.10}$$

The emissions for each scenario increased with increasing distanced traveled. Transportation emissions contributed between about 3-9% if the total depending on distance. The GHG emissions of switchgrass varies between 110.5 and 153.0 kg CO_2 equivalent for every dry MT of switchgrass depending on the scenario, while the literature value was 169.5. The difference is largely due to the cultivation step, which involves fertilizers. The nitrogen fertilizers contribute the most to the overall process due to the emissions of N_2O. N_2O has a GWP of 298, which contributes significantly to GHG emissions.

Energy demand results are shown in Table 3.9 for Ceres switchgrass and for switchgrass using literature data.

Table 3.9: Comparing an average cumulative energy demand of switchgrass with inputs from Ceres and literature (Cherubini and Jungmeier 2010) with a basis of one MJ of switchgrass.

Switchgrass	Ceres (MJ/MJ)	Literature (MJ/MJ)
Non renewable, fossil	8.19E-02	9.84E-02
Non renewable, nuclear	6.54E-03	6.17E-03
Non renewable, biomass	7.21E-06	3.05E-06
Renewable biomass	1.00	1
Renewable water	7.94E-05	1.29E-03
Renewable others	1.45E-03	7.21E-05
Total	1.09	1.11

The highest impact in the CED calculation is the renewable biomass, which mainly accounts for the inherent energy content of the switchgrass. This renewable biomass was calculated with a lower heating value of 16.37 GJ per metric ton (Table 1.2). Fossil fuels like diesel also contribute to the overall process with a total CED of 1.09 (Ceres) and 1.11 (Literature) MJ while the other categories contribute near negligible amounts.

Table 3.10 breaks down the non renewable fossil energy requirements to illustrate where the fossil energy is being used. The data in this table shows that most of the fossil energy is coming from diesel use and fertilizer production. There are also smaller contributions from transport of switchgrass and machinery production used in cultivation and harvesting.

Table 3.10: Average fossil energy demand of switchgrass with inputs from Ceres with a basis of one MT and MJ of switchgrass.

Switchgrass	MJ/MJ
Diesel	3.23E-02
Transport	9.04E-03
Potassium	8.86E-03
Phosphate	7.70E-03
Urea	6.35E-03
Total Fertilizers	2.85E-02
Machinery production	8.36E-03
Ammonium nitrate	5.63E-03
Remaining	3.68E-03
Total	8.19E-02

3.3.3 Wild Algae

The results for the wild algae LCA were calculated using different types of energy inputs for electricity. The U.S. mix scenario will be used for the rest of the wild algae LCA. The results in Table 3.11 indicate that using coal as a source of energy for the production of the wild algae has the highest greenhouse gas impact, which is 962 kg CO_2 eq per dry MT of algae. The Lowest GHG impact results obtained are from the hydroelectricity power and nuclear energy, which are 164 kg and 169 kg CO_2 equivalents, respectively. In this study U.S. mix was chosen as the base case electricity source, which release 550 kg CO_2 equivalent. The GHG impacts of wild algae are dependent strongly on location of the production due to the mix of primary energy sources in the electricity mix.

Table 3.11: Comparison of GHG emissions with different electricity derived energies with units of kg of CO2 eq. per dry metric ton of algae and an algae density of 300 g/m3.

	Coal	**Nuclear**	**U.S. mix**	**Hydro**	**Biomass**
Pump shed	627	6.43	305	2.5	23
Harvest	133	1.36	64.6	0.5	4.88
De-watering	185	144	164	144	145
Transport	16.8	16.8	16.8	16.8	16.8
Total	962	169	550	164	190

The main categories of the algae production system which are considered for the LCA analysis are pumping at the pump shed, new harvest units, dewatering, and transport. Table 3.11 shows the GHG emissions per one dry metric ton for each stage and assuming different types of derived electricity. The total GHG emissions are 550 kg CO_2 eq. per metric ton dry algae biomass for the U.S. mix energy scenario. The largest contribution to this total is from the pump shed stage, which pumps the water and algae solution throughout the process. De-watering stage uses chemical additives to aid in separating water from the algae biomass and the assumed additives are responsible for the large GHG emission in this stage.

The algae density contributes significantly to the GHG emissions. If the algae density is doubled, the pump shed and harvest stages will be reduced by 50% as well as slightly reducing GHG emissions in the de-watering step. Also, the type of derived electricity has a major impact on GHG emissions as can be seen in the Table 3.11.

An alternative scenario that was modeled was a waste water treatment credit for an avoided ammonia removal process using denitrification. In this scenario, wild algae was grown using the nutrients present in a typical wastewater treatment plant effluent. This scenario assumes US Grid electricity, which gives a large credit of -1250 kg of CO2 eq. / MT of wild Algae for the impacts avoided when wastewater treatment is replaced with Aquaflow Algae production. To arrive at this result, the inputs from UOP (communication by Steve Lupton) were for the treatment of 1 m^3 (1 metric ton) of wastewater containing 50 mg NH3/L (0.05 kg NH3/ton wastewater). Because each dry ton of algae is 5.8% N, then each ton dry biomass contains 58 kg of N. About 1/2 of the CO_2 eq. emissions avoided are from the mineralization of the methanol needed for denitrification of the NH_3 in a WWT plant.

Table 3.12 shows the cumulative energy demand for all the electricity scenarios. The LHV was found to be 16.59 GJ per metric ton of algae (Table 1.2). This table shows that renewable biomass represents the largest portion of the CED in all scenarios studied.

Table 3.12: Cumulative energy demand for various types of derived electricity in MJ eq. per MJ of algae

	Coal	Nuclear	U.S. mix	Hydro	Biomass
Non renewable fossil	8.98E-01	2.98E-01	6.80E-01	2.94E-01	2.94E-01
Non renewable nuclear	2.28E-02	6.39E-01	1.60E-01	1.81E-02	1.78E-02
Non renewable biomass	1.41E-07	1.12E-07	1.81E-07	1.02E-07	1.00E-07
Renewable biomass	1.00	1.00	1.00	1.00	1.00
Renewable others	2.50E-04	1.86E-04	8.44E-04	1.81E-04	1.77E-04
Renewable water	2.72E-03	2.19E-03	1.46E-02	1.49E-01	1.87E-03
Total	1.92	1.94	1.86	1.46	1.31

The non renewable fossil energy demand was broken down into more detail to show what inputs used the most fossil energy, which is shown in Table 3.13. Electricity and chemicals for nutrients contributed the most to the fossil energy demand, and transportation contributed the rest of the fossil energy. This case assumed U.S. mix of electricity for this analysis.

Table 3.13: Fossil energy demand for U.S. mix electricity scenario with a basis of one MJ

Fossil Energy Demand U.S. Mix	MJ/MJ
Electricity	0.39
Chemicals	0.28
Transportation	0.02
Total	0.68

3.3.4 Open Pond Algae

Open pond algae inputs from the PARTNER report (Stratton et al. 2010) were used to generate the GHG emission results in SimaPro. The results are summarized in Table 3.14. The inputs that contributed the most to the overall GHG emissions were the nutrients. The calculated nutrient- GHG emission was high compared to the PARTNER report value of 115 kg CO_2 eq. per MT of algae (likely due to the assumed N fertilizer in this thesis research for open pond algae – ammonium nitrate, which has a high GHG emission factor compared to other N fertilizers). For this preliminary screening, this study uses the PARTNER report values for nutrients instead of the Ecoinvent results from SimaPro (447 kg of CO_2 eq. per dry MT of algae). Other inputs that contributed significantly to the overall GHG emissions electric motor driven pumps used in both the de-watering stage and the cultivation stages.

Table 3.14: GHG emissions associated with the production of open pond algae with a basis of one dry MT of algae.

Open Pond Algae	kg CO_2 eq.
Cultivation	
CO_2 requirements	35
Direct injection of CO_2	42
Nitrogen fertilizers	453
Superphosphate	74.9
Potassium sulfate	43
Nutrient supply	3.98
Mixing	69.2
Water supply	56.4
Harvesting/de-watering	
Vacuum belt filter	11.7
Dewater 5 – 40% solids	100
Drying	
Natural Gas	574
Transportation	13.7
Total (SimaPro nutrient results – solar drying)	903
Total (PARTNER report nutrient results – solar drying)	447
Total (PARTNER, 75% nutrient recycle – solar drying)	361
Total (PARTNER with natural gas drying)	1021

There are two scenarios for open pond algae; the first is 75% of the nutrients are recycled so only 25% of the nutrients are required. The other scenario is using natural gas to dry the algae instead of using solar drying. The nutrient recycle reduced the amount of nutrients required and therefore reduced the GHG emissions. The natural gas drying requires 2.05 kWh / kg of algae. This energy requirement is based on the amount of water that has to be removed and assuming a 70% efficient drying process, which resulted in an increase of 574 kg of CO_2 per MT of dry algae.

The CED is shown in Table 3.15, which breaks down the types of energy that were used in the production of open pond algae. This shows that renewable biomass contributed significantly to the overall amount of energy because of the large amount of algae that is collected in this process. Non renewable fossil energy also contributed a lot of energy to this process, while the rest contributed lesser amounts.

Table 3.15: CED for open pond algae production assuming solar drying with a basis of one dry MT of algae

Cumulative Energy Demand	MJ/MJ
Non renewable fossil	4.06E-01
Non renewable nuclear	8.86E-02
Non renewable biomass	2.58E-05
Renewable biomass	1.01
Renewable others	7.74E-04
Renewable water	9.96E-03
Total	1.51

The fossil energy demand is broken down into more detail in Table 3.16. This table shows that the fossil energy consumption came from the electric motor-driven pumps, nutrient production, and transportation. The electricity needed for the pumps contributed the most fossil energy to open pond algae production.

Table 3.16: FED for open pond algae production with a basis of one dry MT of algae

Fossil Energy Demand	MJ/MJ
Electricity	1.66E-01
Ammonium nitrate	1.47E-01
Single superphosphate	5.03E-02
Potassium sulfate	3.18E-02
Transport	1.11E-02
Total	4.06E-1

3.3.5 Sugar Cane Bagasse

The GHG emissions of sugar cane ethanol production generated by SimaPro and CARB are shown in Table 3.17. The results from EPA Renewable Fuels Standard (RFS2) (EPA 2010a) are also listed and compared to the CARB (CARB 2009a)study.

Table 3.17: GHG emissions of sugar cane ethanol, comparing CARB results to the EPA RFS2.

g CO_2 eq./MJ EtOH	SimaPro	CARB	EPA RFS2
Sugar Cane Farming	9.77	9.9	36.02
Ag Chemicals Production and Use	6.18	8.7	Included in Farming
Sugar Cane Transport	3.67	2	4.74
Ethanol Production	2.29	1.9	-10.43
LUC (domestic & international)			4.74
Tailpipe Emission	0	0	0.95
Total w/o LUC	21.92	22.5	31.28
Total w/ LUC			36.02

*LUC impact for sugar cane ethanol is not included in the CARB report.

As shown in Table 3.17, the total GHG emissions comparing the CARB results and the SimaPro simulation (using CARB inventory data) are very consistent with each other. Agricultural chemicals production and use is a slightly smaller contributor in the SimaPro simulation mainly because SimaPro uses a different GHG calculation method for fertilizer production. Emissions of N_2O from the farm as a result of N fertilizer application were included in the SimaPro simulations using IPCC emission factor of 0.0135 kg N_2O-N/kg fertilizer N applied. Averaging the two results (SimaPro and CARB) and multiplying by the calculated EA factor results in total sugar cane bagasse GHG emissions of approximately 3.45 g CO_2 eq/MJ EtOH produced. In the RFS2 report, ethanol production emits negative amount of CO_2 because of displacement of marginal Brazilian electricity by power generated with the sugarcane bagasse co-product. Domestic LUC accounts for 0.85 g CO_2 eq/MJ, whereas international LUC impacts range from -4.74 to 11.37 g CO_2 eq/MJ EtOH, resulting in a mean emission value of 3.79 g CO_2 eq/MJ EtOH for total LUC.

The conversion factor between MJ of ethanol produced per kg bagasse residue co-produced, based on yields mentioned above and LHV for ethanol, is 1932.72 MJ EtOH per 25.92 kg bagasse, resulting in a final value for bagasse of 257.25 gCO_2 eq/kg bagasse, without LUC. Figure 3.7 shows the GHG emissions based on one kg of bagasse. LUC impacts were included in the CARB results to present a better comparison between CARB and RFS2 results. The LUC emission was assumed to be the same as shown in the RFS2 report, and the mean emission value was used for this study is 3.79 g CO_2 eq/MJ EtOH.

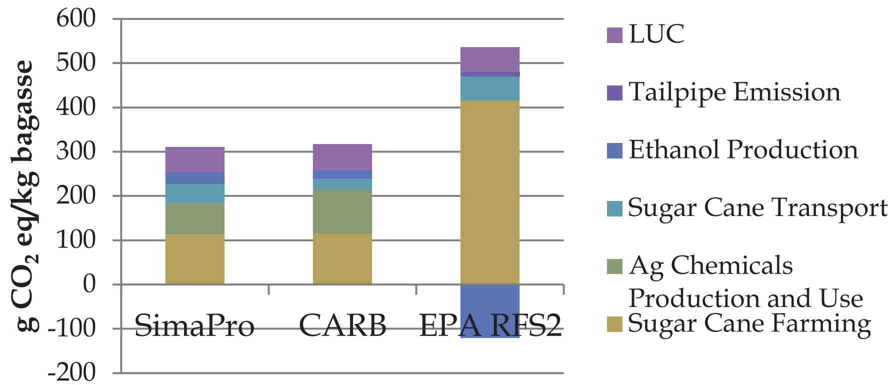

Figure 3.7: GHG emissions of sugar cane ethanol production, comparing CARB results and EPA RFS2.

The next scenario assumed that sugarcane bagasse as a waste product. This means only loading, transport to the biorefinery, and unloading was considered as shown in the Table 3.18.

Table 3.18: GHG emissions of sugar cane bagasse when considered a waste product in kg CO2 eq/ metric ton dry bagasse

Cane Bagasse	kg CO_2 eq. / metric ton cane bagasse
Loading	1.83
Transport	16.80
Unloading	1.83
Total	20.45

The total emissions when assuming cane bagasse as a waste is 20.45 kg CO_2 eq/metric ton bagasse. The main GHG emission was transport, which was assumed to be 100 km and resulted in 16.80 g CO_2 eq/kg bagasse. Cumulative energy demand was also calculated for this waste scenario as shown in the Table 3.19.

Table 3.19: CED for sugarcane bagasse when considering bagasse as a waste product with a basis of one MJ of sugarcane bagasse

Sugarcane Bagasse	MJ/MJ
Non renewable fossil	2.26E-02
Non renewable nuclear	1.20E-03
Non renewable biomass	6.49E-08
Renewable biomass	1.00
Renewable others	1.05E-05
Renewable water	2.31E-04
Total	1.03

The largest contributor to the CED is in renewable energy mainly the renewable biomass, which accounts for the inherent energy content of the bagasse. This renewable biomass was calculated using a LHV 13.66 GJ per metric ton (Table 1.2). Fossil fuels like diesel also contribute to the overall process while the balance contributes near negligible amounts.

The fossil energy is broken down into more detail in Table 3.20. The transport and diesel use contribute the most to the FED. The truck transport contributes the most to the total non renewable fossil energy used in this process. The rest of the inputs have negligible impact on the total fossil energy.

Table 3.20: FED for sugarcane bagasse when considered a waste with a basis of one MJ of bagasse

Fossil Energy Demand	MJ/MJ
Transport truck	2.24E-02
Diesel	1.94E-03
Remaining	1.28E-05
Total	2.43E-02

3.3.6 Corn Stover

Similar to the cane bagasse study, we conducted a LCA study in SimaPro using the inventory data and assumptions from the CARB report (CARB 2009b) to generate the

GHG emissions of ethanol production, assuming corn stover was a co-product. Corn stover was also considered a waste and inventory data from the Morey et al. report (Morey et al. 2010) was used to generate the GHG emission results. The system scope includes corn farming and harvesting, biomass transport and ethanol production. The results generated from SimaPro were then compared to the CARB study. An EPA 2012 projection scenario of the corn stover life cycle was also analyzed to compare the GHG results to the CARB study. The inventory data of corn farming and harvest were obtained directly from the FASOM model (EPA 2010b), which EPA used to conduct their study. The GHG emissions of corn stover collection and storage were obtained from the literature (Sokhansanj et al. 2010). Since land use change (LUC) has been identified as a potentially significant contributor to the environmental profile of biofuels, we also included the LUC impact of corn cultivation in our study (from RFS2).

The inventory data for corn farming and agricultural chemicals were obtained from both the CARB report and EPA study, and the GHG emissions of corn stover were generated in SimaPro. The GHG emissions of corn cultivation and harvest in the CARB report are in g CO_2 eq./MJ EtOH basis, and they were converted to per kg corn stover basis using ethanol yield, which is 2.72 and 2.62 gal/bu for dry mill and wet mill, respectively. The GHG emission of stover collection was obtained from a study conducted by Sokhansanj (Sokhansanj et al. 2010). The LUC impact of corn ethanol is listed in the CARB report as 30 g CO_2 eq/MJ, and it was converted to gram per kg of corn stover basis as shown in equation 3.11. The GHG emissions results are shown in the Table 3.21 and Figure 3.8.

$$\frac{30\ g\ CO_2\ eq.}{MJ\ of\ EtOH} * \frac{80.5 MJ\ of\ EtOH}{1\ gal\ of\ EtOH} * \frac{2.72\ gal\ EtOH}{56\ lbs\ of\ corn} * \frac{1\ lb\ of\ corn}{1\ lb\ of\ corn\ stover} * \frac{2.205 lbs}{1 kg} * 0.5156 = 133.38\ g\ CO_2\ eq.\ /\ kg\ of\ corn\ stover \qquad (3.11)$$

Table 3.21: GHG emissions of corn stover, comparing SimaPro simulation and CARB results

g CO_2 eq/kg corn stover	Corn stover (CARB data)	Corn stover (EPA data)	CARB (dry mill)	CARB (wet mill)
Corn farming	24.21	17.90	25.12	24.88
Ag chemicals production and use	112.99	56.79	134.27	134.26
Stover collection	6.7	6.7	6.7	6.7
LUC	133.38	133.38	133.38	128.48
Total w/o LUC	143.9	81.4	166.1	165.9
Total w/ LUC	277.28	214.77	299.48	294.32

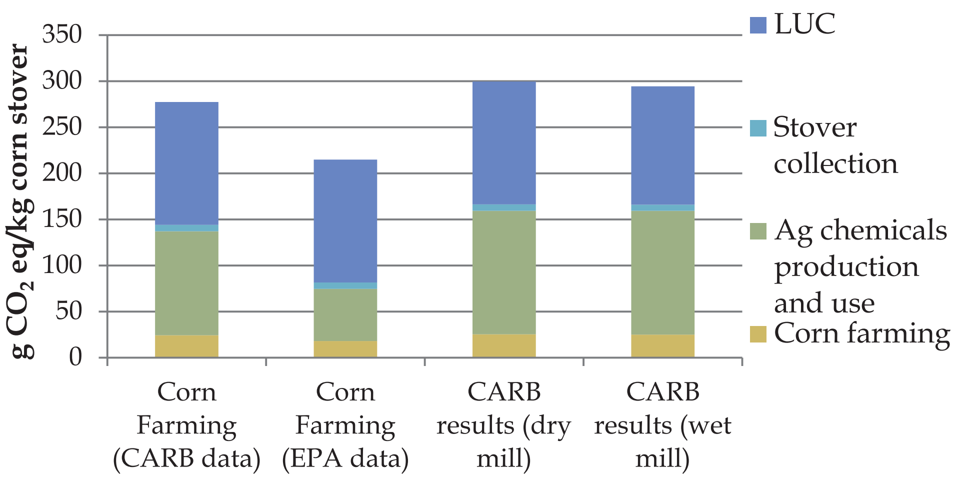

Figure 3.8: GHG emissions of corn stover, comparing SimaPro simulation and CARB results

The total GHG emissions from the SimaPro simulation using CARB data (left most bar in Figure 3.8) and the CARB results (right-most bars in Figure 3.8) are very consistent with each other. Agricultural chemicals production and use is a smaller contributor in the SimaPro simulation mainly because SimaPro uses a different GHG calculation method for fertilizer production. However, the results generated using the EPA data are much lower than the other three cases, mainly because the fertilizer and energy use in the EPA scenario is much less than in the CARB study. LUC is a major GHG contributor, accounting for approximately 50% of the total emissions for all cases.

