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Comparative Life Cycle Assessments of Lignocellulosic and Algae Biomass Conversion to Various Energy Products through Different Pathways

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Comparative Life Cycle Assessments of Lignocellulosic and Algae Biomass Conversion to Various Energy Products through Different Pathways

by

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DEDICATION

Dedico esta tesis a mi padre, Alonso, quien SIEMPRE ha creído en mis sueños y en mi capacidad de hacerlos realidad. A mi madre, Claudia, quien SIEMPRE me ha apoyado, cuidado, protegido, y guiado a través de su dulzura y firmeza. Ustedes son el mejor regalo que Dios me ha enviado.

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ABSTRACT

Bioenergy has the potential to reduce the world's dependence on fossil fuels, and to decrease the CO_2 emissions due to fossil combustion. Lignocellulosic and algae biomass have been presented as promising feedstocks for bioenergy production.

In this study, a comparative Life Cycle Assessment (LCA) has been developed to evaluate the environmental impacts associated with different energy products via different routes across the whole life of algal and lignocellulosic bioenergy. Results were compared per energy basis, the production of 1 million BTU of energy products.

For the development of the comparative algae biomass conversion LCA, algal biomass was converted to liquid biofuels via a thermochemical gasification and Fischer-Tropsch Synthesis (FTS) process; and to electricity and heat via anaerobic digestion and combined heat and power (CHP) process.

Overall results from the algae biomass conversion LCA showed that the process that converts algae biomass through anaerobic digestion and CHP process to electricity and heat had the highest overall environmental impact. Results also showed that the impact categories that appear to contribute the most to the overall impacts are ecotoxicity, human health non-cancer, and human health cancer.

For the development of the comparative lignocellulosic biomass conversion LCA, lignocellulosic biomass was converted to ethanol and higher alcohols through

thermochemical gasification and alcohol synthesis process, to liquid biofuels via thermochemical gasification and FTS process, and to liquid biofuels via a thermochemical gasification and FTS process that uses methane.

Overall results from the lignocellulosic biomass conversion LCA showed that the process that converts lignocellulosic biomass into alcohols has the highest overall environmental impact. Results also showed that the impact categories that appear to contribute the most to the overall impacts are ecotoxicity, human health non-cancer, human health cancer, and global warming.

This study determined that cultivated algae biomass feedstock has much higher environmental impacts compared with lignocellulosic biomass feedstock from forestation and agriculture byproducts. It was also concluded that thermochemical gasification and FTS process showed higher efficiency when converting biomass to bioenergy.

In addition, the five biomass to bioenergy conversion pathways used in the development of this LCA study were compared. Results showed that the pathway with lignocellulosic biomass (feedstock), thermochemical gasification and alcohol synthesis process (conversion process), and ethanol and higher alcohols (energy products) has the largest environmental impact.

CHAPTER 1

INTRODUCTION

Bioenergy has attracted much attention in the last decades due to increasing concerns about the world's dependence on fossil fuels, the increasing CO_2 emissions due to fossil fuel combustion, and the future fossil fuels scarcity (Spitzer & Tustin, 2011). Bioenergy is a general term used to describe any type of energy (e.g., electricity, heat, and liquid fuels) derived from biological sources (Cushion et al., 2010). Biofuels are one form of bioenergy, specifically referring to transportation fuels produced from renewable biological sources (Agency, 2009). Such renewable sources are called feedstocks.

Depending on the type of feedstocks used, biofuels are classified in three generations (Ganduglia, 2009):

- First generation biofuels are derived from food such as corn, sugar beet, sugar cane, soybean, and palm oil. For example, corn ethanol and soybean biodiesel are the first generation biofuels that are currently being produced.
- Second generation biofuels are derived from lignocellulosic biomass which include primary and secondary forestation and agriculture byproducts such as corn stalks, wheat straw, grasses, switchgrass, and waste wood. Cellulosic bioethanol, synthetic biofuels, and bio-oil are second generation biofuels that could be mass produced by 2012 according to scientific consensus.

- Third generation biofuels are derived from aquatic – based feedstocks, such as algae and cyanobacteria. This generation of biofuels is often called the advanced generation. Up to date this type of biofuels are still in research and pilot test stage.

It is not possible to generalize the advantages and disadvantages of various types of bioenergy in terms of environmental impacts, given that it can be produced from different types of feedstocks through various processes. However, there is an increasing concern about environmental impacts of bioenergy across their life cycles (Hazell & Pachauri, 2006; Environmental Audit Committee, 2008).

In an attempt to increase energy security and mitigate greenhouse gas emissions, the United States Environmental Protection Agency (EPA) has developed the Renewable Fuel Standard (RFS) program under the Energy Policy Act of 2005. This program focuses on the regulations for the biofuels industry, which established for the first time in the United States history the required amount of biofuels to be mixed with gasoline. This program was expanded under the Energy Independence and Security Act (EISA) of 2007. Under the program's expansion the volume of biofuels required increased from 9 billion gallons in 2008 to 36 billion gallons by 2022 (Environmental Protection Agency, 2011). The RFS expansion also established the threshold for lifecycle greenhouse gas (GHG) emissions reduction from the production and use of biofuels.

With the objective of evaluating environmental impacts, life cycle assessment (LCA) methodology has been developed. LCA identifies and evaluates the environmental impacts of a product, service, or production process throughout their life cycle (Technical Committee ISORC 207, 1997). To examine the environmental impacts of various biofuels, many LCA studies have been conducted (Soratana et al., 2011; Campbell et al., 2010; Brentner et al., 2011; Lardon et al., 2009; Sander et al., 2010; Clarens et al., 2009; Collet et al., 2010; Bright et al., 2009; Fu et al., 2003; Kemppainen et al., 2005; Gonzalez et al., 2010; Mu et al., 2010; & Cherubini et al., 2009).

Previous LCA studies have found some limitations associated with the first generations of biofuels. This generation of biofuels has significant carbon emissions associated with biomass production, transportation and conversion. Also, there is a large requirement of fertile land and potable water, which causes food and water prices to increase since demand is increased (Eisentraut, 2010).

Lignocellulosic biomass has been presented as a promising feedstock by some research (Carriquiry et al., 2011). Producing biofuels from lignocellulosic biomass has the potential to overcome some limitations of the first generation biofuels. Since the feedstocks used to produce lignocellulosic biofuels are mainly waste, or can be grown on marginal lands that are not suitable for food crops, it solves the ethical dilemma of using food to produce fuels and will not cause the increase in food prices. In addition, less fossil fuel energy is required to grow, collect, and convert these types of feedstocks (Carriquiry et al., 2011).

Similar as lignocellulosic biofuels, algal bioenergy production does not compete with food. Algae has attracted a great deal of attention because it has many benefits, such as rapid conversion and capture of CO_2 compared with other terrestrial plants, non-exigent cultivation characteristics, no requirement for fertile land, potential usage of wastewater as nutrient resources and power plant flue gas as carbon sources in cultivation, high lipid content, and a wide variety of potential energy products (EERE, 2010). Also, it has the potential to alleviate environmental degradation associated with excess nutrient releases to the environment (Clarens et al., 2010).

Previous LCA studies on algae and lignocellulosic bioenergy have provided important information about environmental impacts associated with bioenergy systems. However, LCA studies have looked at limited energy products, such as biodiesel from algae, and ethanol from lignocellulosic biomass. In addition, limited conversion processes have been investigated. Therefore, various energy products through different conversion processes need to be evaluated in order to assess environmental impacts of different bioenergy pathways.

The overall goal of this research is to evaluate the environmental impacts associated with different energy products via different routes across the whole life of algal and lignocellulosic bioenergy. This study is based on the development of two comparative LCAs, which analyzes two types of feedstocks converted through different conversion processes into various energy products. Figure 1 shows the feedstocks, conversion processes, and energy products analyzed in this study.