Kim and his research team published a paper in 2009 (Kim et al. 2009), presenting the corn stove GHG emissions results from their LCA study. The overall GHG emissions of corn stover ranged from -40 to 91 g CO_2 eq/kg stover, depending on different locations of the corn farms. However, their study used a displacement allocation approach to calculate the life cycle emissions, whereas our study uses an energy allocation approach. In the Kim and Dale (2009) study , there is a large CO_2 credit given to the avoided grain emissions, because corn stover are collected from the farm, thus nitrogen related emissions from the soil due to stover decomposition (i.e., N_2O, NOx, NO_3-) are greatly reduced.

In the second scenario, stover was considered a waste and therefore assumed zero environmental burden. The only GHG contributions come from material collection, storage, and transport of the raw stover to the pyrolysis plant, which is shown in Table 3.22 below.

Table 3.22: GHG emissions of corn stover when considered a waste product in kg CO2 eq/ metric ton corn stover

Corn Stover	**kg CO_2 eq.**
Transport	4.86
Fertilizer replenishment	42.47
Collection	10.99
Loading and unloading	3.19
Total	61.52

The total emissions when assuming corn stover as a waste is 61.52 kg CO_2 eq./metric ton of stover. The main GHG emission was fertilizer replenishment, which was needed since the stover acts as a source of fertilizer N, P, and K if left in the field. When stover is collected nutrients are lost and need to be replaced. We did not include any N_2O emissions change when stover is removed because IPCC method does not distinguish between synthetic N and stover N with respect to N_2O emissions. Fertilizer use results in nearly 70% of the total GHG emissions. The rest of the emissions only slightly impact the total emissions. CED was also calculated for this waste scenario as shown in Table 3.23.

Table 3.23: CED for corn stover when considering stover as a waste product with a basis of one MJ of corn stover

Cargill corn stover	MJ/MJ
Non renewable fossil	5.99E-02
Non renewable nuclear	3.16E-03
Non renewable biomass	3.24E-06
Renewable biomass	1.00
Renewable others	5.55E-05
Renewable water	5.45E-04
Total	1.06

The highest impact in the CED is in renewable energy mainly the renewable biomass, which accounts for the inherent energy content of the stover. This renewable biomass was calculated with a LHV 16.5 GJ per metric ton. Fossil fuels like diesel also contribute to the overall result while the rest have almost negligible amounts.

The non renewable fossil energy is broken down into more detail in Table 3.24. This shows that ammonia production, the major N fertilizer used, contributes the most the non renewable fossil energy use. Potassium and phosphate fertilizers as well as diesel and lubricating oil also contribute to the fossil energy in the production on corn stover.

Table 3.24: FED for corn stover when considered a waste with a basis of one MJ of corn stover

Fossil Energy Demand	MJ/MJ
Ammonia	2.32E-02
Diesel	1.68E-02
Potassium sulfate	1.63E-02
Diammonium phosphate	3.33E-03
Lubricating oil	1.62E-04
Total	5.99E-02

3.3.7 Waste Wood

The waste wood LC GHG results are based on the inputs provided in the input section. Table 3.25 shows GHG emissions for the major waste wood production stages.

Table 3.25: Waste wood process stages and their corresponding GHG emissions with a basis of one dry metric ton.

Waste Wood Process	kg CO_2 eq.
Collecting/Loading	12.6
Transportation	6.4
Unloading/Storage	7.1
Chipping & Grinding	4.0
Total	30.1

The main GHG emissions were emitted during collecting/loading, which was 12.6 kg CO_2 equivalent for every dry MT of waste wood. The chipping and grinding stage was the least significant. The main component in the chipping and grinding step was electricity because the main source of electricity in Washington State is from hydroelectricity. The GHG emission was low for this step.

Energy demand results are shown in Table 3.26 for Grays Harbor waste wood.

Table 3.26: Cumulative energy demand of the waste wood process with a basis of one MJ of waste wood.

Waste Wood Process	MJ/MJ
Non Renewable, Fossil	3.06E-02
Non renewable, nuclear	7.78E-04
Non renewable, biomass	5.11E-08
Renewable biomass	1
Renewable water	1.25E-04
Renewable others	1.07E-05
Total	1.03

The highest impact in the CED is in renewable energy, mainly the renewable biomass, which accounts for the inherent energy content of the waste wood. This renewable biomass was calculated with an assumed value of 20 GJ per metric ton. Fossil fuels like diesel also contribute to the overall process with 578 MJ/MJ while the rest have almost negligible amounts.

Fossil energy is broken down into more detail in Table 3.27. This breakdown shows that diesel consumption was the input that used the most fossil energy. Transport of the waste wood also contributed a significant amount, while machinery production and the chipper and grinder production contributed the least to the fossil energy demand for waste wood production.

Table 3.27: FED for waste wood process with a basis of one MJ of waste wood

Waste Wood Process	MJ/MJ
Diesel	2.33E-02
Transport	6.77E-03
Machinery	5.49E-04
Chopper	2.01E-05
Total	3.06E-02

3.3.8 Guinea Grass

The analysis of guinea grass used the inputs given in the input section to calculate GHG emissions. Two scenarios were developed to characterize the impact of vegetation removal (minimal or medium) and another scenario was developed based on unmanaged lands. Table 3.28 shows GHG emissions from the various production stages and for scenarios of minimal and medium prior vegetation as well as unmanaged lands. The unmanaged land only includes the harvest stage (Unmanaged land) and transport.

Table 3.28: Guinea grass process stages assuming managed land and their corresponding GHG emissions with a basis of one dry metric ton

Guinea Grass (Tenbruggencate) Process	kg CO_2 eq./MT GG
Land prep. minimal vegetation	0.06
Land prep. medium vegetation	0.19
Cultivation	97.8
Harvest (Managed Land)	7.4
Transport	29.6
Total	135

Table 3.29: Guinea grass process stages assuming unmanaged land and their corresponding GHG emissions with a basis of one dry metric ton

Guinea Grass (Tenbruggencate) Process	kg CO_2 eq./MT GG
Land prep. minimal vegetation	0.06
Land prep. medium vegetation	0.19
Harvest (Unmanaged Lands)	14.8
Transport	29.6
Total (Unmanaged Land Scenario)	44.4

The calculation for the combustion of the diesel fuel needed for the guinea grass land preparation with medium vegetation is shown

$$\frac{15\ gal}{acre} * \frac{1\ acre}{60\ green\ MT} * \frac{1\ green\ MT}{0.80\ dry\ MT} * \frac{3.785\ L}{1\ gal} * \frac{0.85\ kg\ diesel}{1\ L} * \frac{1}{20\ years} * \frac{3.17\ kg\ of\ CO_2}{1\ kg\ of\ diesel} = 0.16\ \frac{kg\ of\ CO_2\ from\ diesel}{1\ dry\ MT} \tag{3.12}$$

where, 15 gal of diesel fuel per acre, 60 MT of guinea grass per acre were given provided by Imperium and the 20% moisture content was from the elemental analysis of a harvested guinea grass sample as performed by Ensyn Technologies. The elemental analysis of guinea grass showed that 0.7 mass% was nitrogen on a dry basis. This value can be used to estimate CO_2 and N_2O emissions from the estimated urea application as shown in equation 3.13.

$$\frac{0.007kg\ of\ N}{1kg\ of\ GG} * \frac{1000kg}{1MT} * \frac{60kg\ of\ urea}{28kg\ of\ N} * \frac{12kg\ of\ C}{60\ kg\ of\ urea} * \frac{44\ kg\ of\ CO_2}{12\ kg\ of\ C} = 11.00\ \frac{kg\ CO_2\ from\ urea}{1\ dry\ MT} \tag{3.13}$$

Guinea grass grown on managed land has a large GHG emission in the cultivation step primarily due to the use of fertilizers. The cultivation step accounted for 85.4 kg CO_2 equivalent for every dry MT of guinea grass. The land preparation and harvest stages contributed least to the overall process. The overall GHG emissions were 122 and 123 kg CO_2 equivalent for every dry MT of guinea grass depending on the amount of tree removal required during the land preparation. Due to the lower yield, the harvest of unmanaged land had twice the GHG emission then compared to the managed land harvest step because twice the amount of fuel is being used to harvest the same amount of guinea grass. However, the overall GHG emission for this scenario was far less than the managed land scenarios. This was because only the harvest and transportation steps were needed, which resulted in a GHG emission of 44.4 kg CO_2 equivalent for every dry MT of guinea grass. This is most likely not a long lasting option since the nutrients in the soil will likely decrease over time, which will in turn lead to a drop in guinea grass yields.

Energy demand results for guinea grass are shown in Table 3.30.

Table 3.30: Average cumulative energy demand of the land preparation scenarios for guinea grass on managed lands with a basis of one MJ

Guinea Grass	MJ/MJ
Non renewable, Fossil	8.92E-02
Non renewable, nuclear	5.65E-03
Non renewable, biomass	1.49E-07
Renewable biomass	1.00
Renewable water	1.01E-03
Renewable others	8.5E-05
Total	1.1

The highest impact in the CED is the renewable biomass, which mainly accounts for the inherent energy content of the guinea grass. This renewable biomass was calculated with an assumed LHV value of 14.8 GJ per metric ton. Fossil fuels like diesel also contribute to the overall process with 0.0892 MJ/MJ while the rest have almost negligible amounts.

The non renewable fossil energy for guinea grass is broken down into more detail in Table 3.31. This table shows transport by truck uses the most fossil energy in this analysis. Transport by barge, fertilizers, and diesel also contribute to the fossil energy used in the production of guinea grass.

Table 3.31: FED for guinea grass in Hawaii on managed land with a basis of one MJ of guinea grass

Fossil Energy Demand	MJ/MJ
Urea	2.96E-02
Transport truck	1.67E-02
Potassium sulfate	1.54E-02
Transport barge	1.53E-02
Diesel	6.55E-03
Thomas meal	4.36E-03
Remaining	1.29E-03
Total	0.0892

Chapter 4 Inputs and Results for Stabilized PyOil Production

4.1 Inputs for Pretreatment, Pyrolysis, and Stabilization

The inputs for pretreatment, pyrolysis, and stabilization for each feedstock are shown in Table A4.1 and Table A4.2 of appendix 4 including water inputs. Pyrolysis has inputs such as electricity and natural gas as well as a co-product of steam. Stabilization has inputs such as electricity and steam as well as ethanol as a flush solvent and a co-product of filter cake. Water is used during pyrolysis and stabilization process. This water exits the system as a spent brine waste stream. Figure 4.1 provides a simplified block flow diagram of the pretreatment, pyrolysis, and stabilization process. The inputs for each processing step are used in SimaPro 7.2 to calculate GHG emissions, CED/FED, and aggregated to estimate how much water is used in the overall process.

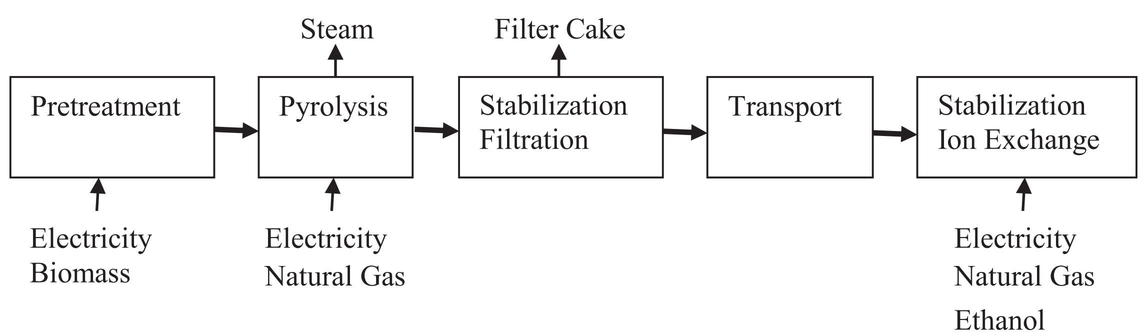

Figure 4.1: Process flow diagram for stabilized pyrolysis oil including significant inputs and co-products

4.2 Results

The inputs for pretreatment, pyrolysis, and stabilization provided by UOP are summarized in appendix 4. The same inputs were used to calculate GHG emissions using both displacement and energy allocation methodology. CED and FED results are shown for each feedstock. The results summarized in the immediately following sections of this report focus on displacement allocation.

4.2.1 Albizia

Inputs for pyrolysis and stabilization of albizia biomass were used to generate GHG emission results shown in Table 4.1. The results use displacement allocation in the first two columns and energy allocation in the last two columns. Results are expressed in units of kg of CO_2 eq. per metric ton of stabilized pyrolysis oil and grams of CO_2 eq. per MJ of stabilized pyrolysis oil. This scope of the analysis includes pretreatment, pyrolysis and stabilization of the pyrolysis oil. Stabilization is broken down into two steps, filtration and ion exchange. Albizia biomass, a raw material input to the pyrolysis step incorporates inputs from albizia production to arrive at this result.

Table 4.1: GHG emissions (CO2 eq.) for stabilized pyrolysis oil derived from albizia using both displacement and energy allocation with functional units of metric tons of stabilized pyrolysis oil and MJ of stabilized pyrolysis oil

Albizia	kg/MT (Dis)	g/MJ (Dis)	kg/MT (Spatari et al.)	g/MJ (Spatari et al.)
Pretreatment				
Primary Sizing	23.7	1.77	19.5	1.46
Secondary Sizing & Handling	19.8	1.48	16.3	1.22
Total	43.5	3.25	35.8	2.67
Pyrolysis				
Raw Materials				
Albizia	117	8.77	96.5	7.21
Sand	1.26E-02	9.43E-04	1.04E-02	7.75E-04
Sand Transport	0.10	7.57E-03	8.33E-02	6.23E-03
Total	117	8.78	96.6	7.22
RTP Utilities				
Natural Gas	2.73E-02	2.04E-03	2.24E-02	1.68E-03
Water	4.06	0.30	3.34	0.25
Steam	-187	-14.0		
Air	0.37	2.78E-02	0.31	2.28E-02
Electricity	229	17.1	188	14.1
Total	46.5	3.48	192	14.3
Waste Streams				
Ash to landfill	0.31	2.35E-02	0.26	1.94E-02
Total	0.31	2.35E-02	0.26	1.94E-02
Pyrolysis Total	208	15.5	324	24.2
Filtration				
Pyrolysis Oil	208	15.53	324	24.2
Filter cake	-96.2	-7.19		
Transportation	19.1	1.42	18.0	1.35
Filtration Total	131	9.77	342	25.6
Ion Exchange				
Utilities				
Electricity	7.12E-02	5.32E-03	7.12E-02	5.32E-03
Steam	0.26	1.97E-02	0.26	1.97E-02
Total	0.34	2.51E-02	0.34	2.51E-02
Raw Materials				
Filtered pyoil	131.3	9.80	342.3	25.6
Ethanol	33.4	2.50	33.4	2.50
Sulfuric Acid	0.33	2.46E-02	0.33	2.46E-02
NaOH	4.38	0.33	4.38	0.33
NaCl	0.55	4.13E-02	0.55	4.13E-02
Rinse water	9.24E-04	6.91E-05	9.24E-04	6.91E-05

Total	169	12.7	381	28.5
Waste Streams				
Spent Brine	2.61E-02	1.95E-03	2.61E-02	1.95E-03
Stabilized PyOil Total	170	12.7	381	28.5

The main contributor of GHG emissions shown in Table 4.1 is electricity use during pyrolysis, which accounts for 17.1 g/MJ. However, this is offset by a large steam credit produced during pyrolysis, which is 14.0 g/MJ. Another co-product during this process is filter cake which can be combusted to produce steam providing a GHG credit of 7.19 g/MJ assuming it displaces coal used to produce steam. Corn ethanol is used as a flush solvent and contributes 2.50 g/MJ. In the downstream hydroprocessing step, the ethanol is converted to ethane which is in turn steam reformed to produce a portion of the required hydrogen. The entire process contributes 12.7 g/MJ, 3.93 g/MJ from pretreatment, pyrolysis, and stabilization. The balance of the GHG emissions occur during the production of the albizia biomass. Energy allocation results in higher GHG emissions than displacement allocation, consistent with what is normally observed in other biofuel life cycle assessments.

Table 4.2 shows the CED results for stabilized pyrolysis oil derived from albizia using displacement allocation. In order to produce one MJ of stabilized pyrolysis oil 2.44 MJ of renewable biomass energy and 0.114MJ of non renewable fossil energy is required. Minor amounts of energy derived from other sources are also included in Table 4.2. It is important that renewable energy contributes significantly to this process because that is one of the targeted advantage for this fuel compared to other existing fuels such as coal.