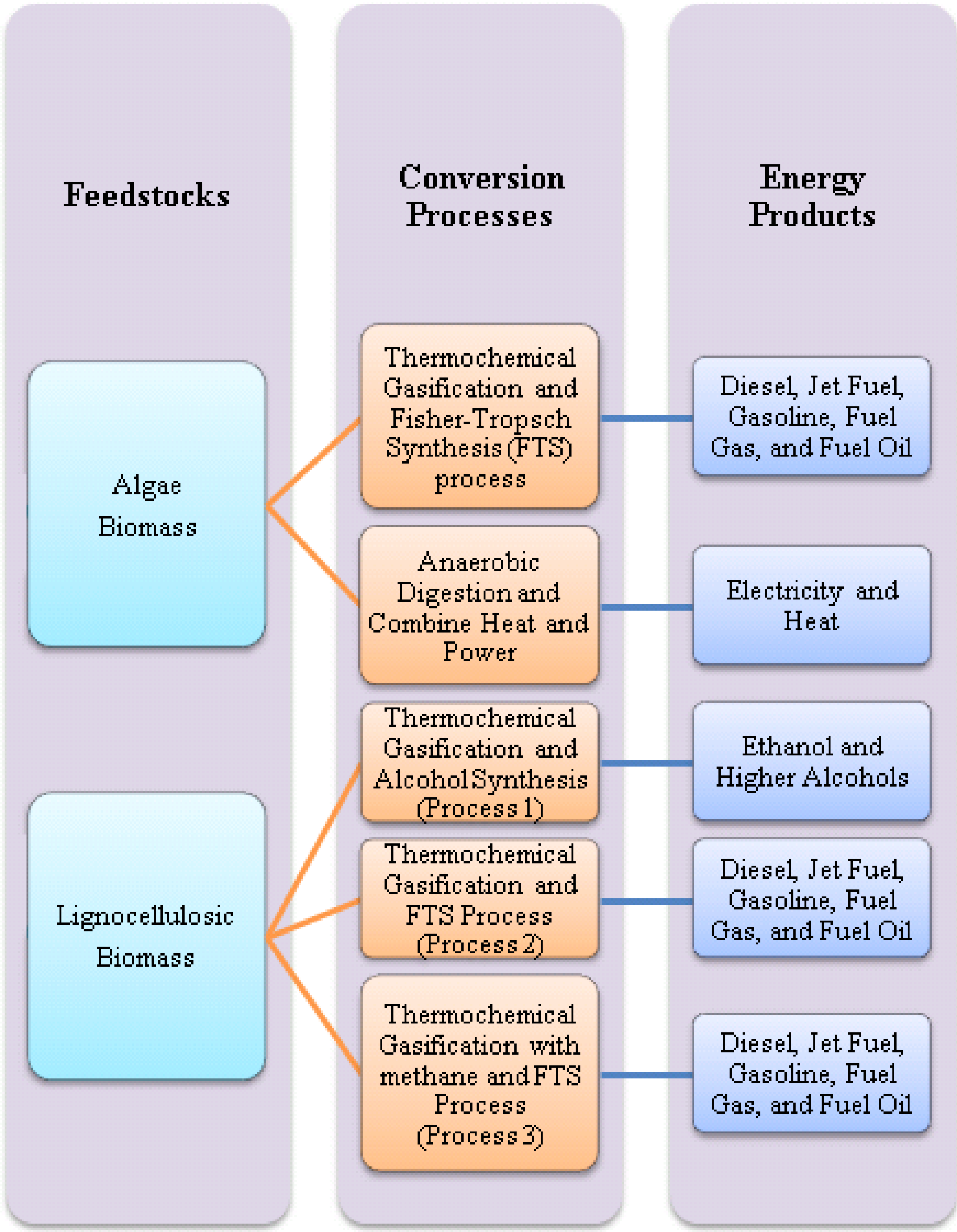

Figure 1. Feedstocks, conversion processes, and energy products analyzed

The algae bioenergy production system under investigation uses wastewater centrate as a feed stream to provide water and nutrients required for algae growth in photo-bioreactor and flue gas as the CO_2 source, assuming the production process is co-located with a power plant. Algal biomass is harvested and dewatered through flocculation. As it can be seen in Figure 1, two conversion routes are considered in this research: 1) algal biomass converted to liquid biofuels via a thermochemical gasification and Fischer Tropsch (FTS) process; and 2) algal biomass converted to electricity and heat via anaerobic digestion and combined heat and power (CHP) process.

The lignocellulosic bioenergy production system under investigation involves the conversion of cellulosic biomass through thermochemical gasification. For each of the three pathways studied, cellulosic biomass and water are fed into the process where gasification occurs. Syngas produced from the gasification process is cleaned up, conditioned, and then converted to the energy products through FTS process. Different energy products are separated depending on their molecular weights as it can be seen in Figure 1.

Accordingly, the specific objectives of this study are:

- To conduct a comparative LCA of algae biomass conversion to a variety of energy products for four different scenarios and identify the process and scenario that have lower environmental impacts.
- To conduct a comparative LCA of lignocellulosic biomass conversion to a variety of energy products and identify the process that have lower environmental impacts.
- To compare the algae and lignocellulosic biomass supply processes to identify the feedstock with lower environmental impacts.
- To compare the five biomass conversion technologies used in this study to identify the technology with lower environmental impacts, and higher energy efficiency.

- To compare results for the two comparative LCA studies to identify the pathway (conversion process and end energy product) with lower environmental impacts.
- To identify opportunities for process improvement across the algae and lignocellulosic bioenergy life cycle.

CHAPTER 2

BACKGROUND

2.1. Life Cycle Assessment

Environmental sustainability focuses on natural resource usage, environmental impact management, human well-being, and biodiversity (Christine et al., 2008). This all encompassing concept drives the efforts to assess environmental impacts and processes. LCA is a methodology used to evaluate and quantify the environmental impacts of a product or service throughout their entire life cycle (Scientific Applications International Corporation, 2006). The first LCA is considered to be the study conducted by the Midwest Research Institute in the United States in 1969 for the Coca Cola Company to investigate fuel and raw materials consumption in the manufacturing process of beverage containers (Kasprzak & Klos, 2011). Since then LCA methodology has been shaped and constantly improved over the years. The first standard for LCA methodology - ISO (International Standards of Organization) 14040 Environmental Management Life Cycle Assessment was issued in 1997 and revised in 2006 (Technical Committee ISORC 207, 1997).

According to the standard, an LCA consists of four main phases, as can be seen in Figure 2.

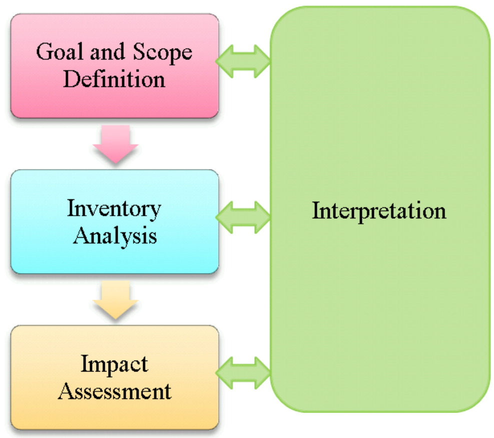

Figure 2. LCA's methodology. (ISO, 1997)

- Phase 1 - Goal and Scope definition:

The purpose of this phase is to define the intended goal of the LCA and the extent to which the product system is going to be studied. In this phase the purpose of the study is defined, and the system boundaries are set. A LCA's system boundary can be set to different extends depending on the goal of the study. 'Cradle to cradle' system boundaries include the extraction of raw materials from the earth, to production and distribution, all the way to usage, disposal, and recycling (Guinee, 2002). Figure 3 shows the typical 'cradle to cradle' system boundaries of an LCA.