Table 4.2: CED for stabilized pyrolysis oil derived from albizia using displacement allocation with a functional unit of one MJ of stabilized pyrolysis oil

Cumulative Energy Demand	MJ/MJ
Non renewable fossil	0.114
Non renewable nuclear	9.52E-02
Non renewable biomass	6.13E-07
Renewable biomass	2.44
Renewable others	4.81E-04
Renewable water	9.1E-03
Total	2.66

Table 4.3 breaks down the non renewable fossil energy from Table 4.2 to determine what inputs consume the most fossil energy. Electricity use is the leading contributor of fossil energy at 0.239 MJ/MJ. Diesel, transportation, and ethanol also contribute to the overall fossil energy use. The steam and filter cake co-products provide energy credits of 0.233 and 0.069 respectively. The total fossil energy used for this process is 0.114 MJ per MJ of stabilized pyrolysis oil derived from albizia.

Table 4.3: FED for stabilized pyrolysis oil derived from albizia using displacement allocation with a functional unit of one MJ of stabilized pyrolysis oil

Fossil Energy Demand	MJ/MJ
Electricity	0.239
Diesel	6.05 E-02
Truck transport	5.17E-02
Barge transport	2.68E-02
Ethanol	2.52E-02
Filter Cake	-6.9E-02
Steam Credit	-0.233
Remaining	1.31E-02
Total	0.114

4.2.2 Feedstocks other than Albizia

Inputs for pyrolysis and stabilization derived from each feedstock other than albizia were used to generate GHG emission results shown in Tables 4.4A and B. More detailed results are provided in Appendix 6. The results reflect displacement allocation with units of grams of CO_2 eq. per MJ of stabilized pyrolysis oil. This analysis includes pretreatment, pyrolysis, and stabilization of the pyrolysis oil. Stabilization is broken down into two steps, filtration and ion exchange. Each feedstock is a raw material input during pyrolysis and therefore uses inputs from the corresponding feedstock production to arrive at this result.

Table 4.4A: GHG emissions (CO2 eq.) for stabilized pyrolysis oil using displacement allocation with a functional unit of one MJ of stabilized pyrolysis oil

GHG Emissions	Bagasse	Guinea Grass	Open Pond Algae	Corn Stover
Pretreatment	1.85	2.32	2.56	2.18
RTP Raw Materials				
Biomass feedstock	1.38	12.3	25.8 20.7[1]	6.36
Other raw materials	3.14E-03	3.81E-03	3.67E-03	4.09E-03
RTP Utilities				
Steam Credit	-5.47	-1.98	-7.13	-9.97
Electricity	8.25	9.96	8.16	13.5
Other (utilities and waste treatment)	0.20	0.32	0.20	0.40
PyOil Stabilization				
Filter cake credit	-3.70	-4.45	-4.93	-7.64
Transportation of filtered pyoil	0.90	1.01	0.77	1.13
Steam	1.35E-02	3.98E-02	1.46E-02	1.76E-02
Ethanol	1.71	5.15	1.88	2.31
Other (Materials, Utilities, and Waste Treatment)	0.69	1.91	0.70	0.91
Stabilized PyOil Total	5.82	26.6	28.0 22.9[1]	9.20

[1]Open Pond Algae (75% recycle)

Table 4.4B: Continuation of GHG emissions for stabilized pyrolysis oil using displacement allocation with a functional unit of one MJ of stabilized pyrolysis oil

GHG Emissions	LA Corn Stover	Switchgrass	Waste Wood	Wild Algae
Pretreatment	2.27	2.68	2.60	2.55
RTP Raw Materials				
Biomass feedstock	6.40	12.03	4.05	51.0 -38.9(1)
Other raw materials	9.57E-03	3.72E-03	8.98E-03	3.69E-03
RTP Utilities				
Steam Credit	-20.5	-9.1	-15.1	-2.33
Electricity	15.8	11.6	16.2	8.64
Other (utilities and waste treatment)	0.29	0.28	0.28	0.36
PyOil Stabilization				
Filter cake credit	-6.51	-5.04	-5.35	-8.09
Transportation of filtered pyoil	1.22	1.18	1.15	0.72
Steam	9.24E-03	1.78E-02	1.44E-02	4.93E-02
Ethanol	1.25	2.24	1.90	6.26
Other (Materials, Utilities, and Waste Treatment)	0.21	0.84	0.32	2.34
Stabilized PyOil Total	0.45	16.7	6.07	61.5 -28.4(1)

(1)Wild Algae with waste water treatment credit

One of the largest contributors of GHG emissions is the RTP raw materials, in particular the biomass feedstock. Feedstocks that are considered waste products (waste wood, low ash corn stover, and sugarcane bagasse) that do not require fertilizer inputs have the lowest emissions. Feedstocks requiring fertilizer have higher GHG emission. Natural gas is used to produce fertilizers like urea, ammonium nitrate, etc. and a large amount of CO_2 emissions are produced in this process. The largest contributor of GHG emissions to produce a biomass feedstock is wild algae. This is attributed to the large amount of water that needs to be processed and removed during the algae harvesting process. This process requires a large amount of electricity, which results in large GHG emissions. If wild algae is grown on waste water treatment effluent and a credit is taken for avoiding a separate denitrification step then the wild algae emissions are by far the lowest.

Another large GHG emission is electricity. Stabilized pyrolysis oil derived from open pond algae has the highest lower heating value. This large lower heating value resulted in the lowest electricity emissions based on MJ of stabilized pyrolysis oil.

During the RTP process steam is generated by the excess heat that is produced in the reheat section of the pyrolysis. This steam credit was accounted for using displacement allocation as shown in Tables 4.4A and B. Energy allocation results are shown in Appendix 6. This steam credit has a significant impact on the total GHG emissions as shown in low ash corn stover case, where the calculated steam credit was -20.5 g/MJ. Because of this large credit the total emissions for this process using low ash corn stover as the feedstock was 0.45 g/MJ. The larger total emissions for guinea grass feedstock, 26.6 g/MJ, is due to the large biomass and electricity inputs.

Tables 4.5A and B shows the CED results for stabilized pyrolysis oil derived from each feedstock using displacement allocation.

Table 4.5A: CED for stabilized pyrolysis oil using displacement allocation with a functional unit of one MJ of stabilized pyrolysis oil

CED (MJ/MJ)	Bagasse	Guinea Grass	Open Pond Algae	Corn Stover
Non renewable fossil	5.52E-02	0.279	0.472	0.100
Non renewable nuclear	5.05E-02	7.86E-02	0.154	7.92E-02
Non renewable biomass	3.93E-07	1.3E-06	3.03E-05	5.92E-06
Renewable biomass	0.941	1.46	1.22	1.77
Renewable others	2.87E-04	6.27E-04	1.18E-03	4.85E-04
Renewable water	4.97E-03	8.73E-03	1.65E-02	7.92E-03
Total	1.05	1.83	1.87	1.96

Table 4.5B: Continuation of CED for stabilized pyrolysis oil using displacement allocation with a functional unit of one MJ of stabilized pyrolysis oil

CED (MJ/MJ)	LA Corn Stover	Switchgrass	Waste Wood	Wild Algae
Non renewable fossil	-5.03E-02	0.135	2.01E-02	0.932
Non renewable nuclear	7.78E-02	7.75E-02	8.44E-02	0.260
Non renewable biomass	5.26E-06	1.08E-05	3.51E-07	1.54E-06
Renewable biomass	1.65	1.50	1.99	1.38
Renewable others	3.93E-04	4.85E-04	3.98E-04	1.54E-03
Renewable water	7.35E-03	8.59E-03	7.82E-03	2.48E-02
Total	1.68	1.72	2.10	2.60

In order to produce one MJ of stabilized pyrolysis oil 1.05 to 2.60 MJ of energy is required. Biomass contributes the most energy as expected, because that is what the fuel is derived from. The remaining energy is used to process, transport, or stabilize the fuel. The higher energy demand is associated with fertilizers, and large electricity usage similar to the GHG results discussion on the previous page. It is important that renewable energy contributes significantly to this process because that is one of the targeted advantages to this fuel compared to fossil fuels such as coal.

Tables 4.6A and B below show the FED results for stabilized pyrolysis oil derived from each feedstock using displacement allocation.

Table 4.6A: FED for stabilized pyrolysis oil using displacement allocation with a functional unit of one MJ of stabilized pyrolysis oil

FED (MJ/MJ)	Bagasse	Guinea Grass	OP Algae	Corn Stover
Electricity	0.119	0.144	0.319	0.184
Truck Transport	3.42E-02	3.78E-02	2.50E-02	1.79E-02
Ethanol	1.72E-02	5.18E-02	1.89E-02	2.32E-02
Fertilizer	---	3.89E-02	0.267	6.74E-02
Filter Cake	-3.55E-02	-4.26E-02	-4.74E-02	-7.33E-02
Steam Credit	-9.13E-02	-3.24E-02	-0.119	-0.167
Remaining	1.14E-02	8.2E-02	1.01E-02	4.78E-02
Total	5.52E-02	0.279	0.472	0.100

Table 4.6B: Continuation of FED for stabilized pyrolysis oil using displacement allocation with a functional unit of one MJ of stabilized pyrolysis oil

FED (MJ/MJ)	LA Corn Stover	Switchgrass	Waste Wood	Wild Algae
Electricity	0.199	0.167	0.220	0.591
Truck Transport	1.81E-02	3.16E-02	3.12E-02	3.34E-02
Ethanol	1.18E-02	2.26E-02	1.91E-02	6.32E-02
Fertilizer	6.92E-02	2.39E-02	---	0.33[1]
Filter Cake	-5.89E-02	-4.83E-02	-5.13E-02	-7.76E-02
Steam Credit	-0.322	-0.151	-0.252	-3.81E-02
Remaining	3.24E-02	8.96E-02	5.33E-02	3.00E-02
Total	-5.03E-02	0.135	2.01E-02	0.932

[1]This is chemical additives used during wild algae production

Electricity is one of the largest emissions contributing between 0.119 to 0.591 MJ/MJ for sugarcane bagasse and wild algae respectively. The electricity was used during the pretreatment and pyrolysis steps and the harvesting step for wild algae. Two co-products were produced, filter cake from filtering the pyrolysis oil, and steam produced from the excess heat generated in the RTP process. The credits from these co-products help minimize the net FED. The steam has the largest credit ranging between -0.0324 to -0.322 MJ/MJ for guinea grass and low ash corn stover respectively. Wild algae has the highest FED at 0.932 MJ/MJ because of the large amount of electricity and the amount of chemical additives used during the feedstock production stage. Low ash corn stover has a FED of -0.0503 MJ/MJ because of the large amount of steam produced in this process.

Chapter 5: Inputs and Results for Hydrocarbon Biofuel Production

5.1 Inputs

The inputs for upgrading stabilized pyrolysis oil for each feedstock are shown in Table A5.1 of Appendix 5. The main inputs are electricity and natural gas utilities and natural gas used to produce hydrogen for the process. There is a steam credit associated with hydrogen production and a steam credit during upgrading. There is cooling water and boiler feed water used in the upgrading process and de-mineralized water used in the integrated hydrogen process. Figure 5.1 shows a simplified block flow diagram of the upgrading process. These inputs are used in SimaPro 7.2 to calculate GHG emissions, CED/FED, and to show how much water is used in the process.

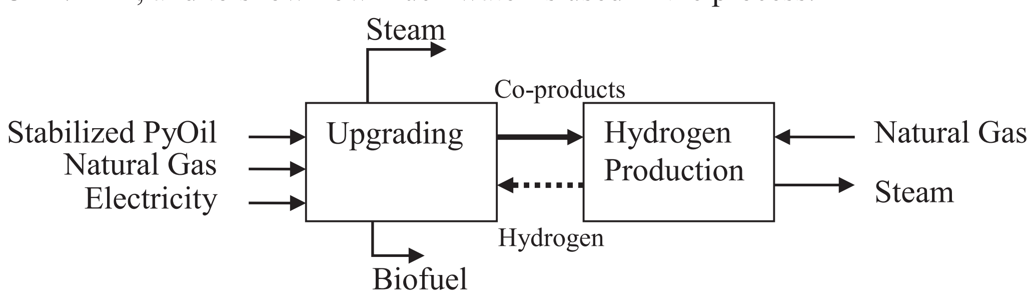

Figure 5.1: Simplified Block flow diagram of the upgrading process

Transportation inputs of petroleum products to consumer from the NETL report (NETL 2008) were used to estimate the transportation inputs for the Biofuels generated in this process. Each biofuel needs to be transported to gas stations for consumer use. The inputs in Table 5.6 from the NETL report were used in this study for transporting biofuel to the consumer.

5.2 Results

Inputs supplied by UOP as shown in Appendix 5, were used to calculate GHG emissions for each biomass feedstock using displacement and energy allocation. CED and FED results were also calculated for each feedstock. The results that are discussed use displacement allocation and the functional unit is 1 MJ of biofuel.

5.2.1 Albizia

Inputs for upgrading stabilized pyrolysis bio-oil derived from albizia were used to generate the GHG emission results shown in Table 5.1. The results for displacement allocation are in the first two columns and the results for energy allocation in the last two columns. Each allocation method shows results in both kg of CO_2 eq. per metric ton of biofuels and grams of CO_2 eq. per MJ of biofuel. The feedstock production, pyrolysis and stabilization results are shown in the first three rows and the upgrading results are broken down into more detail in the latter rows.

Table 5.1: GHG emissions (CO2 eq.) for biofuel derived from albizia for both displacement (Dis) and energy allocation (Spatari et al.) with two functional units of metric tons of biofuel and MJ of biofuel.

Albizia Results	kg /MT (Dis)	g/MJ (Dis)	kg /MT (Spatari et al.)	g/MJ (Spatari et al.)
Feedstock Production	360	8.37	237	5.51
Pyrolysis	277	6.45	559	13.01
Stabilization	-117	-2.72	140	3.26
Upgrading				
Raw material				
Stabilized pyoil	520	12.10	936	21.8
Effluents				
Wastewater	0.61	1.42E-02	0.49	1.14E-02
Utilities				
Electricity	181	4.21	145	3.37
Natural gas	101	2.35	80.9	1.88
Water	0.63	1.47E-02	0.51	1.18E-02
Steam	-202	-4.70		
Solid waste	1.11E-02	2.58E-04	8.89E-03	2.07E-04
Integrated H_2 Plant				
Natural gas	1050	24.4	841	19.6
Demineralized water	9.73E-02	2.26E-03	7.79E-02	1.81E-03
HP steam	-581	-13.5		
Electricity	54.2	1.26	43.4	1.01
Transportation	8.86	0.21	7.10	0.17
Overall Total	1134	26.4	2055	47.79

The main contributor of GHG emissions is the natural gas used to produce hydrogen. When looking at the results for displacement allocation, the natural gas used in upgrading utilities and in integrated H_2 production contributes 92% of the total GHG emissions for the entire process. There is also a large credit of high pressure (HP) steam (13.5 g/MJ) in the integrated hydrogen process, which reduces the overall GHG emissions significantly. Another important result is the electricity use, which contributes 4.21 g/MJ during upgrading. Steam is also produced during upgrading step and a credit of 4.70 g/MJ is associated with this co-product. Conventional non-renewable gasoline contributes 90.12 g/MJ, while the albizia derived biofuel contributes 26.4 g/MJ, which is a 70.7% GHG savings.

Table 5.2 shows the CED results for this biofuel. Renewable biomass contributes 2.33 MJ of energy to produce one MJ of biofuel, and in which fossil fuels contribute 0.333 MJ to produce one MJ of biofuels. This is important because renewable fuels should contribute the most energy to this process otherwise there would be no reason to switch from fossil fuels to this biofuels derived from albizia.

Table 5.2: CED for biofuel derived from albizia using displacement allocation with a functional unit of one MJ of biofuel

Cumulative Energy Demand	MJ/MJ
Non renewable fossil	0.333
Non renewable nuclear	0.12
Non renewable biomass	7.57E-07
Renewable biomass	2.33
Renewable others	6.86E-04
Renewable water	1.17E-02
Total	2.8

Table 5.3 breaks down the non renewable fossil energy to determine what inputs use the most fossil energy. This table shows that natural gas is the leading contributor of fossil energy. Natural gas contributes 0.461 MJ of energy per MJ of biofuels. However, this natural gas not only produces hydrogen for the process but also produces steam. Excess steam has a credit of 0.527 MJ of energy per MJ of biofuels, which more than offsets the

fossil energy from natural gas. The fossil energy portion is 0.333 MJ per MJ of biofuels derived from albizia.

Table 5.3: FED for biofuel derived from albizia using displacement allocation with a functional unit of one MJ of biofuel

Fossil Energy Demand	MJ/MJ
Natural gas	0.461
Electricity	0.292
Diesel	5.77E-02
Truck transport	4.93E-02
Barge transport	2.56E-02
Ethanol	2.4E-02
Filter cake	-6.57E-02
Steam credit	-0.527
Remaining	1.55E-02
Total	0.333

5.2.2 Feedstocks Excluding Albizia

Inputs for upgrading stabilized pyrolysis oil derived from each feedstock other than albizia were used to generate GHG emission results shown in Tables 5.4A and B. More detailed results are shown in Appendix 6. The results in these tables are for displacement allocation with units of grams of CO_2 eq. per MJ of upgraded pyrolysis oil. The upgrading step is split into two stages, the integrated hydrogen plant and the upgrading step. The integrated hydrogen step uses steam methane reforming to produce hydrogen from the HC gases produced in the upgrading reaction as well as from imported natural gas. The hydrogen is then reacted with the stabilized pyrolysis oil to form upgraded pyrolysis oil, which is the final biofuel product.

Table 5.4A: GHG emissions (g CO2 eq/MJ) for upgraded pyrolysis oil using displacement allocation with a functional unit of one MJ of upgraded pyrolysis oil

Results	Bagasse	Guinea Grass	Open Pond Algae	Corn Stover
Feedstock Production	1.55	14.1	30.4/24.5[1]	6.63
Pyrolysis	5.41	12.1	4.47	6.36
Stabilization	-0.45	4.19	-1.85	-3.41
Upgrading				
Steam credit	-3.49	-4.09	-3.16	-4.09
Electricity	3.12	3.67	2.81	3.67
Natural gas	1.75	2.07	1.58	2.06
Other (Materials, Utilities, waste)	1.11E-02	1.30E-02	9.98E-03	1.30E-02
Integrated H_2 Plant				
Natural gas	11.2	13.9	10.3	19.0
Steam credit	-9.49	-11.8	-9.49	-11.2
Other (Materials, Utilities)	1.10	1.31	1.10	1.25
Biofuel Total	10.7	35.5	36.2/30.2[1]	20.3

[1]Nutrient recycle

Table 5.4B: GHG emissions (g CO2 eq/MJ) continued for upgraded pyrolysis oil using displacement allocation with a functional unit of one MJ of upgraded pyrolysis oil

Results	Low Ash (LA) Corn Stover	Switchgrass	Waste Wood	Wild Algae
Feedstock Production	6.73	11.9	4.08	66.4/-50.7[1]
Pyrolysis	-2.23	5.36	3.97	12.0
Stabilization	-4.04	-0.76	-1.99	1.67
Upgrading				
Steam credit	-4.37	-4.02	-3.98	-3.49
Electricity	3.93	3.60	3.56	3.09
Natural gas	2.20	2.02	2.00	1.74
Other (Materials, Utilities, waste)	2.65E-02	2.34E-02	0.13	1.59E-02
Integrated H_2 Plant				
Natural gas	25.8	27.7	21.6	2.65
Steam credit	-12.0	-12.8	-11.4	-11.0
Other (Materials, Utilities)	1.33	1.40	1.28	1.23
Biofuel Total	17.4	34.4	19.3	74.3/ -42.8[1]

[1]Wastewater treatment Credit

Feedstock production, pyrolysis, and stabilization process steps are discussed in more detail in Chapters 3 and 4. Feedstock production was dominated by fertilizer and electricity use, which cause GHG emission to increase. Pyrolysis and stabilization emissions were controlled primarily by the electricity use and co-product credits. Upgrading emissions were dominated by natural gas used to generate hydrogen in the integrated hydrogen plant. Steam credits also play a significant role in the final GHG emissions.

Natural gas usage depends on the amount of co-product produced in the upgrading step. The more HC gas produce as a co-product the less natural gas is required to generate hydrogen. GHG emission from steam reforming of natural gas range from 2.65 to 27.7 g/MJ from biofuels derived from wild algae and switchgrass, respectively.

The amount of steam that is produced during upgrading and resulting from methane steam reforming are similar between each feedstock biofuel, but does significantly reduce the overall emissions. The steam credit is the largest in the integrated hydrogen plant with the credit of GHG emission from switchgrass derived biofuel at -12.8 g/MJ. The largest steam credit from upgrading is -4.37 g/MJ from low ash corn stover derived biofuel.

Tables 5.5A and B show the CED results for each biofuel derived from each feedstock excluding albizia using displacement allocation.

Table 5.5A: CED for upgraded pyrolysis oil using displacement allocation with a functional unit of one MJ of upgraded pyrolysis oil

CED (MJ/MJ)	Bagasse	Guinea Grass	Open Pond Algae	Corn Stover
Non renewable fossil	0.118	0.388	0.596	0.271
Non renewable nuclear	7.62E-02	0.113	0.20	0.108
Non renewable biomass	4.96E-07	1.48E-06	3.58E-05	6.32E-06
Renewable biomass	1.05	1.67	1.44	1.85
Renewable others	4.49E-04	8.63E-04	1.51E-03	6.92E-04
Renewable water	7.45E-03	1.22E-02	2.12E-02	1.08E-02
Total	1.25	2.18	2.26	2.24

Table 5.5B: CED (continued) for upgraded pyrolysis oil using displacement allocation with a functional unit of one MJ of upgraded pyrolysis oil

CED (MJ/MJ)	LA Corn Stover	Switchgrass	Waste Wood	Wild Algae
Non renewable fossil	0.219	0.426	0.227	1.1
Non renewable nuclear	0.115	0.104	0.111	0.355
Non renewable biomass	6.02E-06	1.09E-05	5.24E-07	1.91E-06
Renewable biomass	1.84	1.48	2.00	1.79
Renewable others	6.62E-04	7.14E-04	6.02E-04	2.08E-03
Renewable water	1.12E-02	1.15E-02	1.06E-02	3.37E-02
Total	2.14	2.03	2.35	3.28

In order to produce one MJ of biofuel 1.25 to 3.28 MJ of energy is required, depending on biomass type. Biomass energy contributes the most energy as expected, because that is what the fuel is derived from. The remaining energy is used to process, transport, or stabilize the fuel. The higher energy demand is associated with fertilizers and electricity usage. The energy associated with fertilizer production is shown mostly in non renewable fossil energy because most fertilizers are derived from fossil fuels like natural gas. Electricity assumes the U.S. grid electricity, which uses most of the energy sources but is dominated by non renewable fossil energy

Tables 5.6A and B show the FED results for biofuels derived from each feedstock other than albizia using displacement allocation.

Table 5.6A: FED for upgraded pyrolysis oil using displacement allocation with a functional unit of one MJ of upgraded pyrolysis oil

FED (MJ/MJ)	Bagasse	Guinea Grass	Open Pond Algae	Corn Stover
Natural Gas	0.224	0.276	0.204	0.363
Electricity	0.18	0.22	0.419	0.247
Truck transport	3.81E-02	4.32E-02	3.03E-02	1.87E-02
Fertilizer	---	4.44E-02	0.314	7.03E-02
Ethanol	1.92E-02	5.91E-02	2.23E-02	2.42E-02
Filter cake	-3.96E-02	-4.87E-02	-5.59E-02	-7.64E-02
Steam credit	-0.319	-0.303	-0.352	-0.429
Remaining	1.57E-02	9.67E-02	1.41E-02	5.29E-02
Total	0.118	0.388	0.596	0.271

Table 5.6B: FED continued for upgraded pyrolysis oil using displacement allocation with a functional unit of one MJ of upgraded pyrolysis oil

FED (MJ/MJ)	LA Corn Stover	Switchgrass	Waste Wood	Wild Algae
Natural gas	0.483	0.514	0.407	7.57E-02
Electricity	0.281	0.221	0.275	0.817
Truck transport	2.02E-02	3.12E-02	3.13E-02	4.43E-02
Ethanol	1.32E-02	2.23E-02	1.92E-02	8.22E-02
Fertilizer	7.13E-02	3.25E-02	---	0.429(1)
Filter cake	-6.58E-02	-4.77E-02	-5.16E-02	-0.101
Steam credit	-0.633	-0.43	-0.511	-0.291
Remaining	4.54E-02	8.25E-02	5.77E-02	4.11E-02
Total	0.215	0.426	0.227	1.10

(1)This is chemical additives used during wild algae production

Natural gas and electricity are the largest fossil energy inputs for each biofuel. The electricity FED is the largest in the wild and open pond algae because of the large electricity inputs during feedstock production. Natural gas FED is the largest in the remaining biofuels because of the large input used to generate hydrogen. The natural gas contributes between 0.0757 to 0.514 MJ/MJ for wild algae and swithchgrass respectively. Two co-products are produced; filter cake from filtering the pyrolysis oil, and steam produce by the excess heat during pyrolysis. These co-products help minimize the FED. The steam has the largest credit ranging between -0.633 to -0.291 MJ/MJ for low ash corn stover and wild algae respectively. Wild algae has the highest FED at 1.10 MJ/MJ because of the large amount of electricity and natural gas use. Sugarcane bagasse has the lowest FED of 0.118 MJ/MJ because of the large amount of steam produced in this process and the low amount of natural gas and electricity required.

Chapter 6 LCA Summary, Conclusions and Recommendations

6.1 Summary and Conclusions

6.1.1 Feedstock Production

The feedstocks analyzed in this study covered a wide range of types; residues from agriculture and forests, energy crops such as switchgrass and managed guinea grass, and algae. The biomass types that released the least amount of GHG emissions were feedstocks that are considered waste products as shown in Figure 6.1. The figures in chapter 6 were developed from the results in chapter 5. The different scenarios, including nutrient recycle and waste water treatment, were not included in these figures.

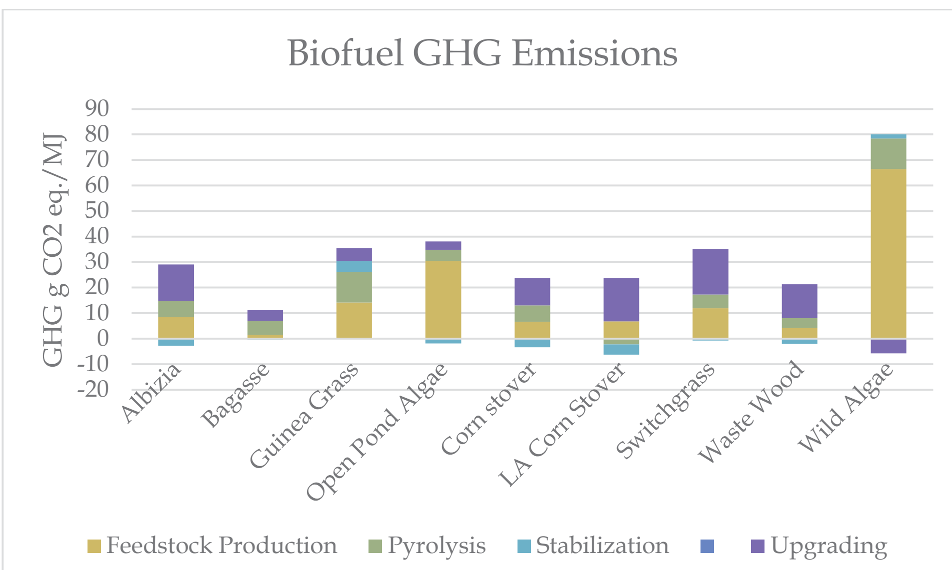

Figure 6.1 GHG emissions showing each stage of each biofuel with a functional unit of 1 MJ of biofuel for displacement allocation

Feedstocks like sugarcane bagasse and waste wood had no fertilizer inputs, which greatly increase the GHG emissions as well as the fossil energy demand as shown in Figure 6.2. Sugarcane bagasse was the best feedstock because after sugar is extracted from sugarcane the bagasse is left. This is why sugarcane bagasse emits a low amount of GHGs. There is no cultivation, which includes fertilizers, no harvest, which uses diesel and no collection of the biomass because the sugarcane was collected for sugar production, not for biofuel.

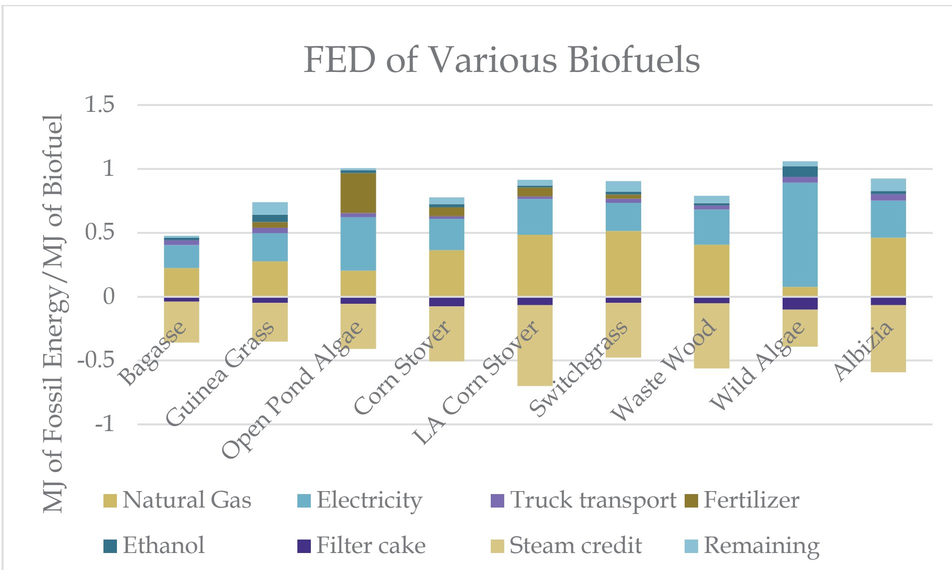

Figure 6.2 FED of each biofuel with a functional unit of one MJ of Biofuel for displacement allocation

Waste wood is similar to bagasse but waste wood needs to be collected and chipping and grinding is required, which increases the GHG emissions, FED, and CED which is shown in Figure 6.3. Both algae cases have the highest GHG emissions due to large electricity inputs used to pump, and dewater the algae. However, if algae were cultivated as part of wastewater treatment, a large energy and GHG emission credit for avoiding a nutrient removal step may be warranted and could make algae a promising feedstock.

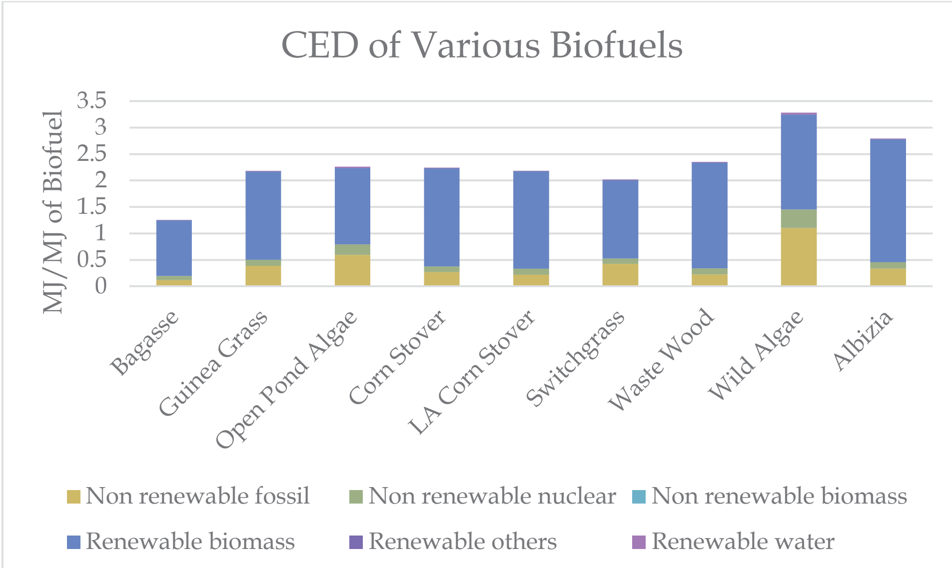

Figure 6.3 Total CED for each biofuel with a function unit of one MJ for displacement allocation

Sugarcane bagasse does have the lowest GHG emissions and uses the least amount of fossil fuels, but is currently not grown very much in the United States. If large amount of sugarcane bagasse were needed to make biofuels, significant imports of cane from Brazil may be needed. Switchgrass is native to much of the United States and has a yield of 13.6 MT/ha in many locations. Switchgrass also usually sequesters carbon in the soil, which results in a high dLUC credit compared to many prior land uses. Switchgrass also grows on marginal lands and may not compete with food crops or create iLUC impacts. When looking at sustainability and feedstock availability in the United States switchgrass has the potential to be a very significant feedstock.

6.1.2 Pyrolysis and Stabilization

Stabilized pyrolysis oil derived from low ash corn stover releases only -4.04 g of CO_2/MJ of biofuel and fossil energy credits more than offset fossil energy consumption with a net -0.0503 MJ of fossil energy/MJ of stabilized pyrolysis oil. This low GHG emission and negative fossil energy use is because of the displacement credit from the co-products. Stabilized pyrolysis oil is potentially an attractive fuel for electricity production to replace coal or other types of nonrenewable fuels currently used to produce electricity. Stabilized pyrolysis oil from sugarcane bagasse and waste wood also had low GHG emissions, while stabilized pyrolysis oil from algae had the highest GHG emissions and FED because of high inputs for algae production.

6.1.3 Upgrading to Hydrocarbon Biofuels

The upgrading input that had the largest effect on the overall GHG emissions was the natural gas used to produce hydrogen. Natural gas used to produce hydrogen usually was also the main contributor of fossil energy. The total GHG emissions ranged from 10.7 to 74.3 g CO_2 eq./MJ for sugarcane bagasse and wild algae respectively as shown in Figure 6.4. The remaining biofuel results depend on the amount of natural gas during upgrading and fertilizer inputs and fuel inputs during feedstock production.

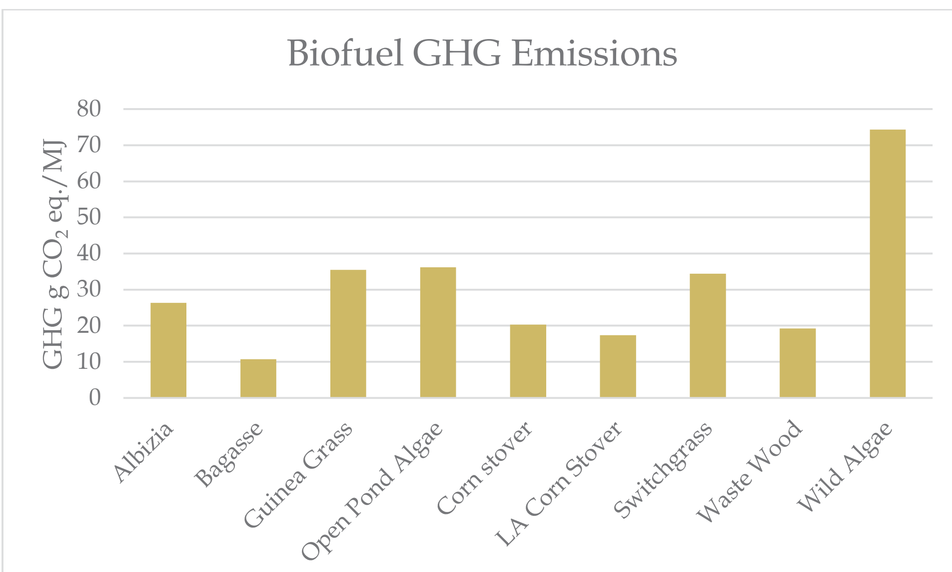

Figure 6.4 GHG emissions of each biofuel with a functional unit of 1 MJ of biofuel for displacement allocation

The biofuel that had the lowest GHG emissions was derived from sugarcane bagasse, which had a GHG emission percent savings compared to conventional nonrenewable gasoline of 88%. Wild algae released the most emissions but still saved 19% compared to nonrenewable gasoline. With the exception of wild algae derived biofuel the rest of the biofuels had a GHG emission savings of more than 50% compared to gasoline. Therefore, based on this study pyrolysis-based biofuels produced from a variety of biomass feedstocks will meet the GHG savings target for advanced biofuels of 50% and in some the 60% threshold for cellulosic fuels as mandated by the Renewable Fuels Standard.

Similar to the GHG emission sugarcane bagasse had the lowest total CED and FED as shown in Figure 6.5 and 6.6. Sugarcane bagasse uses 0.118 MJ of fossil fuels for every MJ of biofuel and 1.25 MJ of total energy for every MJ of biofuel. The difference between the FED and CED is mostly energy from renewable biomass (1.05 MJ/MJ) as shown in Figure 6.3. The biofuels that are derived from a waste like waste wood and bagasse have the lowest FED and CED. As more fertilizers and fuel is used in feedstock production the higher the FED and CED as the biofuels derived from guinea grass and switchgrass shows in Figure 6.5. The algae derived biofuel used the most electricity in feedstock production and resulted in the largest FED and CED.