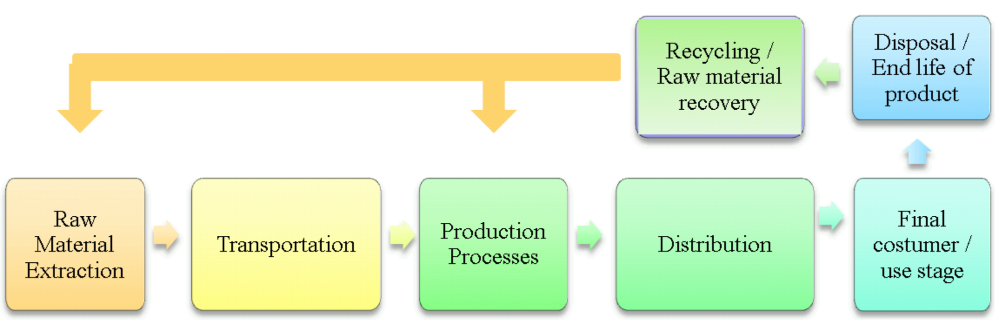

Figure 3. LCA's 'cradle to cradle' system boundaries

LCA's system boundaries can also be set to 'cradle to gate' (including from raw material extraction to the production stage), 'cradle to grave' (including from raw material extraction to the use stage of the product), 'gate to gate' (does not include raw material extraction, only analyzes environmental impacts from the production processes itself).

In LCA's first phase, the functional unit is established. According to the ISO Standard for LCA, the functional unit is the reference unit that will be used to describe the quantified results of the product system's performance (Technical Committee ISORC 207, 1997).

- Phase 2 - Inventory Analysis:

This phase is also known as the Life Cycle Inventory (LCI). In the LCI, a flow chart of the system is developed to show mass and energy flows included in the processes. The mass and energy inputs and outputs are then compiled and quantified throughout the entire life cycle of the system (Technical Committee ISORC 207, 1997). The gathered data will be classified into either foreground or background data. Foreground data includes all of the mass and energy flows that are part of the production process. Background data includes the upstream and downstream processes included in the system boundary - processes for energy and material supply and for waste stream treatment respectively (Scientific Applications International Corporation, 2006).

- Phase 3 - Impact Assessment:

This phase consists of evaluating the environmental and potential human health impacts of the system. In this phase, the impact methodology and impact categories are defined (e.g., global warming, eutrophication, human health cancer). Classification step is then performed to assign LCI results to the corresponding impact category (e.g., SO_2 will be assigned to acidification impact). Following the classification, the potential impact of each assigned inventory data is quantified within the impact categories (e.g., the potential impact of arsenic on human health cancer). Characterization results for each impact category will have different units (e.g., Kg CO_2 equiv. for global warming, Kg benzene equiv. for human health cancer). The next steps in a life cycle impact assessment are optional, including normalization, grouping of indicators, and weighting to incorporate the social value of different environmental impacts. Normalization allows for easy comparison that presents the impacts in relative numbers to a norm instead of absolute numbers (Technical Committee ISORC 207, 1997).

- Phase 4 - Interpretation:

The fourth phase is where the results are interpreted with regard to the goal of the study and recommendations are made.

2.2. Current Status of Biofuels

Global biofuels production has been rapidly increasing over the past decade. In 2008, global biofuels production was at 68 billion liters of bio-ethanol (from sugar cane and corn) and 15 billion liters of biodiesel (Beck, 2009). The leading biofuels producer is the United States with corn based ethanol, trailed by Brazil with sugar cane based ethanol, and the European Union with biodiesel mainly from canola and sunflower feedstocks (Hazell & Pachauri, 2006).

As it was explained in Chapter 1, depending on the type of feedstocks used, biofuels are classified in three generations. First generation biofuels account for most of the global biofuels production. Second-generation biofuels are still at a point where the investment is high and, in comparison, the production is low. However, it has been projected that the second generation biofuels production should increase to 300 million gallons per year (Castano, 2011). The technologies for second generation biofuels production can use a wider range of feedstock and potentially have a greater yield than those for the first generation biofuels. Third generation biofuels are still under research, and to date it has not been reported any large scale commercial production of these biofuels. Table 1 summarizes the feedstocks use, current technologies, energy products, advantages and disadvantages for three generations of biofuels.

Table 1. Summary for biofuels generations

1st Generation Biofuels				
Feedstocks	**Current Technologies**	**Energy Product**	**Advantages**	**Disadvantages**
Rapeseed, soybean, palm oil, jatropha, vegetable oil, Corn, sugarcane, sugar beets, cereal, cassava, maize	Transesterification, fermentation, and hydrolisis	Biodiesel, and Bio-ethanol	• Reduction in use of fossil fuels • Renewable source (Ganduglia, 2009)	• Significant carbon emissions • Impacts associated with fertilizers use • Large requirement of fertile land and potable water • Dilemma regarding competition with food
2nd Generation Biofuels				
Feedstocks	**Current Technologies**	**Energy Product**	**Advantages**	**Disadvantages**
Lignocellulosic biomass such as wheat straw, corn stover, wood and special energy crop	Hydrolysis to fermentation, Gasification to Fischer-Tropsch	Bio-ethanol, biodiesel, biohydrogen, biomethane, bio-DME, mixed alcohols, and hydrocarbons	• No competition with food • Reduction in fossil fuel use • Renewable source • If waste cellulose is used, impacts associated with fertilizer consumption, and water and land requirement could be eliminated • A wide variety of potential energy products can be obtained (Ganduglia, 2009)	• Availability at large scale is a concern • Still under research • Limitations and consequences for large-scale production are not known yet

Table 1 (Continued)

3rd Generation Biofuels				
Feedstocks	**Current Technologies**	**Energy Product**	**Advantages**	**Disadvantages**
Microalgae and macroalgae	Transesterific-ation, anaerobic digestion, gasification	Biodiesel, bioethanol, biomethanol, biobutanol, biogas, hydrocarbons	• No competition with food • Rapid conversion and capture of CO_2 • Non-exigent cultivation characteristics • No requirement for fertile land • Potential usage of waste stream in the process • High growth rates and lipid content • Renewable source • A wide variety of potential energy products can be obtained (EERE, 2010)	• Still under research • Large environmental impacts associated with power consumption during cultivation stage (EERE, 2010)

2.3. Literature Review: LCAs on Algae Bioenergy Systems

To understand the environmental impacts associated with algae bioenergy systems, life cycle assessment has been conducted (Soratana et al., 2011; Campbell et al., 2010; Brentner et al., 2011; Lardon et al., 2009; Sander et al., 2010; Clarens et al., 2009; & Collet et al., 2010).

Research shows that there are very few existing LCA studies on the production of bioenergy from algae that evaluate the entire life cycle's environmental impacts. To date, available literature on algae LCAs have been developed to address specific issues from algae bioenergy production, such as the source for nutrients and carbon for the algae cultivation stage, cultivation methods, harvesting and dewatering methods, and the biomass conversion technology.

Algae cultivation process has attracted a great deal of attention since it has been identified as the main contributor to the environmental impacts associated with algae bioenergy production. In response to this, some LCA studies have been developed that focus on the algae cultivation stage. Soratana et al. (2011) compared 20 different scenarios for microalgae cultivation. The LCA was based on a 'cradle to gate' system boundary. The functional unit was the production of 3650 Kg of microalgal biomass. This LCA is different from previous LCAs with a focus on the algae production process itself and not including bioenergy production. The scenarios evaluated in this study were different combinations of various inputs for the algae cultivation stage, including two nutrient sources (fertilizers and wastewater), two carbon sources (chemical CO_2 and flue gas), and five materials to build the photobioreactors. The materials for the photobioreactors construction analyzed in this LCA include: glass, polyvinyl chloride

(PVC), polycarbonate (PC), polymethyl methacrylate (PMMA) and high-density polyethylene (HDPE). Results from this study demonstrated that the utilization of wastewater for algae cultivation reduces eutrophication impacts, and the utilization of flue gas reduces global warming potential. Also, the study determined that HDPE is the best material to use for photobioreactors construction (Soratana et al., 2011).