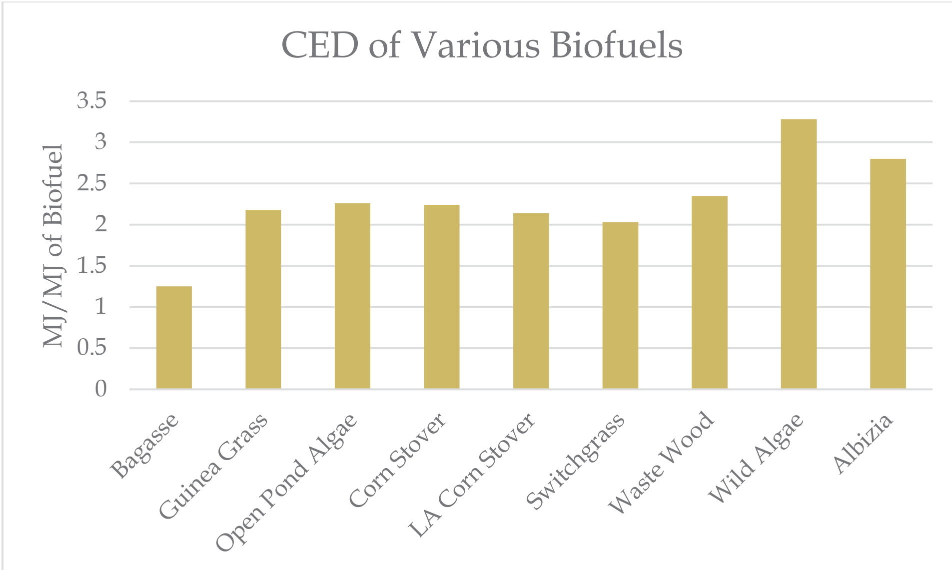

Figure 6.5 Total FED for each biofuel with a function unit of one MJ for displacement allocation

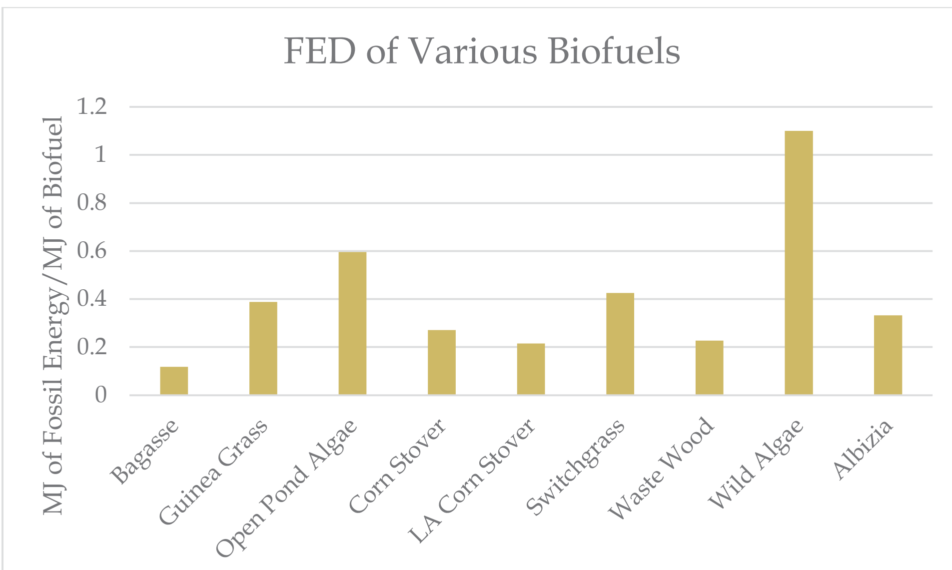

Figure 6.6 Total FED for each biofuel with a function unit of one MJ for displacement allocation

6.2 Recommendations

The LCA results in this MS thesis leads to the recommendation that biofuels derived from waste products like sugarcane bagasse and waste wood should be used whenever possible as the feedstock to produce biofuels. When there is limited supply of waste products energy crops such as grasses and woody biomass may also be considered because, with the exception of wild algae, energy crop based biofuels also can reduce the GHG emissions by more than 50% compared to nonrenewable gasoline.

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Appendix 1

No Tables or figures associated with chapter 1 in appendix and therefore left blank.

Appendix 2

Table A2.1: EAF of each feedstock for pyrolysis, stabilization, and upgrading.

	Pyrolysis	Stabilization	Upgrading
Albizia	0.87	0.95	0.80
Corn Stover	0.88	0.93	0.83
Corn Stover Low Ash	0.77	0.94	0.82
Switchgrass	0.89	0.95	0.81
Guinea Grass	0.97	0.96	0.82
Sugarcane Bagasse	0.93	0.96	0.85
Waste Wood	0.83	0.95	0.83
Wild Algae	0.97	0.92	0.84
Open Pond Algae	0.91	0.95	0.85

Albizia

$$\frac{1\ kg\ of\ pyrolysis\ oil*16.6\ LHV\ of\ pyrolysis\ oil}{1\ kg\ of\ pyrolysis\ oil*16.6\ LHV\ of\ pyrolysis\ oil+0.78\ kg\ of\ steam*3.2\ primary\ energy\ of\ steam}=0.87$$

$$\frac{0.958\ kg\ of\ filtered\ pyoil*16.188\ LHV\ of\ filtered\ pyoil}{0.958\ kg\ of\ filtered\ pyoil*16.188\ LHV\ of\ filtered\ pyoil+0.042\ kg\ of\ filter\ cake*21.3\ LHV\ of\ filter\ cake}=0.95$$

$$\frac{1\ kg\ of\ biofuel*43\ LHV\ of\ biofuel}{01\ kg\ of\ biofuel*43\ LHV\ of\ biofuel+3.34\ kg\ of\ steam*3.2\ primary\ energy\ of\ steam}=0.80$$

Corn Stover

$$\frac{1\ kg\ of\ pyrolysis\ oil*16.4\ LHV\ of\ pyrolysis\ oil}{1\ kg\ of\ pyrolysis\ oil*16.4\ LHV\ of\ pyrolysis\ oil+0.68\ kg\ of\ steam*3.2\ primary\ energy\ of\ steam}=0.88$$

$$\frac{0.93\ kg\ of\ filtered\ pyoil*16.492\ LHV\ of\ filtered\ pyoil}{0.93\ kg\ of\ filtered\ pyoil*16.492\ LHV\ of\ filtered\ pyoil+0.07\ kg\ of\ filter\ cake*16.6\ LHV\ of\ filter\ cake}=0.93$$

$$\frac{1\ kg\ of\ biofuel*43\ LHV\ of\ biofuel}{01\ kg\ of\ biofuel*43\ LHV\ of\ biofuel+2.8\ kg\ of\ steam*3.2\ primary\ energy\ of\ steam}=0.83$$

Low Ash Corn Stover

$$\frac{1\,kg\ of\ pyrolysis\ oil*14.4\ LHV\ of\ pyrolysis\ oil}{1\,kg\ of\ pyrolysis\ oil*14.4\ LHV\ of\ pyrolysis\ oil+1.33\,kg\ of\ steam*3.2\ primary\ energy\ of\ steam}=0.77$$

$$\frac{0.956\,kg\ of\ filtered\ pyoil*15.638\ LHV\ of\ filtered\ pyoil}{0.956\,kg\ of\ filtered\ pyoil*15.638\ LHV\ of\ filtered\ pyoil+0.044\,kg\ of\ filter\ cake*21.6\ LHV\ of\ filter\ cake}$$
$$=0.94$$

$$\frac{1\,kg\ of\ biofuel*43\ LHV\ of\ biofuel}{01\,kg\ of\ biofuel*43\ LHV\ of\ biofuel+3.0\,kg\ of\ steam*3.2\ primary\ energy\ of\ steam}=0.82$$

Switchgrass

$$\frac{1\,kg\ of\ pyrolysis\ oil*16.6\ LHV\ of\ pyrolysis\ oil}{1\,kg\ of\ pyrolysis\ oil*16.6\ LHV\ of\ pyrolysis\ oil+0.61\,kg\ of\ steam*3.2\ primary\ energy\ of\ steam}=0.89$$

$$\frac{0.961\,kg\ of\ filtered\ pyoil*16.188\ LHV\ of\ filtered\ pyoil}{0.961\,kg\ of\ filtered\ pyoil*16.188\ LHV\ of\ filtered\ pyoil+0.039\,kg\ of\ filter\ cake*21.3\ LHV\ of\ filter\ cake}$$
$$=0.95$$

$$\frac{1\,kg\ of\ biofuel*43\ LHV\ of\ biofuel}{01\,kg\ of\ biofuel*43\ LHV\ of\ biofuel+3.0\,kg\ of\ steam*3..08\ primary\ energy\ of\ steam}=0.81$$

Guinea Grass

$$\frac{1\,kg\ of\ pyrolysis\ oil*17\ LHV\ of\ pyrolysis\ oil}{1\,kg\ of\ pyrolysis\ oil*17\ LHV\ of\ pyrolysis\ oil+0.15\,kg\ of\ steam*3.2\ primary\ energy\ of\ steam}=0.97$$

$$\frac{0.949\,kg\ of\ filtered\ pyoil*17.624\ LHV\ of\ filtered\ pyoil}{0.949\,kg\ of\ filtered\ pyoil*17.624\ LHV\ of\ filtered\ pyoil+0.051\,kg\ of\ filter\ cake*15.2\ LHV\ of\ filter\ cake}$$
$$=0.96$$

$$\frac{1\,kg\ of\ biofuel*43\ LHV\ of\ biofuel}{01\,kg\ of\ biofuel*43\ LHV\ of\ biofuel+2.92\,kg\ of\ steam*3.2\ primary\ energy\ of\ steam}=0.82$$

Sugarcane Bagasse

$$\frac{1\,kg\ of\ pyrolysis\ oil*20.6\ LHV\ of\ pyrolysis\ oil}{1\,kg\ of\ pyrolysis\ oil*20.6\ LHV\ of\ pyrolysis\ oil+0.49\,kg\ of\ steam*3.2\ primary\ energy\ of\ steam}=0.93$$

$$\frac{0.968\,kg\ of\ filtered\ pyoil*20.934\ LHV\ of\ filtered\ pyoil}{0.968\,kg\ of\ filtered\ pyoil*20.934\ LHV\ of\ filtered\ pyoil+0.032\,kg\ of\ filter\ cake*23\ LHV\ of\ filter\ cake}=$$
$$0.96$$

$$\frac{1\ kg\ of\ biofuel*43\ LHV\ of\ biofuel}{01\ kg\ of\ biofuel*43\ LHV\ of\ biofuel+2.38\ kg\ of\ steam*3.2\ primary\ energy\ of\ steam} = 0.85$$

Waste Wood

$$\frac{1\ kg\ of\ pyrolysis\ oil*16.6\ LHV\ of\ pyrolysis\ oil}{1\ kg\ of\ pyrolysis\ oil*16.6\ LHV\ of\ pyrolysis\ oil+1.05\ kg\ of\ steam*3.2\ primary\ energy\ of\ steam} = 0.83$$

$$\frac{0.961\ kg\ of\ filtered\ pyoil*15.638\ LHV\ of\ filtered\ pyoil}{0.956\ kg\ of\ filtered\ pyoil*15.638\ LHV\ of\ filtered\ pyoil+0.044\ kg\ of\ filter\ cake*21.6\ LHV\ of\ filter\ cake} = 0.95$$

$$\frac{1\ kg\ of\ biofuel*43\ LHV\ of\ biofuel}{01\ kg\ of\ biofuel*43\ LHV\ of\ biofuel+2.83\ kg\ of\ steam*3.2\ primary\ energy\ of\ steam} = 0.83$$

Wild Algae

$$\frac{1\ kg\ of\ pyrolysis\ oil*23.6\ LHV\ of\ pyrolysis\ oil}{1\ kg\ of\ pyrolysis\ oil*23.6\ LHV\ of\ pyrolysis\ oil+0.24\ kg\ of\ steam*3.2\ primary\ energy\ of\ steam} = 0.97$$

$$\frac{0.898\ kg\ of\ filtered\ pyoil*24.146\ LHV\ of\ filtered\ pyoil}{0.898\ kg\ of\ filtered\ pyoil*24.146\ LHV\ of\ filtered\ pyoil+0.102\ kg\ of\ filter\ cake*18.3\ LHV\ of\ filter\ cake} = 0.92$$

$$\frac{1\ kg\ of\ biofuel*43\ LHV\ of\ biofuel}{01\ kg\ of\ biofuel*43\ LHV\ of\ biofuel+2.65\ kg\ of\ steam*3.2\ primary\ energy\ of\ steam} = 0.84$$

Open Pond Algae

$$\frac{1\ kg\ of\ pyrolysis\ oil*24.5\ LHV\ of\ pyrolysis\ oil}{1\ kg\ of\ pyrolysis\ oil*24.5\ LHV\ of\ pyrolysis\ oil+0.73\ kg\ of\ steam*3.2\ primary\ energy\ of\ steam} = 0.91$$

$$\frac{0.952\ kg\ of\ filtered\ pyoil*24.561\ LHV\ of\ filtered\ pyoil}{0.952\ kg\ of\ filtered\ pyoil*24.561\ LHV\ of\ filtered\ pyoil+0.048\ kg\ of\ filter\ cake*23.7\ LHV\ of\ filter\ cake} = 0.95$$

$$\frac{1\ kg\ of\ biofuel*43\ LHV\ of\ biofuel}{01\ kg\ of\ biofuel*43\ LHV\ of\ biofuel+2.32\ kg\ of\ steam*3.2\ primary\ energy\ of\ steam} = 0.85$$

Appendix 3

Table A3.1: Albizia inputs mostly from the UP Survey and some from Grays Harbor (see Table A3.6) with a basis of one dry metric ton.

Albizia	UP Survey / Grays Harbor	Units
Chainsaw Harvest		
Lubricating Oil	0.0748	kg
Gasoline	0.436	kg
Diesel	0.828	kg
Combustion-Diesel	0.828	kg
Combustion-Gasoline	0.436	kg
Collecting/Loading		
Diesel	3.34	kg
Combustion-Diesel	3.34	kg
Machinery	9.26E-6	p
Transportation		
Transport truck	80.6	tkm
Transport Barge	403	tkm
Unloading/Storage		
Diesel	1.86	kg
Combustion-Diesel	1.86	kg
Machinery	9.26E-9	p
Chipping and Grinding		
Diesel	1.05	kg
Combustion-Diesel	1.05	kg
Electricity-Hawaiian	23.4	kWh
Chipper and Grinder	5.51E-6	p
Collecting/Loading		
Diesel	3.34	kg
Combustion-Diesel	3.34	kg
Machinery	9.26E-6	p

Table A3.2: Switchgrass inputs for three scenarios (SimaPro, Ceres, and Literature) at different transportation distances (15, 25, and 50 miles) from Ceres and inputs from literature with a basis of one dry metric ton

Switchgrass Inputs	SimaPro	Ceres	Literature*	Units
Land Prep. / Planting				
Diesel		0.97	---	kg/ha
Grease		2.72E-03	---	kg/ha
Hydraulic oil		3.40E-03	---	kg/ha
Lubricating oil		5.79E-03	---	kg/ha
Combustion-Diesel		0.97	---	kg/ha
Combustion-Lubricating Oil		5.79E-03	---	kg/ha
Cultivating				
Diesel		12.1	---	kg/ha
Nitrogen (Table A3.3)				
Potassium sulfate, as K_2O		106	54	kg/ha
Monoammonium phosphate, as P_2O_5		101	17	kg/ha
Limestone		640	150	kg/ha
CO_2 from limestone application		640	150	kg/ha
Hydraulic oil		4.28E-02	---	kg/ha
Grease		3.42E-02	---	kg/ha
Lubricating oil		7.28E-02	---	kg/ha
Combustion-Diesel		12.1	---	kg/ha
Tractor production	0.687	---	---	kg/ha
Agricultural machinery production	0.241	---	---	kg/ha
Combustion-Lubricating Oil		7.28E-02		kg/ha
Harvest				
Diesel		139	---	kg/ha
Lubricating oil		0.83	---	kg/ha
Hydraulic oil		0.49	---	kg/ha
Grease		0.39	---	kg/ha
Combustion-Diesel		139	---	kg/ha
Agricultural machinery production	26.6	---	---	kg/ha
Tractor production	6.14	---	---	kg/ha
Combustion-Lubricating Oil		0.83	---	kg/ha
Transportation 15 miles scenario Ceres				

Truck	24.19	---	tkm
Transportation 25 miles scenario Ceres			
Truck	40.32	---	tkm
Transportation 50 miles scenario Ceres			
Truck	80.65	---	tkm
Switchgrass Transportation			
Truck	---	100.00	tkm

*(Cherubini and Jungmeier 2010)

Table A3.3: Nitrogen fertilizer related inputs for switchgrass at several different location scenarios with units of kg per one dry metric ton.