To address the importance of alternative sources of CO_2 in the algae cultivation stage, some LCA studies have analyzed different sources of CO_2. Campbell et al. (2010) analyzed the potential environmental impacts of producing biodiesel derived from microalgae. The LCA was based on a ‘cradle to grave’ system boundary. The functional unit was the one-kilometer distance with one tone of freight driven by a diesel engine truck. This LCA compares the production of biodiesel from algae with biodiesel from canola and ultra-low sulfur diesel. Three different carbon sources: delivery of CO_2 in pure form through a pipe from a contiguous ammonia plant, supply of flue gas with a 15% CO_2 concentration from a contiguous power plant, and chemical CO_2 supply by truck, were considered in the algae cultivation. This study concluded that when compared with canola and ultra-low sulfur diesel, algae biodiesel showed favorable greenhouse gas (GHG) emissions. The study also concluded that the best carbon supply scenario for the algae cultivation is the CO_2 from a contiguous ammonia plant (Campbell et al., 2010).

Previous LCA studies have also focused on the environmental impacts from photobioreactors. Brentner et al. (2011) compared various algal biodiesel production methods to identify the most promising pathways for large scale production. The LCA was based on a ‘cradle to gate’ system boundary. The functional unit was the production of 10 GJ of biodiesel. In this LCA, the production system was divided into five different stages: microalgae cultivation, harvesting and dewatering, lipid extraction, transesterification, and byproduct management. For each one of these stages different technologies were included and 160 pathways were analyzed. Results from this study indicated that the best results in terms of environmental impacts were obtained when using flat panel bioreactors for algae cultivation (Brentner et al., 2011).

Some research indicates that algae cultivation can have a large environmental footprint driven by upstream impacts, such as the demand for CO_2 and fertilizers (Lardon et al., 2009). Lardon et al. (2009) analyzed the environmental impacts of microalgae biodiesel production, and compared the results to rapeseed, soybeen and palm biodiesel and petroleum diesel production. The LCA was based on a 'cradle to grave' system boundary. The functional unit was the combustion of 1 MJ of fuel in a diesel engine. This LCA's system included the cultivation of Chlorella Vulgaris in open raceways, and considered four different algae production scenarios. The four scenarios included algae cultivation under nutrient rich conditions, nitrogen starvation, oil extraction from wet biomass, and oil extraction from dry biomass. This study showed that algae cultivation under nutrient rich conditions had a higher growth rate. Also, it concluded that the scenario with starved nitrogen conditions and oil extraction from wet biomass was the only one that showed a positive energy balance. This study also concluded that fertilizer supply had the largest environmental impacts, which lead to the conclusion of using wastewater to offset most of the environmental impacts associated with this process (Lardon et al., 2009).

In an attempt to address the increasing eutrophication potential in water bodies, and the large environmental impacts from fertilizer supply to algae cultivation, some

LCA studies have used wastewater as a source of nutrients for their process. Sander et al. (2010) analyzed the biodiesel production from algae grown in photobioreactors/indoors ponds using wastewater after secondary treatment. The LCA was based on a 'cradle to gate' system boundary. The functional unit was chosen to be 1000 MJ energy from algal biodiesel at a refueling station (Sander et al., 2010). Clarens et al. (2009) compared the environmental impacts of producing algae biomass to those from switchgrass, canola, and corn production. This study's scope only included the processes required for algae cultivation. This LCA was based on a 'cradle to gate' system boundary. The functional unit was the production of 317 GJ of biomass-derived energy. This LCA's system design included the cultivation of algae in raceway ponds using different water and nutrient supply scenarios. The scenarios include the supply of fresh water to algae cultivation (base case), as well as the supply of wastewater from conventional activated sludge, biological nutrient removal, and source separated urine. This LCA's results affirm that all of the four scenarios studied presented net positive energy balances. The results from this study were considered controversial by the algae scientific community, given that this study concluded that algae has larger GHG emissions, nutrient requirement, and water use than corn, switchgrass, and canola (Starbuck, 2011). Clarens et al. (2009) also concluded that the use of wastewater can offset some of the environmental impacts related to algae cultivation (Clarens et al., 2009).

Collet et al. (2010) analyzed the production of methane from algae, and compared the results to biodiesel from algae and the first generation feedstocks. The LCA was based on a 'cradle to grave' system boundary. The functional unit was the production of one MJ by the combustion of the energy product in an internal combustion engine.

Chlorella Vulgaris is grown in open raceways, and the liquid digestates from the anaerobic digestion stage provides part of the nutrients for the algae cultivation. This study found that the environmental impacts associated with the production of biogas from algae are from the electricity consumption of the process. This LCA was the first one to use anaerobic digestion experimental data (Collet et al., 2010).

Previous LCA studies on algae bioenergy have provided important information about environmental impacts associated with algae bioenergy system. However, there are still knowledge gaps that need to be addressed. Those LCA studies have mainly looked at algae biomass conversion to biodiesel through esterification. There are limited studies on biogas production through anaerobic digestion (Collet et al., 2010) and other types of biofuels (Sander et al., 2010). Some research has pointed out the need for new algae biomass conversion technologies (Sander et al., 2010). To date, there are no LCA studies that have investigated the environmental impacts from algae biomass conversion to a variety of hydrocarbon fuels. Therefore, different conversion processes with associated energy products need to be evaluated in order to assess environmental impacts of algae bioenergy pathways.

2.4. Literature Review: LCAs on Lignocellulosic Bioenergy Systems

Lignocellulosic feedstocks suited for energy production include: agricultural residue, forestry residue, grasses, municipal and other wastes, and trees. To understand the environmental impacts associated with lignocellulosic bioenergy systems, a number of LCA studies have been conducted (Bright et al., 2009; Fu et al., 2003; Kemppainen et al., 2005; Gonzalez et al., 2010; Mu et al., 2010; & Cherubini et al., 2009).

Previous LCA studies have covered the environmental impacts associated with different type of feedstocks, biomass conversion technologies, and a few energy products.

Ethanol seems to be the most studied energy product derived from lignocellulosic biomass. Bright et al. (2009) evaluated the production and use of wood-based bio-ethanol, and compared the results to a reference gasoline system. The system boundaries for the LCA are 'cradle to grave' (extraction, handling, biomass processing, and use). The functional unit was a distance traveled of 150,000 Km^2 (assumed vehicle lifetime). The study looked at two wood-to-ethanol conversion technologies (biochemical and thermochemical) which were the basis for four E85 production systems. GHG emissions were reduced by 44%-62% on E85 transportation in comparison to a gasoline reference system. The thermochemical wood-to-ethanol conversion technology performed the best in every category compared to the biochemical technology (Bright et al., 2009).

Fu et al. (2003) evaluated bio-ethanol production from three different feedstock sources, including agricultural and wood waste, and from cultivation if demand is high enough. The system boundaries are 'cradle to grave'. The functional unit used is one-kilometer distance driven by new passenger cars. The study looked at the conversion of cellulosic biomass through enzymatic hydrolysis for the production of bioethanol to make an E10 blended fuel. When biofuel is used to produce steam to breakdown the biomass E10 displays environmental improvements in GHG emissions compared to gasoline, however if electricity from fossil fuels is used in the ethanol production process, the results are more favorable for gasoline (Fu et al., 2003).

Kemppainen et al. (2005) evaluated ethanol production from two feedstocks, virgin timber sources or recycled news print from an urban area. The system boundaries for the LCA are 'cradle to gate'. The functional unit used is a constant feed rate of 83,333 kg/h of dry biomass for both feedstocks. The study looked at the same fermentation based conversion process for converting both feedstocks into lignocellulosic ethanol. The timber process generated a lower environmental and human health impact and consumed less electricity, but the news print feedstock has a overall lower composite environmental impact (Kemppainen et al., 2005).