Nitrogen Fertilizer	**#1**	**#2**	**#3**	**#4**	**#5**
Urea, as N					
Ammonium nitrate, as N					
N_2O emission from N fertilizer					
CO_2 from urea application					

Nitrogen Fertilizer	**#6**	**#7**	**#8**	**#9**	**#10**
Urea, as N					
Ammonium nitrate, as N					
N_2O emission from N fertilizer					
CO_2 from urea application					

Table A3.4: Average annual CO2 Sequestration for switchgrass at several locations (from Ceres)

Locations	**kg CO_2 / dry MT**
Munich, ND	96
Streeter, ND	48
Bristol, SD	248
Highmore, SD	77
Huron, SD	-31
Ethan, SD	-37
Crofton, NE	41
Atkinson, NE	66
Douglas, NE	120
Lawrence, NE	123
Average	75

Table A3.5: Inventory data for algae cultivation, harvesting, and transport for Aquaflow Bionomic Corporation with a basis of one dry metric ton and an algae density of 300 g/m3. (C.D. = Confidential Data)

Wild Algae	Inputs	Units
Cultivation		
chemical additives	**C.D.**	metric tons
Pump shed		
motor (0)	**C.D.**	kWh
motor (1)	**C.D.**	kWh
motor (Inc.)	**C.D.**	kWh
motor (3)	**C.D.**	kWh
motor (5)	**C.D.**	kWh
New Harvest Units		
motor (6)	**C.D.**	kWh
motor (7)	**C.D.**	kWh
motor (8)	**C.D.**	kWh
motor (9)	**C.D.**	kWh
motor (10)	**C.D.**	kWh
motor (11)	**C.D.**	kWh
De-watering		
motor (12)	**C.D.**	kWh
motor (13)	**C.D.**	kWh
Transportation	**C.D.**	tkm

Table A3.6: Waste wood inputs with a basis of one dry metric ton (C.D. = Confidential Data)

Waste Wood	Grays Harbor	UP Survey	Units
Collecting/Loading			
Materials/Assemblies			
Diesel		3.34	kg
Processes			
Combustion-Diesel		3.34	kg
Machinery		9.26E-06	p
Transportation			
Processes			
Transport truck	**C.D.**		tkm
Unloading/Storage			
Materials/Assemblies			
Diesel		1.86	kg
Processes			
Combustion-Diesel		1.86	kg
Machinery		9.26E-06	p
Chipping and Grinding			
Materials/Assemblies			
Diesel		0.11	kg
Processes			
Combustion-Diesel		0.11	kg
Electricity WA State Emissions	**C.D.**		kWh
Chipper and Grinder		5.51E-06	p

Table A3.7: Guinea grass inputs for two scenarios with different land preparation requirements and a scenario on unmanaged land with a basis of one dry metric ton (C.D. = Confidential Data)

Guinea Grass Inputs	SimaPro	Inputs	Units
Land Prep minimal vegetation			
Materials/Assemblies			
Diesel		**C.D.**	kg
Processes			
Combustion-Diesel		**C.D.**	kg
Land Prep medium vegetation			
Materials/Assemblies			
Diesel		**C.D.**	kg
Processes			
Combustion-Diesel		**C.D.**	kg
Cultivation			
Materials/Assemblies			
Diesel		**C.D.**	kg
Urea, as N		**C.D.**	kg
N_2O emission from N fertilizer		**C.D.**	kg
CO_2 from urea application		**C.D.**	kg
Potassium sulfate, as K_2O		**C.D.**	kg
Thomas meal, as P_2O_5		**C.D.**	kg
Lubricating oil		**C.D.**	kg
Hydraulic oil		**C.D.**	kg
Grease		**C.D.**	kg
Processes			
Combustion-Diesel		**C.D.**	kg
Tractor, production	0.687	---	kg/ha
Agricultural machinery production	0.241	---	kg/ha
Combustion-Lubricating Oil		**C.D.**	kg
Harvest (Unmanaged Land)			
Materials/Assemblies			
Diesel		**C.D.**	kg
Grease		**C.D.**	kg
Hydraulic oil		**C.D.**	kg
Lubricating oil		**C.D.**	kg
Processes			
Combustion-Diesel		**C.D.**	kg
Tractor, production	26.6	---	kg/ha

Agricultural machinery production	6.14	---	kg/ha
Combustion-Lubricating Oil		**C.D.**	kg
Harvest (Managed Land)			
Materials/Assemblies			
Diesel		**C.D.**	kg
Grease		**C.D.**	kg
Hydraulic oil		**C.D.**	kg
Lubricating oil		**C.D.**	kg
Processes			
Combustion-Diesel		**C.D.**	kg
Tractor, production	26.6	---	kg/ha
Agricultural machinery production	6.14	---	kg/ha
Combustion-Lubricating Oil		**C.D.**	kg
Transport			
Materials/Assemblies			
Diesel (Trucking)		**C.D.**	kg
Diesel (Oceanic barge)		**C.D.**	kg
Processes			
Truck		**C.D.**	tkm
Oceanic barge		**C.D.**	tkm

Table A.3.8 Hawaiian Electricity Mix(U.S. EPA 2005)

Emissions	lb of emissions per MWh
CO_2	1731.01
CH_4	165.4
N_2O	29.96

Appendix 4

Table A4.1: Inputs for each feedstock for pretreatment and pyrolysis

FEEDSTOCK TYPE	Units	Bagasse	Stover	Guinea Grass	Switchgrass	Wild Algae
Functional Unit						
Pyrolysis Oil	kg					
LHV	MJ/kg					
Density	kg/liter					
Pretreatment						
Electricity	kWh					
Electricity	kWh					
Raw Materials						
Dry Biomass*	kg					
Sand	kg					
RTP Utilities						
Electricity	kWh					
Natural Gas	SCF					
150 psig Steam export (-)	lb					
Cooling Water (25->29 C)	gal					
Heated Water (75-> 65 C)	gal					
Instrument Air (100 psig dry)	SCF					
Waste Streams						
Ash (to landfill or reuse?)	kg					
Co-Products						
Char (all combusted)	kg					
Fuel Gas (all combusted)	kg					

Confidential Data

Confidential Data

Table A4.1 continued

FEEDSTOCK TYPE	Units	Open Pond Algae	Waste Wood	Low Ash Stover	Albizia
Functional Unit					
Pyrolysis Oil	kg				
LHV	MJ/kg				
Density	kg/liter				
Pretreatment					
Electricity	kWh				
Electricity	kWh				
Raw Materials					
Dry Biomass*	kg				
Sand	kg				
RTP Utilities					
Electricity	kWh				
Natural Gas	SCF				
150 psig Steam export	lb				
Cooling Water (25->29 C)	gal				
Heated Water (75-> 65 C)	gal				
Instrument Air (100 psig dry)	SCF				
Waste Streams					
Ash (to landfill or reuse?)	kg				
Co-Products					
Char (all combusted)	kg				
Fuel Gas (all combusted)	kg				

Table A4.2: Inputs for each feedstock for stabilization

FEEDSTOCK TYPE	Units	Bagasse	Stover	Guinea Grass	Switchgrass	Wild Algae
Functional Unit						
Raw Pyrolysis Oil	kg					
LHV	MJ/kg					
Density of Raw Pyrolysis Oil	kg/liter					
1. Filtration at Site						
Products						
Filtered PyOil	kg					
Filtered PyOil LHV	MJ/kg					
PyOil Allocation Factor						
Filter Cake	kg					
Filter Cake LHV	MJ/kg					
Filter Cake Allocation Factor						
2. Transportation						
Filtered PyOil to Refinery	km					
Filter Cake to Heat Recovery	km					
3. Ion Exchange at Refinery						
a. Utilities						
Electricity	kWh					
Steam	kg					
b. Raw Material						
Filtered PyOil						
Ethanol	kg					
98% H_2SO_4	kg					
50% NaOH	kg					
10% NaCl	kg					

Confidential Data

Confidential Data

Rinse Water	kg
c. Waste Streams	
Spent Brine to Disposal	kg
Products	
Stabilized PyOil*	kg
Stabilized PyOil (NETL)	kg
Stabilized Pyoil LHV	MJ/kg
*** with ethanol**	

Confidential Data

Table A4.2 continued

FEEDSTOCK TYPE		Open Pond Algae	Waste Wood	Low Ash Stover	Albizia
Functional Unit					
Raw Pyrolysis Oil	kg				
LHV	MJ/kg				
Density of Raw Pyrolysis Oil	kg/liter				
1. Filtration at Site					
Products					
Filtered PyOil	kg				
Filtered PyOil LHV	MJ/kg				
PyOil Allocation Factor		Confidential Data			
Filter Cake	kg				
Filter Cake LHV	MJ/kg				
Filter Cake Allocation Factor					
2. Transportation					
Filtered PyOil to Refinery	km				
Filter Cake to Heat Recovery	km				
3. Ion Exchange at Refinery					
a. Utilities					
Electricity	kWh				
Steam	kg				
b. Raw Material		Confidential Data			
Filtered PyOil					
Ethanol	kg				
98% H_2SO_4	kg				
50% NaOH	kg				
10% NaCl	kg				

Rinse Water	kg
c. Waste Streams	
Spent Brine to Disposal	kg
Products	
Stabilized PyOil*	kg
Stabilized PyOil (NETL)	kg
Stabilized Pyoil LHV	MJ/kg
*** with ethanol**	

Confidential Data

Appendix 5

Table A5.1a: Upgrading inputs for all feedstocks. HC=hydrocarbon, CW=cooling water, BFW=boiler feed water, Demin.=demineralized, HP=high pressure.

Feedstock	Units	Bagasse	Stover	Guinea Grass	Switchgrass
HC Biofuel	kg				
Raw Material					
Stabilized PyOil	kg				
H_2	kg				
Co-Product					
HC Gas[1]	kg				
Effluents					
Wastewater	kg				
CO_2 (biogenic)	kg				
Utilities					
Power	kWh				
Natural Gas	kg				
CW	m^3				
BFW	tonne				
Steam	tonne				
Solid Waste	kg				
Integrated H_2 Plant					
Natural Gas	kg				
Demin. H_2O	tonne				
HP steam	tonne				
Electricity	kWh				

[1] All available HC gas is used to generate hydrogen in the integrated hydrogen plant

Confidential Data

Confidential Data

Table A5.1b: Upgrading inputs for all feedstock. HC=hydrocarbon, CW=cooling water, BFW=boiler feed water, Demin.=demineralized, HP=high pressure.

Feedstock	Units	Wild Algae	Open Pond Algae	Waste Wood	Low Ash Corn Stover	Albizia
HC Biofuel	kg					
Raw Material						
Stabilized PyOil	kg					
H_2	kg					
Co-Products						
HC Gas[1]	kg					
Effluents						
Wastewater	kg					
CO_2 (biogenic)	kg					
Utilities						
Power	kWh					
Natural Gas	kg					
CW	m^3					
BFW	tonne					
Steam	tonne					
Solid Waste	kg					
Integrated H2 Plant						
Natural Gas	kg					
Demin. H_2O	tonne					
HP steam	tonne					
Electricity	kWh					

[1] All available HC gas is used to generate hydrogen in the integrated hydrogen plant

Confidential Data

Confidential Data

Table A5.2a: Water use for each feedstock in gallons of water per kg of biofuel assuming 2% and 5% water consumption for cooling water (CW) and boiler feed water (BFW), respectively

Water Use	Bagasse	Stover	Guinea Grass	Switchgrass
Feedstock Production				
Pyrolysis				
Cooling water (25-29°C)				
Heated Water (60-75°C)				
Stabilization				
Rinse Water				
Spent Brine				
Water from 98% H_2SO_4				
Water from 50% NaOH				
Water from 10% NaCl				
Upgrading				
Cooling water				
Boiler Feed Water				
Wastewater				
Integrated H_2 Plant				
Demineralized Water				
WWT using CHG				
Cooling water Make-up				
Total (gallons/kg biofuel)				

Confidential Data

Confidential Data

Table A5.2b: Water use for each feedstock in gallons of water per kg of biofuel assuming 2% and 5% water consumption for cooling water (CW) and boiler feed water (BFW) respectively

Water Use	Wild Algae	OP Algae	Wood	Stover LA	Albizia
Feedstock Production					
Pyrolysis					
Cooling water (25-29°C)					
Heated Water (60-75°C)			Confidential Data		
Stabilization					
Rinse Water					
Spent Brine					
Water from 98% H_2SO_4					
Water from 50% NaOH					
Water from 10% NaCl					
Upgrading					
Cooling water					
Boiler Feed Water			Confidential Data		
Wastewater					
Integrated H_2 Plant					
Demineralized Water					
WWT using CHG					
Cooling water Make-up					
Total (gallons/kg biofuel)					

Appendix 6

Table A6.1: GHG emissions for stabilized pyrolysis oil derived from sugarcane bagasse using both displacement and energy allocation with two functional units of metric tons of stabilized pyrolysis oil and MJ of stabilized pyrolysis oil

Bagasse	kg/MT (Displacement)	g/MJ (Displacement)	kg/MT (Spatari et al.)	g/MJ (Spatari et al.)
Pretreatment				
Primary Sizing	19.6	0.93	17.6	0.83
Secondary Sizing & Handling	19.6	0.93	17.6	0.83
Total	39.1	1.85	35.1	1.66
Pyrolysis				
Raw Materials				
Bagasse	29.2	1.38	26.2	1.24
Sand	7.33E-03	3.47E-04	6.58E-03	3.11E-04
Sand Transport	5.89E-02	2.79E-03	5.28E-02	2.50E-03
Total	29.3	1.39	26.3	1.24
RTP Utilities				
Natural Gas	1.79E-02	8.49E-04	1.61E-02	7.62E-04
Water	3.64	0.17	3.26	0.15
Steam	-116	-5.47		
Air	0.33	1.58E-02	0.30	1.42E-02
Electricity	174	8.25	156	7.40
Total	62.8	2.97	160	7.57
Waste Streams				
Ash to landfill	0.34	1.61E-02	0.31	1.45E-02

Total	0.34	1.61E-02	0.31	1.45E-02
Pyrolysis total	132	6.22	222	10.5
Filtration				
Pyrolysis Oil	132	6.22	222	10.5
Filter cake	-78.2	-3.70		
Transportation	19.0	0.90	18.4	0.87
Filtration Total	72.4	3.42	240	11.4
Ion Exchange				
Utilities				
Electricity	0.78	3.70E-02	0.78	3.70E-02
Steam	0.29	1.35E-02	0.29	1.35E-02
Total	1.07	5.05E-02	1.07	5.05E-02
Raw Materials				
Filtered pyoil	72.4	3.42	240	11.4
Ethanol	36.1	1.71	36.1	1.71
Sulfuric Acid	0.84	0.04	0.84	0.04
NaOH	11.2	0.53	11.2	0.53
NaCl	1.39	6.59E-02	1.39	6.59E-02
Rinse water	2.34E-03	1.11E-04	2.34E-03	1.11E-04
Total	122	5.77	290	13.7
Waste Streams				
Spent Brine	6.62E-02	3.13E-03	6.62E-02	3.13E-03
Stabilized PyOil Total	123	5.82	291	13.8

Table A6.2: CED for stabilized pyrolysis oil derived from sugarcane bagasse using displacement allocation with a functional unit of one MJ of stabilized pyrolysis oil

Cumulative Energy Demand	MJ/MJ
Non renewable fossil	5.52E-02
Non renewable nuclear	5.05E-02
Non renewable biomass	3.93E-07
Renewable biomass	0.941
Renewable others	2.87E-04
Renewable water	4.97E-03
Total	1.05

Table A6.3: FED for stabilized pyrolysis oil derived from sugarcane bagasse using displacement allocation with a functional unit of one MJ of stabilized pyrolysis oil

Fossil Energy Demand	MJ/MJ
Electricity	0.119
Truck transport	3.42E-02
Ethanol	1.72E-02
Filter Cake	-3.55E-02
Steam Credit	-9.13E-02
Remaining	1.14E-02
Total	5.52E-02

Table A6.4: GHG emissions for stabilized pyrolysis oil derived from guinea grass using both displacement and energy allocation with two functional units of metric tons of stabilized pyrolysis oil and MJ of stabilized pyrolysis oil

Guinea Grass	kg/MT (Displacement)	g/MJ (Displacement)	kg/MT (Spatari et al.)	g/MJ (Spatari et al.)
Pretreatment				
Primary Sizing	23.1	1.26	21.5	1.17
Secondary Sizing & Handling	19.3	1.06	18.0	0.98
Total	42.5	2.32	39.4	2.15
Pyrolysis				
Raw Materials				
Guinea Grass	225	12.3	209	11.4
Sand	7.72E-03	4.22E-04	7.17E-03	3.92E-04
Sand Transport	6.21E-02	3.39E-03	5.77E-02	3.15E-03
Total	225	12.3	209	11.4
RTP Utilities				
Natural Gas	2.02E-02	1.11E-03	1.88E-02	1.03E-03
Water	4.11	0.22	3.81	0.21
Steam	-36.3	-1.98		
Air	0.40	2.16E-02	0.37	2.01E-02
Electricity	182	9.96	169	9.25
Total	151	8.23	174	9.48
Waste Streams				
Ash to landfill	1.41	7.72E-02	1.31	7.17E-02
Total	1.41	7.72E-02	1.31	7.17E-02
Pyrolysis total	420	22.9	424	23.1
Filtration				
Pyrolysis Oil	420	22.9	424	23.1

Filter cake	-81.5	-4.45		
Transportation	18.4	1.01	17.6	0.96
Filtration Total	357	19.5	441	24.1
Ion Exchange				
Utilities				
Electricity	0.21	1.14E-02	0.21	1.14E-02
Steam	0.73	3.98E-02	0.73	0.04
Total	0.94	5.12E-02	0.94	0.05
Raw Materials				
Filtered pyoil	357	19.5	441	24.1
Ethanol	94.2	5.15	94.2	5.15
Sulfuric Acid	2.17	0.12	2.17	0.12
NaOH	29.0	1.58	29.0	1.58
NaCl	3.62	0.20	3.62	0.20
Rinse water	6.07E-03	3.32E-04	6.07E-03	3.32E-04
Total	486	26.5	570	31.1
Waste Streams				
Spent Brine	0.17	9.40E-03	0.17	9.40E-03
Stabilized PyOil Total	487	26.6	571	31.2

Table A6.5: CED for stabilized pyrolysis oil derived from guinea grass using displacement allocation with a functional unit of one MJ of stabilized pyrolysis oil

Cumulative Energy Demand	MJ/MJ
Non renewable fossil	0.279
Non renewable nuclear	7.86E-02
Non renewable biomass	1.3E-06
Renewable biomass	1.46
Renewable others	6.27E-04
Renewable water	8.73E-03
Total	1.83

Table A6.6: FED for stabilized pyrolysis oil derived from guinea grass using displacement allocation with a functional unit of one MJ of stabilized pyrolysis oil

Fossil Energy	MJ/MJ
Electricity	0.144
Ethanol	5.18E-02
Urea	3.89E-02
Truck Transport	3.78E-02
Filter Cake	-4.26E-02
Steam Credit	-3.24E-02
Remaining	8.2E-02
Total	0.279

Table A6.7: GHG emissions for stabilized pyrolysis oil derived from open pond algae using both displacement and energy allocation with two functional units of metric tons of stabilized pyrolysis oil and MJ of stabilized pyrolysis oil

Open Pond Algae	kg/MT (Displacement)	g/MJ (Displacement)	kg/MT (Spatari et al.)	g/MJ (Spatari et al.)
Pyrolysis Oil				
Pretreatment				
Sizing & Handling	63.2	2.56	55.0	2.22
Total	63.2	2.56	55.0	2.22
Raw Materials				
Open Pond Algae	637	25.8	537	21.7
Open Pond Algae (75% recycle)	513	20.7	429	17.4
Sand	9.38E-03	3.79E-04	8.16E-03	3.30E-04
Sand Transport	8.14E-02	3.29E-03	7.08E-02	2.86E-03
Total	513	20.7	537	21.7
Total (75% recycle)	637	25.8	429	17.4
RTP Utilities				
Natural Gas	2.20E-02	8.91E-04	1.92E-02	7.75E-04
Water	3.64	0.15	3.17	0.13
Steam	-176	-7.13		
Air	0.34	1.36E-02	0.29	1.19E-02
Electricity	202	8.16	176	7.10
Total	29.6	1.20	179	7.24
Waste Streams				
Ash to landfill	0.86	3.49E-02	0.75	3.04E-02
Total	0.86	3.49E-02	0.75	3.04E-02
Pyrolysis Total	731	29.5	772	31.2
Pyrolysis Total (75% recycle)	607	24.5	664	26.9

Filtration				
Pyrolysis Oil	731	29.5	772	31.2
Filter cake	-122	-4.93		
Transportation	18.9	0.77	18.0	0.73
Filtration Total	628	25.4	790	31.9
Filtration Total (75% recycle)	504	20.4	682	27.6
Ion Exchange				
Utilities				
Electricity	0.10	4.17E-03	0.10	4.17E-03
Steam	0.36	1.46E-02	0.36	1.46E-02
Total	0.46	1.87E-02	0.46	1.87E-02
Raw Materials				
Filtered pyoil	628	25.4	790	31.9
Ethanol	46.5	1.88	46.5	1.88
Sulfuric Acid	1.07	4.33E-02	1.07	4.33E-02
NaOH	14.4	0.58	14.4	0.58
NaCl	1.79	7.25E-02	1.79	7.25E-02
Rinse water	2.99E-03	1.21E-04	2.99E-03	1.21E-04
Total	691	28.0	854	34.5
Waste Streams				
Spent Brine	8.48E-02	3.43E-03	8.48E-02	3.43E-03
Stabilized PyOil Total	692	28.0	854	34.5
Stabilized PyOil Total (75% recycle)	568	23.0	746	30.2

Table A6.8: CED for stabilized pyrolysis oil derived from open pond algae using displacement allocation and assuming no nutrient recycle with a functional unit of one MJ of stabilized pyrolysis oil

Cumulative Energy Demand	MJ/MJ
Non renewable fossil	0.472
Non renewable nuclear	0.154
Non renewable biomass	3.03E-05
Renewable biomass	1.22
Renewable others	1.18E-03
Renewable water	1.65E-02
Total	1.87

Table A6.9: FED for stabilized pyrolysis oil derived from open pond algae using displacement allocation and assuming no nutrient recycle with a functional unit of one MJ of stabilized pyrolysis oil

Fossil Energy	MJ/MJ
Electricity	0.319
Ammonium nitrate	0.171
Phosphate	5.85E-02
Potassium	3.7E-02
Ethanol	1.89E-02
Truck Transport	2.50 E-02
Filter Cake	-4.74E-02
Steam Credit	-0.119
Remaining	1.01E-02
Total	0.472

Table A6.10: GHG emissions for stabilized pyrolysis oil derived from corn stover using both displacement and energy allocation with two functional units of metric tons of stabilized pyrolysis oil and MJ of stabilized pyrolysis oil

Corn Stover	kg/MT (Displacement)	g/MJ (Displacement)	kg/MT (Spatari et al.)	g/MJ (Spatari et al.)
Pretreatment				
Primary Sizing	20.3	1.21	16.7	0.99
Secondary Sizing & Handling	16.2	0.97	13.3	0.79
Total	36.6	2.18	30.0	1.79
Pyrolysis				
Raw Materials				
Corn Stover	107	6.36	87.6	5.22
Sand	7.62E-03	4.53E-04	6.25E-03	3.72E-04
Sand Transport	6.12E-02	3.64E-03	5.02E-02	2.99E-03
Total	107	6.36	87.7	5.22
RTP Utilities				
Natural Gas	2.67E-02	1.59E-03	2.19E-02	1.30E-03
Water	4.16	0.25	3.41	0.20
Steam	-167	-9.97		
Air	0.42	0.02	0.34	2.03E-02
Electricity	226	13.5	186	11.1
Total	63.6	3.79	190	11.3
Waste Streams				
Ash to landfill	2.18	0.13	1.79	0.11
Total	2.18	0.13	1.79	0.11
Pyrolysis total	209	12.5	309	18.4
	102	6.10	221	13.2
Filtration				
Pyrolysis Oil	209	12.5	309	18.4

Filter cake	-128	-7.64		
Transportation	19.0	1.13	17.7	1.05
Filtration Total	99.8	5.94	327	19.5
Ion Exchange				
Utilities				
Electricity	0.89	5.32E-02	0.89	5.32E-02
Steam	0.30	1.76E-02	0.30	1.76E-02
Total	1.19	7.08E-02	1.19	7.08E-02
Raw Materials				
Filtered pyoil	99.8	5.94	327	19.5
Ethanol	38.8	2.31	38.8	2.31
Sulfuric Acid	0.90	5.34E-02	0.90	5.34E-02
NaOH	12.0	0.71	12.0	0.71
NaCl	1.50	8.94E-02	1.50	8.94E-02
Rinse water	2.50E-03	1.49E-04	2.50E-03	1.49E-04
Total	153	9.11	380	22.6
Waste Streams				
Spent Brine	7.09E-02	4.22E-03	7.09E-02	4.22E-03
Stabilized PyOil Total	154	9.19	381	22.7

Table A6.11: CED for stabilized pyrolysis oil derived from corn stover using displacement allocation with a functional unit of one MJ of stabilized pyrolysis oil

Cumulative Energy Demand	MJ/MJ
Non renewable fossil	0.100
Non renewable nuclear	7.92E-02
Non renewable biomass	5.92E-06
Renewable biomass	1.77
Renewable others	4.85E-04
Renewable water	7.92E-03
Total	1.96

Table A6.12: FED for stabilized pyrolysis oil derived from corn stover using displacement allocation with a functional unit of one

Fossil Energy	MJ/MJ
Electricity	0.184
Ammonia	3.96E-02
Diesel	2.87E-02
Potassium	2.78E-02
Ethanol	2.32E-02
Truck Transport	1.79E-02
Filter Cake	-7.33E-02
Steam Credit	-0.167
Remaining	1.91E-02
Total	0.100

Table A6.13 GHG emissions for stabilized pyrolysis oil derived from low ash corn stover using both displacement and energy allocation with two functional units of metric tons of stabilized pyrolysis oil and MJ of stabilized pyrolysis oil

LA Corn Stover	kg/MT (Displacement)	g/MJ (Displacement)	kg/MT (Spatari et al.)	g/MJ (Spatari et al.)
Pretreatment				
Primary Sizing	20.0	1.26	14.5	0.92
Secondary Sizing & Handling	15.9	1.01	11.6	0.73
Total	35.9	2.27	26.1	1.65
Pyrolysis				
Raw Materials				
LA Corn Stover	101	6.40	73.4	4.64
Sand	1.67E-02	1.05E-03	1.21E-02	7.65E-04
Sand Transport	0.13	8.52E-03	0.10	6.18E-03
Total	101	6.41	73.5	4.65
RTP Utilities				
Natural Gas	2.88E-02	1.82E-03	2.09E-02	1.32E-03
Water	4.04	0.26	2.93	0.19
Steam	-324	-20.5		
Air	0.37	2.37E-02	0.27	1.72E-02
Electricity	249	15.8	181	11.5
Total	-70.1	-4.44	184	11.7
Waste Streams				
Ash to landfill	0.54	3.45E-02	0.39	2.50E-02
Total	0.54	3.45E-02	0.39	2.50E-02
Pyrolysis total	67.7	4.28	284 211	18.0 13.3
Filtration				

Pyrolysis Oil	67.7	4.28	284	17.98
Filter cake	-103	-6.51		
Transportation	19.2	1.22	18.1	1.14
Filtration Total	-16.1	-1.02	302	19.1
Ion Exchange				
Utilities				
Electricity	3.99E-02	2.53E-03	3.99E-02	2.53E-03
Steam	0.15	9.24E-03	0.15	9.24E-03
Total	0.19	1.18E-02	0.19	1.18E-02
Raw Materials				
Filtered pyoil	-16.1	-1.02	302	19.1
Ethanol	19.7	1.25	19.7	1.25
Sulfuric Acid	0.19	1.22E-02	0.19	1.22E-02
NaOH	2.61	0.17	2.61	0.17
NaCl	0.33	2.07E-02	0.33	2.07E-02
Rinse water	5.45E-04	3.45E-05	5.45E-04	3.45E-05
Total	6.76	0.43	325	20.6
Waste Streams				
Spent Brine	1.54E-02	9.75E-04	1.54E-02	9.75E-04
Stabilized PyOil Total	6.96	0.44	325	20.6

Table A6.14: CED for stabilized pyrolysis oil derived from low ash corn stover using displacement allocation with a functional unit of one MJ of stabilized pyrolysis oil

Cumulative Energy Demand	MJ/MJ
Non renewable fossil	-5.03E-02
Non renewable nuclear	7.78E-02
Non renewable biomass	5.26E-06
Renewable biomass	1.65
Renewable others	3.93E-04
Renewable water	7.35E-03
Total	1.68

Table A6.15: FED for stabilized pyrolysis oil derived from low ash corn stover using displacement allocation with a functional unit of one MJ of stabilized pyrolysis oil

Fossil Energy Demand	MJ/MJ
Electricity	0.199
Ammonia	3.75E-02
Diesel	2.72E-02
Potassium	2.63E-02
Truck Transport	1.81E-02
Ethanol	1.18E-02
Phosphate	5.37E-03
Filter Cake	-5.89E-02
Steam Credit	-0.322
Remaining	5.18E-03
Total	-5.03E-02

Table A6.16: GHG emissions for stabilized pyrolysis oil derived from switchgrass using both displacement and energy allocation with two functional units of metric tons of stabilized pyrolysis oil and MJ of stabilized pyrolysis oil

Switchgrass	**kg/MT (Displacement)**	**g/MJ (Displacement)**	**kg/MT (Spatari et al.)**	**g/MJ (Spatari et al.)**
Pretreatment				
Primary Sizing	23.6	1.46	20.0	1.24
Secondary Sizing & Handling	19.7	1.22	16.7	1.04
Total	43.3	2.68	36.8	2.28
Pyrolysis				
Raw Materials				
Switchgrass	194	12.03	165	10.2
Sand	6.64E-03	4.11E-04	5.63E-03	3.49E-04
Sand Transport	5.34E-02	3.31E-03	4.53E-02	2.81E-03
Total	194	12.0	165	10.2
RTP Utilities				
Natural Gas	2.06E-02	1.28E-03	1.75E-02	1.08E-03
Water	3.69	0.23	3.13	0.19
Steam	-147	-9.10		
Air	0.34	2.08E-02	0.29	1.77E-02
Electricity	187	11.6	159	9.82
Total	43.9	2.71	162	10.0
Waste Streams				
Ash to landfill	0.48	2.98E-02	0.41	2.53E-02
Total	0.48	2.98E-02	0.41	2.53E-02
Pyrolysis total	282	17.5	364	22.5
Filtration				
Pyrolysis Oil	282	17.5	364	22.5

Filter cake	-81.4	-5.04		
Transportation	19.0	1.18	18.1	1.12
Filtration Total	220	13.6	382	23.7
Ion Exchange				
Utilities				
Electricity	7.87E-02	4.87E-03	0.08	4.87E-03
Steam	0.29	1.78E-02	0.29	1.78E-02
Total	0.37	2.26E-02	0.37	2.26E-02
Raw Materials				
Filtered pyoil	220	13.6	382	23.7
Ethanol	36.2	2.24	36.2	2.24
Sulfuric Acid	0.83	5.14E-02	0.83	5.14E-02
NaOH	11.1	0.69	11.1	0.69
NaCl	1.40	8.68E-02	1.40	8.68E-02
Rinse water	2.34E-03	1.45E-04	2.34E-03	1.45E-04
Total	269	16.7	432	26.7
Waste Streams				
Spent Brine	6.61E-02	4.09E-03	6.61E-02	4.09E-03
Stabilized PyOil Total	270	16.7	432	26.8

Table A6.17: CED for stabilized pyrolysis oil derived from switchgrass using displacement allocation with a functional unit of one MJ of stabilized pyrolysis oil

Cumulative Energy Demand	MJ/MJ
Non renewable fossil	0.135
Non renewable nuclear	7.75E-02
Non renewable biomass	1.08E-05
Renewable biomass	1.50
Renewable others	4.85E-04
Renewable water	8.59E-03
Total	1.72

Table A6.18: FED for stabilized pyrolysis oil derived from switchgrass using displacement allocation with a functional unit of one MJ of stabilized pyrolysis oil

Fossil Energy Demand	MJ/MJ
Electricity	0.167
Diesel	4.64E-02
Truck Transport	3.16E-02
Ethanol	2.26E-02
Potassium	1.28E-02
Phosphate	1.11E-02
Filter Cake	-4.83E-02
Steam Credit	-0.151
Remaining	4.32E-02
Total	0.135

Table A6.19: GHG emissions for stabilized pyrolysis oil derived from waste wood using both displacement and energy allocation with two functional units of metric tons of stabilized pyrolysis oil and MJ of stabilized pyrolysis oil

Waste Wood	kg/MT (Displacement)	g/MJ (Displacement)	kg/MT (Spatari et al.)	g/MJ (Spatari et al.)
Pretreatment				
Primary Sizing	23.6	1.42	18.7	1.12
Secondary Sizing & Handling	19.8	1.19	15.6	0.94
Total	43.4	2.60	34.3	2.06
Pyrolysis				
Raw Materials				
Waste Wood	67.5	4.05	53.3	3.20
Sand	1.65E-02	9.89E-04	1.30E-02	7.81E-04
Sand Transport	0.13	7.99E-03	0.11	6.31E-03
Total	67.6	4.06	53.4	3.21
RTP Utilities				
Natural Gas	3.23E-02	1.94E-03	2.55E-02	1.53E-03
Water	4.02	0.24	3.18	0.19
Steam	-252	-15.1		
Air	0.40	2.43E-02	0.32	1.92E-02
Electricity	269	16.2	213	12.8
Total	21.9	1.31	216	13.0
Waste Streams				
Ash to landfill	0.29	1.73E-02	0.23	1.36E-02
Total	0.29	1.73E-02	0.23	1.36E-02
Pyrolysis total	133	7.99	304	18.2
Filtration				
Pyrolysis Oil	133	7.99	304	18.2

Filter cake	-89.1	-5.35		
Transportation	19.1	1.15	18.1	1.09
Filtration Total	63.1	3.79	322	19.3
Ion Exchange				
Utilities				
Electricity	7.10E-02	4.26E-03	7.10E-02	4.26E-03
Steam	0.24	1.44E-02	0.24	1.44E-02
Total	0.31	1.87E-02	0.31	1.87E-02
Raw Materials				
Filtered pyoil	63.1	3.79	322	19.3
Ethanol	31.6	1.90	31.6	1.90
Sulfuric Acid	0.32	1.90E-02	0.32	1.90E-02
NaOH	4.26	0.26	4.26	0.26
NaCl	0.52	3.13E-02	0.52	3.13E-02
Rinse water	8.72E-04	5.23E-05	8.72E-04	5.23E-05
Total	99.8	5.99	359	21.5
Waste Streams				
Spent Brine	2.47E-02	1.48E-03	2.47E-02	1.48E-03
Stabilized PyOil Total	100	6.01	359	21.6
Stabilized PyOil (no / ethanol)	69.2	1.61	357	8.30

Table A6.20: CED for stabilized pyrolysis oil derived from waste wood using displacement allocation with a functional unit of one MJ of stabilized pyrolysis oil

Cumulative Energy Demand	MJ/MJ
Non renewable fossil	2.01E-02
Non renewable nuclear	8.44E-02
Non renewable biomass	3.51E-07
Renewable biomass	1.99
Renewable others	3.98E-04
Renewable water	7.82E-03
Total	2.10

Table A6.21: FED for stabilized pyrolysis oil derived from waste wood using displacement allocation with a functional unit of one MJ of stabilized pyrolysis oil

Fossil Energy Demand	MJ/MJ
Electricity	0.220
Diesel	4.47E-02
Truck Transport	3.12E-02
Ethanol	1.91E-02
Filter Cake	-5.13E-02
Steam Credit	-0.252
Remaining	8.56E-03
Total	2.01E-02

Table A6.22: GHG emissions for stabilized pyrolysis oil derived from wild algae using both displacement and energy allocation with two functional units of metric tons of stabilized pyrolysis oil and MJ of stabilized pyrolysis oil

Wild Algae	kg/MT (Displacement)	g/MJ (Displacement)	kg/MT (Spatari et al.)	g/MJ (Spatari et al.)
Pretreatment				
Sizing & Handling	63.1	2.55	56.3	2.27
Total	63.1	2.55	56.3	2.27
Pyrolysis				
Raw Materials				
Wild Algae	1262	51.0	1126	45.5
Wild Algae (WWT)	-964	-38.9	-859	-34.7
Sand	1.01E-02	4.08E-04	9.01E-03	3.64E-04
Sand Transport	8.12E-02	3.28E-03	7.24E-02	2.93E-03
Total	1263	51.0	1126	45.5
Total (WWT)	-964	-38.9	-859	-34.7
RTP Utilities				
Natural Gas	2.45E-02	9.92E-04	2.19E-02	8.85E-04
Water	3.95	0.16	3.52	0.14
Steam	-57.7	-2.33		
Air	0.40	1.63E-02	0.36	1.46E-02
Electricity	214	8.64	191	7.70
Total	160	6.49	195	7.86
Waste Streams				
Ash to landfill	4.37	0.18	3.89	0.16
Total	4.37	0.18	3.89	0.16
Pyrolysis Total	1490	60.2	1380	55.8
Pyrolysis Total (WWT)	-736	-29.7	-604	-24.4
Filtration				

Pyrolysis Oil	1490	60.2	1380	55.8
Filter cake	-200	-8.09		
Transportation	17.8	0.72	16.4	0.66
Filtration Total	1308	52.9	1397	56.5
Filtration Total (WWT)	-918	-37.1	-588	-23.8
Ion Exchange				
Utilities				
Electricity	0.35	1.40E-02	0.35	1.40E-02
Steam	1.22	4.93E-02	1.22	4.93E-02
Total	1.57	6.33E-02	1.57	6.33E-02
Raw Materials				
Filtered pyoil	1308	52.9	1397	56.5
Ethanol	155	6.26	155	6.26
Sulfuric Acid	3.58	0.14	3.58	0.14
NaOH	47.7	1.93	47.7	1.93
NaCl	6.00	0.24	6.00	0.24
Rinse water	1.00E-02	4.04E-04	1.00E-02	4.04E-04
Total	1520	61.4	1609	65.0
Waste Streams				
Spent Brine	0.28	1.15E-02	0.28	1.15E-02
Stabilized PyOil Total	1522	61.5	1611	65.1
Stabilized PyOil Total (WWT)	-704	-28.4	-374	-15.1

Table A6.23: CED for stabilized pyrolysis oil derived from wild using displacement allocation and no wastewater treatment credit with a functional unit of one MJ of stabilized pyrolysis oil