Gonzalez et al. (2010) evaluated ethanol from five feedstocks, alfalfa stems, poplar, Ethiopian mustard, flax shives and hemp hurds. E10 and E85 fuel mixtures were used and the results were compared to gasoline. The system boundaries for the LCA are 'cradle to grave'. The functional unit used is 1 km distance driven by a flex fuel vehicle. The study looked at the same conversion (acid hydrolysis to simultaneous saccharification, fermentation, and distillation) process for each of the 5 lignocellulosic biomass feedstocks and compared the environmental efficiency of E10, E85, and conventional gasoline. The results showed that GHG emissions can be reduced by using ethanol blends flex fuel engines and the Ethiopian mustard displayed the best environmental results (Gonzalez et al., 2010).

Mu et al. (2010) evaluated ethanol production from four feedstocks, wood chips, corn stover, waste paper, and wheat straw, using two biomass conversion processes - biochemical and thermochemical conversion. The system boundaries for the LCA are 'cradle to gate'. The functional unit used is 1 liter of ethanol. This study concludes that the thermochemical conversion process consumes less fresh water, but the biochemical conversion process has lower GHG emissions and consumes less fossil fuel in the near term. These results contradict those from Bright et al. (2009), which concluded that the thermochemical wood-to-ethanol conversion performed better in every category compared to the biochemical technology. Mu et al. (2010) suggested that the thermochemical conversion process could have better environmental performance if higher molecular mixed alcohols are separated as co-products (Mu et al., 2010).

Limited studies evaluated other lignocellulosic bioenergy products besides ethanol. Cherubini et al. (2009) evaluated the environmental lifecycle impacts of producing bioethanol, electricity, heat, and phenols from two crop residues, corn stover and wheat straw, and compared the results to a fossil fuel reference system. The system boundaries for the LCA are 'cradle to gate'. The functional unit used was the amount of agricultural residues treated per year by each biorefinery system (477 kilotons dry/y). Results demonstrated that when using crop residues as feedstocks on biorefinery systems, GHG emissions were reduced to around 50% and nonrenewable energy savings go beyond 80% compared to results from fossil fuel system (Cherubini et al., 2009).

As discussed above, previous LCA studies have mainly looked at ethanol production from lignocellulosic biomass. To date, there are limited LCA studies that have investigated the environmental impacts of various energy products from lignocellulosic biomass. Therefore, different conversion processes with associated energy products need to be evaluated in order to assess environmental impacts of lignocellulosic bioenergy pathways.

CHAPTER 3

ALGAE BIOMASS CONVERSION LCA

The LCA in this chapter evaluates the environmental impacts associated with different algae biomass energy products from various routes across their life cycle.

3.1. Analyzed Processes

Two production processes were evaluated in this comparative LCA. These processes involve the conversion of algal biomass to energy products through two pathways. The same pre-processing stages of algae are used for both pathways prior to the energy generation stages. Thus, the same type of biomass and quantity is used. The differences between the two pathways are the process design and end products. Algal biomass is converted to liquid biofuels via a thermochemical gasification and FTS process, and to electricity and heat via anaerobic digestion and CHP process. Figure 4 shows a general view of the two biomass conversion processes, and their energy products.

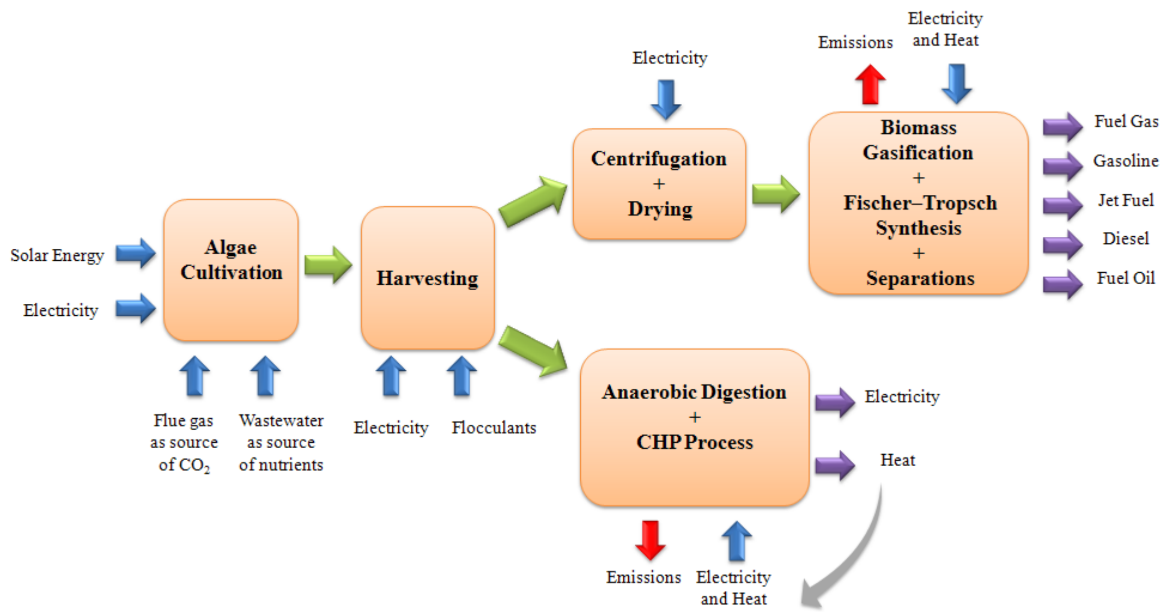

Figure 4. Algae biomass conversion processes' general view

3.1.1. Pre-Processing Stages of Algae Prior to the Energy Generation Stages

Experimental data for the pre-processing stages of algae was obtained from an algae research group from the Department of Civil and Environmental Engineering at University of South Florida (Ergas, 2011).

During the pre-processing stages, algae (Chlorella Vulgaris) are cultivated in photobioreactors using centrate from municipal wastewater as the nutrient source, and power plant flue gas as the CO_2 source. Other inputs to the cultivation stage are: solar energy, and electricity. It is assumed that the production process is co-located with a power plant, and that municipal wastewater is pumped into the process. There is no need to add fertilizers to the process, because it is assumed that the wastewater contains all of the necessary nutrients for algae to grow. When the algal slurry has reached a desired density (2000 mg/L), aluminum sulphate is added to flocculate the algae. Then, the algae are dewatered to reduce the water content. Figure 5 illustrates the process by which algae biomass is obtained.

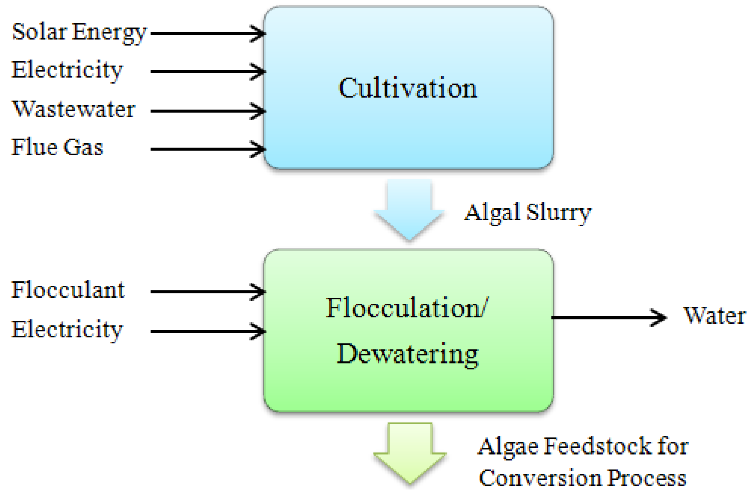

Figure 5. Algae biomass production process

3.1.2. Evaluation Scenarios

Environmental impacts associated with these two conversion processes were evaluated under four different scenarios.