Cumulative Energy Demand	MJ/MJ
Non renewable fossil	0.932
Non renewable nuclear	0.260
Non renewable biomass	1.54E-06
Renewable biomass	1.38
Renewable others	1.54E-03
Renewable water	2.48E-02
Total	2.60

Table A6.24: FED for stabilized pyrolysis oil derived from wild using displacement allocation and no wastewater treatment credit with a functional unit of one MJ of stabilized pyrolysis oil

Fossil Energy	MJ/MJ
Electricity	0.591
Chemical additives	0.330
Ethanol	6.32E-02
Truck Transport	3.34E-02
Filter Cake	-7.76E-02
Steam Credit	-3.81E-02
Remaining	3.00E-02
Total	0.932

Table A6.25: GHG emissions for biofuel derived from sugarcane bagasse using both displacement and energy allocation with two functional units of metric tons of biofuel and MJ of biofuel

Bagasse Results	kg /MT (Displacement)	g/MJ (Displacement)	kg /MT (Spatari et al.)	g/MJ (Spatari et al.)
Feedstock Production	66.4	1.55	50.6	1.18
Pyrolysis	232	5.41	377	8.77
Stabilization	-19.3	-0.45	133	3.10
Upgrading				
Raw Material				
Stabilized pyoil	280	6.50	561	13.1
Effluents				
Waste water	0.32	7.53E-03	0.28	6.40E-03
Utilities				
Electricity	134	3.12	114	2.65
Natural Gas	75.2	1.75	63.9	1.49
Water	0.47	1.09E-02	0.40	9.23E-03
Steam	-150	-3.49		
Solid waste	8.21E-03	1.91E-04	6.97E-03	1.62E-04
Integrated H_2 Plant				
Natural Gas	482	11.2	409	9.52
Demin. Water	6.87E-02	1.60E-03	5.84E-02	1.36E-03
HP Steam	-408	-9.49		
Electricity	38.1	0.89	32.4	0.75
Transportation	8.86	0.21	7.53	0.18
Overall Total	461	10.7	1189	27.65

Table A6.26: CED for biofuel derived from sugarcane bagasse using displacement allocation with a functional unit of one MJ of biofuel

Cumulative Energy Demand	MJ/MJ
Non renewable fossil	0.118
Non renewable nuclear	7.62E-02
Non renewable biomass	4.96E-07
Renewable biomass	1.05
Renewable others	4.49E-04
Renewable water	7.45E-03
Total	1.25

Table A6.27: FED for biofuel derived from sugarcane bagasse using displacement allocation with a functional unit of one MJ of biofuel

Fossil Energy	MJ/MJ
Natural Gas	0.224
Electricity	0.18
Truck transport	3.81E-02
Ethanol	1.92E-02
Filter Cake	-3.96 E-02
Steam Credit	-0.319
Remaining	1.57E-02
Total	0.118

Table A6.28: GHG emissions for biofuel derived from guinea grass using both displacement and energy allocation with two functional units of metric tons of biofuel and MJ of biofuel

Guinea Grass Results	kg /MT (Displacement)	g/MJ (Displacement)	kg /MT (Spatari et al.)	g/MJ (Spatari et al.)
Feedstock Production	605	14.1	461	10.7
Pyrolysis	522	12.1	472	11.0
Stabilization	180	4.19	326	7.57
Upgrading				
Raw Material				
Stabilized pyoil	1306	30.4	1259	29.3
Effluents				
Waste water	0.44	1.01E-02	0.36	8.33E-03
Utilities				
Electricity	158	3.67	130	3.02
Natural Gas	88.8	2.07	72.9	1.70
Water	0.55	1.28E-02	0.45	1.05E-02
Steam	-176	-4.09		
Solid waste	9.74E-03	2.27E-04	8.00E-03	1.86E-04
Integrated H_2 Plant				
Natural Gas	599	13.9	492	11.4
Demin. Water	8.52E-02	1.98E-03	7.00E-02	1.63E-03
HP Steam	-509	-11.8		
Electricity	47.4	1.10	38.9	0.91
Transportation	8.86	0.21	7.3	0.17
Overall Total	1525	35.5	2001	46.5

Table A6.29: CED for biofuel derived from guinea grass using displacement allocation with a functional unit of one MJ of biofuel

Cumulative Energy Demand	MJ/MJ
Non renewable fossil	0.388
Non renewable nuclear	0.113
Non renewable biomass	1.48E-06
Renewable biomass	1.67
Renewable others	8.63E-04
Renewable water	1.22E-02
Total	2.18

Table A6.30: FED for biofuel derived from guinea grass using displacement allocation with a functional unit of one MJ of biofuel

Fossil Energy Demand	MJ/MJ
Natural Gas	0.276
Electricity	0.22
Ethanol	5.91E-02
Urea	4.44E-02
Truck transport	4.32E-02
Filter Cake	-4.87E-02
Steam Credit	-0.303
Remaining	9.67E-02
Total	0.388

Table A6.31: GHG emissions for biofuel derived from open pond algae using both displacement and energy allocation with two functional units of metric tons of biofuel and MJ of biofuel

Open Pond Algae	kg /MT (Displacement)	g/MJ (Displacement)	kg /MT (Spatari et al.)	g/MJ (Spatari et al.)
Feedstock Production	1307	30.4	940	21.9
Feedstock Production (nutrient recycle)	1052	24.5	751	17.5
Pyrolysis	192	4.47	411	9.56
Stabilization	-79.4	-1.85	144	3.35
Upgrading				
Raw Material				
Stabilized pyoil	1420	33.0	1495	34.8
Effluents				
Waste water	0.18	0.00	0.15	3.47E-03
Utilities				
Electricity	121	2.81	103	2.40
Natural Gas	67.9	1.58	57.9	1.35
Water	0.42	9.81E-03	0.36	8.37E-03
Steam	-136	-3.16		
Solid waste	7.45E-03	1.73E-04	6.35E-03	1.48E-04
Integrated H_2 Plant				
Natural Gas	442	10.3	377	8.77
Demin. Water	6.84E-02	1.59E-03	5.83E-02	1.36E-03
HP Steam	-408	-9.49		
Electricity	38.1	0.89	32.5	0.76
Transportation	8.86	0.21	7.56	0.18
Overall Total	1554	36.2	2074	48.2
Overall Total (nutrient	1300	30.2	1885	43.8

recycle)

Table A6.32: CED for biofuel derived from open pond algae using displacement allocation with a functional unit of one MJ of biofuel

Cumulative Energy Demand	MJ/MJ
Non renewable fossil	0.596
Non renewable nuclear	0.2
Non renewable biomass	3.58E-05
Renewable biomass	1.44
Renewable others	1.51E-03
Renewable water	2.12E-02
Total	2.26

Table A6.33: FED for biofuel derived from open pond algae using displacement allocation with a functional unit of one MJ of biofuel

Fossil Energy Demand	MJ/MJ
Electricity	0.228
Natural Gas	0.204
Ammonium nitrate	0.201
Electricity	0.191
Phosphate	6.9E-02
Potassium	4.36E-02
Filter Cake	-5.59E-02
Steam Credit	-0.352
Remaining	6.67E-02
Total	0.596

Table A6.34: GHG emissions for biofuel derived from corn stover using both displacement and energy allocation with two functional units of metric tons of biofuel and MJ of biofuel

Corn Stover Results	kg /MT (Displacement)	g/MJ (Displacement)	kg /MT (Spatari et al.)	g/MJ (Spatari et al.)
Feedstock Production	285	6.63	194	4.51
Pyrolysis	274	6.36	490	11.4
Stabilization	-147	-3.41	159	3.71
Upgrading				
Raw Material				
Stabilized pyoil	412	9.58	843	19.6
Effluents				
Waste water	0.452	0.01	0.37	8.70E-03
Utilities				
Electricity	158	3.67	131	3.04
Natural Gas	88.4	2.06	73.2	1.70
Water	0.55	1.28E-02	0.45	1.06E-02
Steam	-176	-4.09		
Solid waste	9.65E-03	2.24E-04	7.99E-03	1.86E-04
Integrated H_2 Plant				
Natural Gas	817	19.0	676	15.7
Demin. Water	8.06E-02	1.87E-03	6.67E-02	1.55E-03
HP Steam	-481	-11.2		
Electricity	44.8	1.04	37.1	0.86
Transportation	8.86	0.21	7.33	0.17
Overall Total	873	20.3	1768	41.1

Table A6.35: Comparison of literature (Kauffman et al. 2011) GHG emission to MTU/UOP GHG emissions

GHG Comparison	Literature		MTU/UOP
	tCO_2/ha	g/MJ*	g/MJ
Corn Stover Collection	0.12	1.21	1.19
Corn Stover Loading/Unloading	---	---	0.34
Nutrient Replacement	0.12	1.21	4.58
Feedstock Transportation	0.01	0.10	0.52
Fast pyrolysis	0.1	1.01	6.36
Bio-oil transportation	0.38	3.83	1.18
Bio-oil Upgrading	0.42	4.23	10.52
Bio-gasoline distribution	0.02	0.20	0.21
Stabilization	---	---	-4.67
Gasoline Displacement	-3.48	-35.0	---
Biochar fertilizer displacement	-0.07	-0.70	---
Biochar transportation and application	0.06	0.60	---
Biochar sequestration	-0.85	-8.56	---
Feedstock removal	0.19	1.91	---
Total	-2.98	-30.0	20.23

*converted using UOP yields

Table A6.36: CED for biofuel derived from corn stover using displacement allocation with a functional unit of one MJ of biofuel

Cumulative Energy Demand	MJ/MJ
Non renewable fossil	0.271
Non renewable nuclear	0.108
Non renewable biomass	6.32E-06
Renewable biomass	1.85
Renewable others	6.92E-04
Renewable water	1.08E-02
Total	2.24

Table A6.37: FED for biofuel derived from corn stover using displacement allocation with a functional unit of one MJ of biofuel

Fossil Energy Demand	MJ/MJ
Natural Gas	0.363
Electricity	0.247
Truck transport	1.87E-02
Fertilizer	7.03E-02
Ethanol	2.42E-02
Filter Cake	-7.64E-02
Steam Credit	-0.429
Remaining	5.29E-02
Total	0.271

Table A6.38: GHG emissions for biofuel derived from low ash corn stover using both displacement and energy allocation with two functional units of metric tons of biofuel and MJ of biofuel

Low Ash Corn Stover Results	kg /MT (Displacement)	g/MJ (Displacement)	kg /MT (Spatari et al.)	g/MJ (Spatari et al.)
Feedstock Production	289	6.73	172	3.99
Pyrolysis	-95.7	-2.23	493	11.5
Stabilization	-174	-4.04	96.1	2.23
Upgrading				
Raw Material				
Stabilized pyoil	19.9	0.46	760	17.7
Effluents				
Waste water	0.54	1.26E-02	0.44	1.03E-02
Utilities				
Electricity	169	3.93	138	3.21
Natural Gas	94.7	2.20	77.4	1.80
Water	0.59	1.37E-02	0.48	1.12E-02
Steam	-188	-4.37		
Solid waste	1.03E-02	2.40E-04	8.42E-03	1.96E-04
Integrated H_2 Plant				
Natural Gas	1110	25.8	907	21.1
Demin. Water	8.64E-02	2.01E-03	7.06E-02	1.64E-03
HP Steam	-516	-12.0		
Electricity	48	1.12	39.2	0.91
Transportation	8.86	0.21	7.24	0.17
Overall Total	748	17.4	1931	44.9

Table A6.39: CED for biofuel derived from low ash corn stover using displacement allocation with a functional unit of one MJ of biofuel

Cumulative Energy Demand	MJ/MJ
Non renewable fossil	0.215
Non renewable nuclear	0.115
Non renewable biomass	6.02E-06
Renewable biomass	1.84
Renewable others	6.62E-04
Renewable water	1.12E-02
Total	2.14

Table A6.40: FED for biofuel derived from low ash corn stover using displacement allocation with a functional unit of one MJ of biofuel

Fossil Energy Demand	MJ/MJ
Natural Gas	0.363
Electricity	0.246
Ammonia	4.12E-02
Diesel	2.98E-02
Potassium	2.94E-02
Truck transport	2.89 E-02
Ethanol	2.42E-02
Filter Cake	-7.63E-02
Steam Credit	-0.428
Remaining	4.07E-02
Total	0.215

Table A6.41: GHG emissions for biofuel derived from switchgrass using both displacement and energy allocation with two functional units of metric tons of biofuel and MJ of biofuel

Switchgrass Results	kg /MT (Displacement)	g/MJ (Displacement)	kg /MT (Spatari et al.)	g/MJ (Spatari et al.)
Feedstock Production	511	11.9	353	8.20
Pyrolysis	230	5.36	426	9.91
Stabilization	-32.7	-0.76	146	3.38
Upgrading				
Raw Material				
Stabilized pyoil	708	16.5	924	21.5
Effluents				
Waste water	0.46	1.06E-02	0.37	8.63E-03
Utilities				
Electricity	155	3.60	126	2.93
Natural Gas	87.0	2.02	70.8	1.65
Water	0.541	1.26E-02	0.44	1.02E-02
Steam	-173	-4.02		
Solid waste	9.55E-03	2.22E-04	7.77E-03	1.81E-04
Integrated H_2 Plant				
Natural Gas	1190	27.7	968	22.5
Demin. Water	9.20E-02	2.14E-03	7.48E-02	1.74E-03
HP Steam	-549	-12.8		
Electricity	51.1	1.19	41.6	0.97
Transportation	8.86	0.21	7.21	0.17
Overall Total	1480	34.4	2139	49.7

Table A6.42: CED for biofuel derived from switchgrass using displacement allocation with a functional unit of one MJ of biofuel

Cumulative Energy Demand	MJ/MJ
Non renewable fossil	0.426
Non renewable nuclear	0.104
Non renewable biomass	1.09E-05
Renewable biomass	1.48
Renewable others	7.14E-04
Renewable water	1.15E-02
Total	2.03

Table A6.43: FED for biofuel derived from switchgrass using displacement allocation with a functional unit of one MJ of biofuel

Fossil Energy	MJ/MJ
Natural Gas	0.514
Electricity	0.221
Diesel	4.58E-02
Truck transport	3.12 E-02
Ethanol	2.23E-02
Filter Cake	-4.77E-02
Steam Credit	-0.43
Remaining	6.92E-02
Total	0.426

Table A6.44: GHG emissions for biofuel derived from waste wood using both displacement and energy allocation with two functional units of metric tons of biofuel and MJ of biofuel

Waste Wood Results	kg /MT (Displacement)	g/MJ (Displacement)	kg /MT (Spatari et al.)	g/MJ (Spatari et al.)
Feedstock Production	175	4.08	114	2.66
Pyrolysis	171	3.97	538	12.5
Stabilization	-85.7	-1.99	118	2.75
Upgrading				
Raw Material				
Stabilized pyoil	260	6.05	770	17.9
Effluents				
Waste water	0.45	1.05E-02	0.37	8.66E-03
Utilities				
Electricity	153	3.56	126	2.94
Natural Gas	85.8	2.00	70.9	1.65
Water	5.34	0.12	4.41	0.10
Steam	-171	-3.98		
Solid waste	9.55E-03	2.22E-04	7.89E-03	1.83E-04
Integrated H_2 Plant				
Natural Gas	928	21.6	767	17.8
Demin. Water	8.25E-02	1.92E-03	6.81E-02	1.58E-03
HP Steam	-492	-11.4		
Electricity	45.9	1.07	37.9	0.88
Transportation	8.86	0.21	7.32	0.17
Overall Total	832	19.4	1791	41.6
Total (No integrated H_2 plant)	941	21.9	2028	47.2

Total (no ethanol)	892	20.8	1818	42.3
Total (no ethanol, no integrated H_2 **plant)**	925	21.5	1993	46.4

Table A6.45: CED for biofuel derived from waste wood using displacement allocation with a functional unit of one MJ of biofuel

Cumulative Energy Demand	MJ/MJ
Non renewable fossil	0.227
Non renewable nuclear	0.111
Non renewable biomass	5.24E-07
Renewable biomass	2.00
Renewable others	6.02E-04
Renewable water	1.06E-02
Total	2.35

Table A6.46: FED for biofuel derived from waste wood using displacement allocation with a functional unit of one MJ of biofuel

Fossil Energy	MJ/MJ
Natural Gas	0.407
Electricity	0.275
Diesel	4.5E-02
Truck transport	3.13E-02
Ethanol	1.92E-02
Filter Cake	-5.16E-02
Steam Credit	-0.511
Remaining	1.27E-02
Total	0.227

Table A6.47: GHG emissions for biofuel derived from wild algae using both displacement and energy allocation with two functional units of metric tons of biofuel and MJ of biofuel

Wild Algae	kg /MT (Displacement)	g/MJ (Displacement)	kg /MT (Spatari et al.)	g/MJ (Spatari et al.)
Feedstock Production	2854	66.4	2126	49.4
Feedstock Production (WWT credit)	-2179	-50.7	-1623	-37.7
Pyrolysis	516	12.0	481	11.2
Stabilization	71.7	1.67	435	10.1
Upgrading				
Raw Material				
Stabilized pyoil	3442	80.0	3042	70.8
Effluents				
Waste water	0.21	4.88E-03	0.18	4.08E-03
Utilities				
Electricity	133	3.09	111	2.58
Natural Gas	74.8	1.74	62.5	1.45
Water	0.47	1.08E-02	0.39	9.03E-03
Steam	-150	-3.49		
Solid waste	8.21E-03	1.91E-04	6.86E-03	1.59E-04
Integrated H_2 Plant				
Natural Gas	114	2.65	95.2	2.21
Demin. Water	7.91E-02	1.84E-03	6.61E-02	1.54E-03
HP Steam	-471	-11.0		
Electricity	43.9	1.02	36.7	0.85
Transportation	8.86	0.21	7.40	0.17
Overall Total	3196	74.3	3356	78.0

Overall Total (WWT Credit)	-1837	-42.7	-393	-9.13

Table A6.48: CED for biofuel derived from wild algae using displacement allocation with a functional unit of one MJ of biofuel

Cumulative Energy Demand	MJ/MJ
Non renewable fossil	1.1
Non renewable nuclear	0.355
Non renewable biomass	1.91E-06
Renewable biomass	1.79
Renewable others	2.08E-03
Renewable water	3.37E-02
Total	3.28

Table A6.49: FED for biofuel derived from wild algae using displacement allocation with a functional unit of one MJ of biofuel

Fossil Energy Demand	MJ/MJ
Electricity	0.817
Nutrients	0.429
Ethanol	8.22E-02
Natural Gas	7.57E-02
Filter Cake	-0.101
Steam Credit	-0.291
Remaining	8.54E-02
Total	1.1