- First scenario or base case scenario: Wastewater is used as a source of nutrients and flue gas is used as a source of CO_2, assuming the process is co-located with a power plant.
- Second scenario: Fertilizers are used as a source of nutrients, and Flue Gas is used as a source of CO_2.
- Third scenario: Wastewater is used as a source of nutrients, and chemical CO_2 is used as the carbon source.
- Fourth scenario: Fertilizers are used as a source of nutrients, and chemical CO_2 is used as the carbon source.

3.1.3. Process 1: Thermochemical Gasification and Conversion of Algae Biomass to Hydrocarbons

Process 1 is designed by the Department of Chemical Engineering at University of South Florida, which involves the conversion of algae biomass to hydrocarbons through a gasification process and FTS process. Data for process 1 was obtained from the Department of Civil and Environmental Engineering (Ergas, 2011) and Chemical Engineering at University of South Florida (Joseph, 2011) and literature (Stephenson et al., 2010). Figure 6 shows the first process' flow chart.

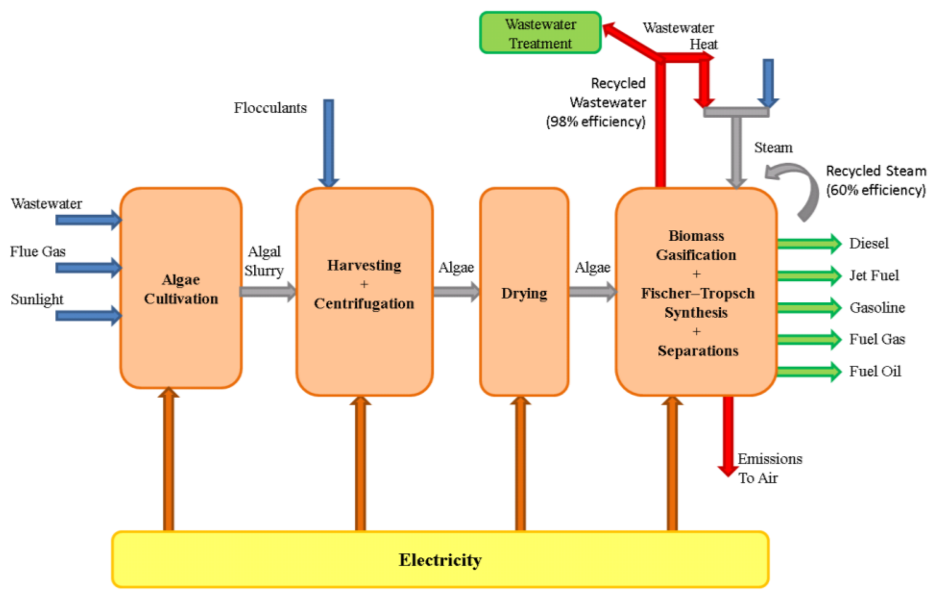

Figure 6. Algae biomass to hydrocarbons conversion process

In this process, after algae are cultivated and harvested as it is explained in section 3.1., algae biomass is taken to a centrifugation process to reduce the water content. Then, the algae go through a drying process until the biomass is suitable for the gasifier. Biomass and water are fed into the gasification process where biomass is converted to syngas. The syngas is cleaned up and conditioned and then converted to liquid hydrocarbons via the FTS process. The mixture of hydrocarbons is separated into fuel gas, gasoline, jet fuel, diesel, and fuel oil based on their molecular weights in a separation process.

Process 1 has five storage tanks, one for each energy product obtained. This process also generates wastewater from the biomass conversion. This process also generates wastewater from the biomass conversion. This stream of wastewater is recycled back to the process, with an assumed efficiency of 98%, to supply the process water requirement. Wastewater generated can meet the water requirement and the remaining wastewater needs to be treated. Carbon dioxide and acid gases are also generated by this conversion process, as shown in Fig. 6.

This process requires external natural gas to provide the steam, and grid electricity as an energy source. Steam generated in the biomass conversion process is recycled back to the process with an assumed efficiency of 60%, to supply part of the process heat requirement.

3.1.4. Process 2: Anaerobic Digestion of Algae Biomass and Combined Heat and Power Process to Electricity

Process 2 involves the conversion of algae biomass to biogas through anaerobic digestion, and then to electricity and heat through a combined heat and power (CHP) process. Data for process 2 was obtained from the Department of Civil and Environmental Engineering at University of South Florida (Ergas, 2011) and literature (Stephenson et al., 2010; Collet et al., 2011; EPA, 2007). Figure 7 shows the second process' flow chart.

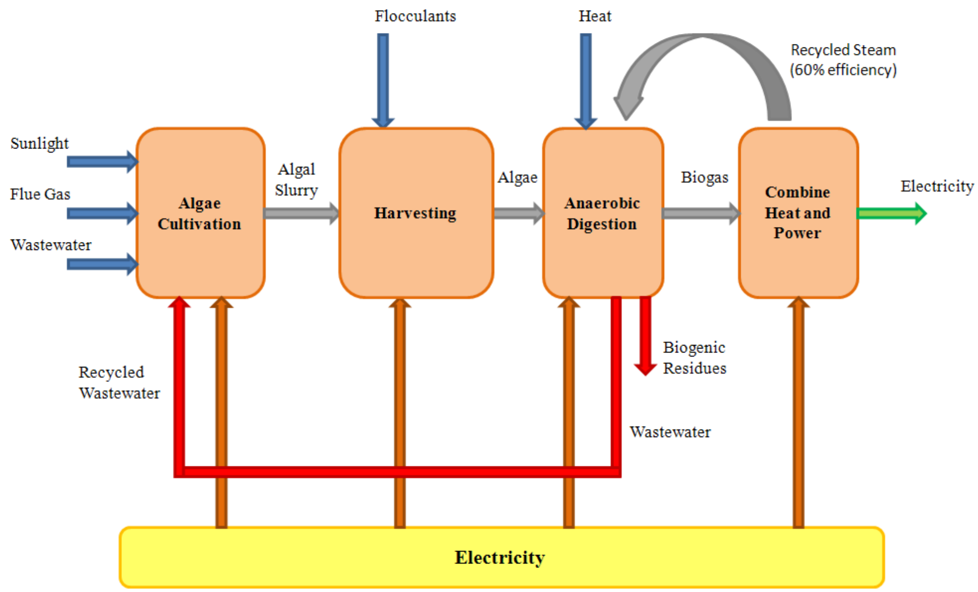

Figure 7. Algae biomass to electricity and heat conversion process

After algae are cultivated and harvested as it is explained in section 3.1.1., algae biomass is digested under anaerobic condition and converted to biogas. This biogas, which consists of mostly methane and CO_2, is taken to a combined heat and power (CHP) process where it is converted to heat and electricity.

The stream of wastewater from the anaerobic digestion process is recycled back to the cultivation stage, which is assumed to have nutrients that would contribute to algae growth. In addition, the biogenic residues from the anaerobic digestion process are considered for land application.

This process requires external natural gas to provide the steam, and grid electricity as an energy source. Steam generated in the CHP process is recycled back to the anaerobic digestion process with an assumed efficiency of 60%, to supply part of the process heat requirement. The electricity produced from the CHP process cannot offset electricity consumption from cultivation, flocculation/dewatering and centrifugation processes.

3.2. Goal and Scope

The goal of this study is to compare the environmental impacts involved in the two processes of converting algae biomass to different energy products and identify the major contributors to the impacts for each process.

The system boundary of this study is considered to be "cradle to gate". This includes the extraction/production and transportation of all raw materials used in the process, the conversion of biomass to energy products, and storage of the products. The infrastructure of the conversion processes, such as buildings, materials for constructions, and equipment, is not included. Also, it does not include the transportation of the liquid fuels to the customers, or the use stage. Figure 8 depicts this study's system boundaries.

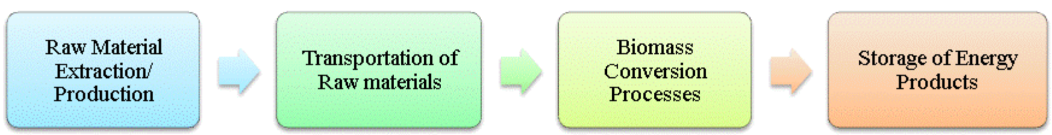

Figure 8. Algae biomass conversion LCAs' system boundaries

The function of electricity and liquid fuel is to provide the energy for different applications. Since the use phase is not considered in this study, the functional unit is chosen to be 1 million BTU. This functional unit allows a fair comparison to be made between the two conversion processes with different energy products.

3.3. Life Cycle Inventory

Relevant data was gathered from various sources and organized to develop the LCA as discussed in this section. This data was collected from a multitude of sources. Data to develop this LCA's inventory is classified into foreground and background data.

3.3.1. Foreground Data

Foreground data includes all of the mass and energy flows that are part of the process (SAIC, 2006).

3.3.1.1. Process 1: Thermochemical Gasification and Conversion of Algae Biomass to Hydrocarbons

Foreground data for the algae biomass conversion process to hydrocarbons was obtained from two main sources. The data for the pre-processing of algae prior to the energy generation stages was obtained from experimental data by University of South Florida (Ergas, 2011), including biomass productivity, flocculant concentration, and dewatering information. In addition, electricity requirement data for the algae biomass supply process was obtained from Stephenson et al. (2010). The foreground data for the algae biomass conversion process to hydrocarbons biofuels was obtained from a production process model developed by University of South Florida (Joseph, 2011). This model provided mass and energy balances, as well as emissions for each of the biomass conversion stages. Table 2 summarizes the mass and energy flows for process 1.

Table 2. Process 1's mass and energy flows

Process Stage	Input	Amount	Units	Output	Amount	Units
Algal Cultivation	Centrate from Municipal Wastewater	1	Kg	Algal Slurry	2.02E-03	Kg
	CO_2	0.61		Water	9.98E-01	
	Electricity	0.05	Kwh			
Dewatering/ Flocculation	Algal Slurry	2.02E-03	Kg	Algae	1.93E-03	Kg
	Water	9.98E-01		Water	3.98E-01	
	Flocculant	1.40E-04		Superna-tant	6.00E-01	
	Electricity	7.94E-05	Kwh			
Centrifugation	Algae	1.93E-03	Kg	Algae	1.84E-03	Kg
	Water	3.98E-01		Water	4.36E-02	
	Electricity	3.17E-04	Kwh	Superna-tant	3.54E-01	
Drying	Algae	1.84E-03	Kg	Steam	4.36E-02	Kwh
	Water	4.36E-02		Algae	1.84E-03	Kg
	Electricity	2.72E-02	Kwh			
Gasification	Algae	1.84E-03	Kg	Ammonia	1.96E-04	Kg
	Steam	1.18E-03	Kwh	Carbon Dioxide	7.62E-04	
	Heat	1.41E-02		Waste-water	9.35E-04	
	Electricity	9.04E-04		Diesel	1.70E-04	
				Fuel Gas	5.56E-04	
				Gasoline	1.82E-04	
				Jet Fuel	1.09E-04	
				Fuel Oil	8.79E-05	
				Steam	1.46E-02	Kwh

3.3.1.2. Process 2: Anaerobic Digestion of Algae Biomass and Combined Heat and Power Process to Electricity

Foreground data for the algae biomass conversion process to electricity was obtained from two main sources. The data for the pre-processing of algae prior to the energy generation stages was obtained from experimental data by University of South Florida (Ergas, 2011; Stephenson et al., 2010). The foreground data for the algae biomass conversion process to electricity was obtained from the Department of Civil and Environmental Engineering at University of South Florida (Ergas, 2011; Collet et al., 2011; EPA, 2007). Table 3 summarizes the mass and energy flows for process 2.

Table 3. Process 2's mass and energy flows

Process Stage	Input	Amount	Units	Output	Amount	Units
Algal Cultivation	Centrate from Municipal Waste-water	1	Kg	Algal Slurry	2.02E-03	Kg
	CO_2	0.61		Water	9.98E-01	
	Electricity	0.05	Kwh			
Dewatering/ Flocculation	Algal Slurry	2.02E-03	Kg	Algae	1.93E-03	Kg
	Water	9.98E-01		Water	3.98E-01	
	Flocculant	1.40E-04		Superna-tant	6.00E-01	
	Electricity	7.94E-05	Kwh			
Anaerobic Digestion	Algae	1.93E-03	Kg	Waste-water	4.00E-01	Kg
	Water	3.98E-01		Biogenic Residues	8.16E-03	
	Sludge	1.74E-02		Biogas	9.60E-03	
	Heat	1.32E-03	Kwh			
	Electricity	2.58E-04				
Combine Heat and Power	Biogas	9.60E-03	Kg	Heat	1.34E-02	Kwh
				Electricity	8.56E-03	

3.3.2. Background Data

Background data includes the upstream and downstream processes that are part of a process, and that supply the energy and materials for the foreground data (SAIC, 2006). Background data for upstream and downstream processes for this comparative LCA was found in various databases and literature. Table 4 and 5 compile all background data, upstream and downstream processes respectively, used by processes 1 and 2.

Table 4. Upstream processes data

Processes	Used by	Source	Description
Aluminum Sulphate Supply	Process 1and 2	Gabi 4	This process includes the emissions and waste associated with the aluminum sulphate production and supply.
Power Supply	Process 1and 2	Gabi	This process includes the emissions and waste generated in the process of electricity production and supply.
Thermal Energy from Natural Gas	Process 1and 2	Gabi	This process includes the emissions and waste generated in the process of thermal energy production and supply.

Table 5. Downstream processes data

Processes	Used by	Source	Description
Wastewater Treatment	Process 1	(Vlasopoulos et al., 2006; & Kohler et al., 2007)	This process was adapted from literature, and it is considered a granular activated carbon (GAC) wastewater treatment process. It includes the emissions and waste associated with the energy required to treat a specific amount of wastewater. It also includes the waste generated (spent carbon) from the process, and the treatment of this waste in landfills. This process does not include any chemicals added for treatment or any other processes not already mentioned in this description.
Landfill	Process 1	Gabi 4	This process is described as the disposal of commercial waste to landfills. It includes all emissions and waste generated by the handling, decomposition and treatment of the waste. This process produces electricity.

3.4. Impact Assessment

In this study, the impact results were normalized and calculated using the following formula:

$$I_{N,i} = \frac{I_i}{N_i}$$

In which, "i" is the impact category, "I_N" is the normalized impact, "I" is the impact results before normalization, and "N" is the normalizing factor. The normalizing factors used in this study are consistent with the TRACI framework. For the calculation of these normalizing factors, Bare et al. (2006) gathered data for impact categories annual emissions from U.S. sources for the most recent year available, in this case 1999. The selection of annual emissions explains why the calculated values show units per year (e.g. kg CO2-Equiv. /year) (Bare et al., 2006). Table 6 presents the tabulated normalizing factor for each impact category considered in this study.

Table 6. Normalization values for TRACI. (Bare et al., 2006)

Impact Category	Tabulated Normalized Value for TRACI	Units
Global Warming	6.85E+12	kg CO_2-Equiv./year
Acidification	2.08E+12	mol H+ Equiv. /year
Eutrophication	5.02E+09	kg N-Equiv. /year
Ecotoxicity	2.06E+10	kg 2,4-Dichlorophenoxyace/year
Human Health Cancer	7.21E+07	kg Benzene-Equiv. /year
Human Health Non Cancer	4.11E+11	kg Toluene-Equiv. /year
Ozone Depletion	8.69E+07	kg CFC 11-Equiv. /year
Smog Air	3.38E+10	kg NOx-Equiv. /year

For this study's purposes weighting among impact categories results is assumed to be the same. The overall impact of producing 1 million BTU of energy products via two different conversion processes using algae biomass feedstock are shown in Figure 9.

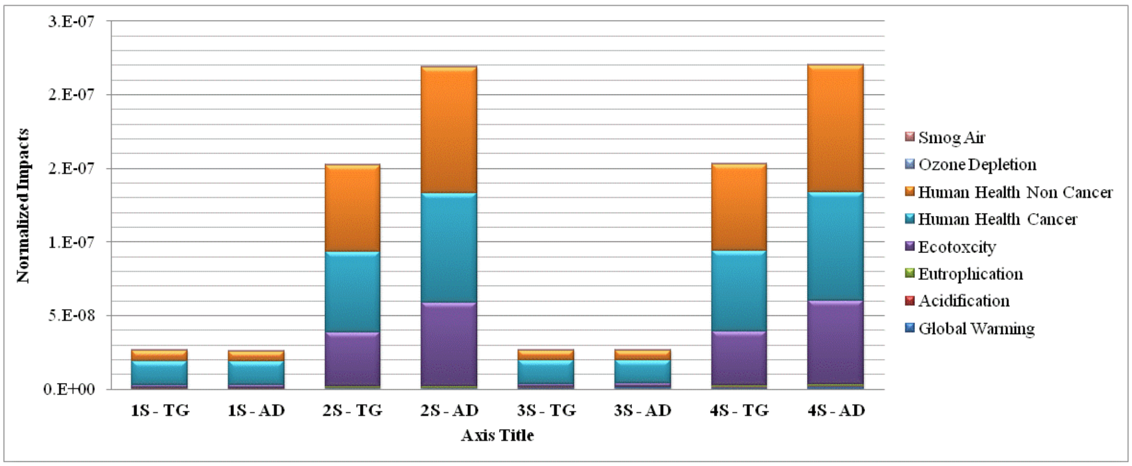

Figure 9. Overall results from the comparative algae biomass conversion LCA[1] (TG: thermochemical gasification; and AD: anaerobic digestion)

As can be seen from Figure 9, process 2 has the highest overall impact. These results can be attributed to the anaerobic digestion process producing less energy than the thermochemical gasification process per kg of algae input. It can also be seen that the impacts vary for each one of the scenarios studied; this will be explained in later sections. The results showed that the categories that appear to have the largest impacts are ecotoxicity, human health non-cancer, and human health cancer. For those categories, the impacts vary for each of the two processes studied. The following sections explain the

[1] **1S:** Wastewater is used as a source of nutrients and flue gas is used as a source of $CO_{2,}$ assuming the process is co-located with a power plant; **2S:** Fertilizers are used as a source of nutrients, and Flue Gas is used as a source of CO_2; **3S:** Wastewater is used as a source of nutrients, and chemical CO_2 is used as the carbon source; **4S:** Fertilizers are used as a source of nutrients, and chemical CO_2 is used as the carbon source.

impact results obtained for both processes. Results will not be discussed for global warming, acidification, eutrophication, ozone depletion, and smog air, since these categories do not have significant impacts as shown in Figure 9.

3.4.1. Ecotoxicity

The contributing factors for high ecotoxicity impact for each process are discussed below.

- Process 1:

Ecotoxicity impacts contributed from upstream processes (UP), conversion processes (CP), and downstream processes (DP). These are shown in Figure 10.

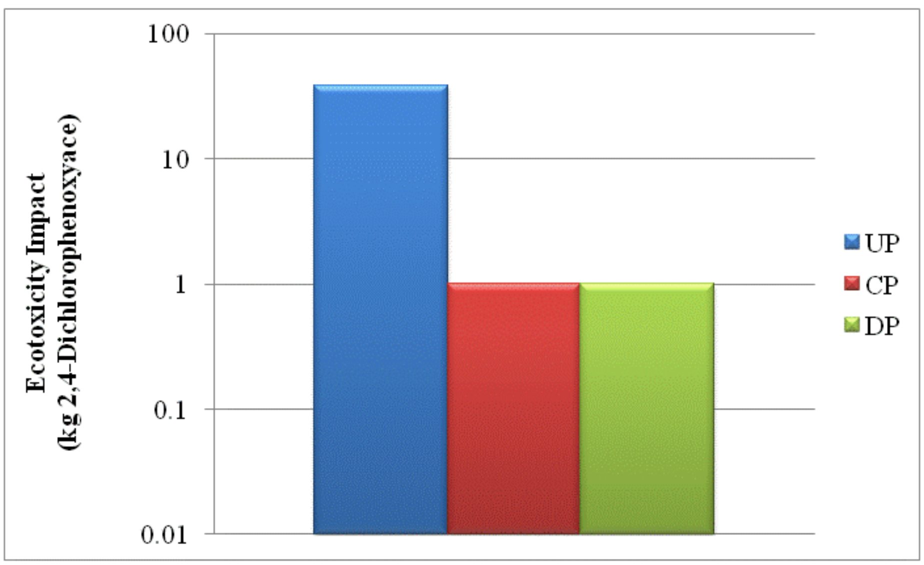

Figure 10. Ecotoxicity impacts for Process 1 (base case scenario)

From Figure 10, it is clear that upstream processes contribute primarily to the overall ecotoxicity impact. The impacts from conversion process itself and downstream processes are negligible compared with that from upstream processes. Figure 11 shows the impacts from each of the upstream processes involved in process 1.

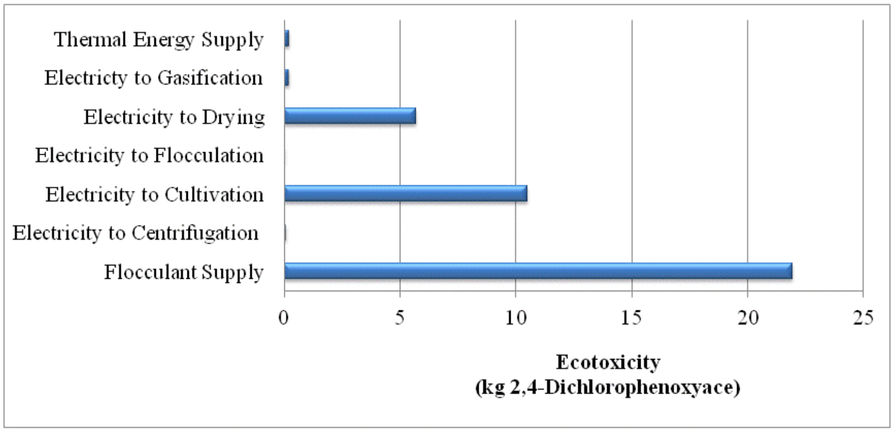

Figure 11. Upstream processes for Process 1 (base case scenario)

It is shown from Figure 11 that aluminum sulphate supply is the major contributor to the ecotoxicity impacts from upstream processes for process 1, followed by, power supply to cultivation, and power supply to drying. Other upstream processes do not show a considerable ecotoxicity potential.

As described in Table 2, the power supply processes include the emissions and waste generated in the process of energy production and distribution to the end user. These emissions and waste pose ecotoxicity potential. Toxic releases to the environment are produced when fossil fuel is burned for electricity production in power plants. The cultivation stage is the stage of the process that has the largest electricity requirement. In the cultivation stage electricity is used by a pump to collect water for further flocculation and dewatering stages. A compressor is also used to pump CO_2 into algae reactors, and this is considered to be the largest electricity consumer in the process. Different compounds that have high ecotoxicity potential are also released in the different stages of the aluminum sulphate supply process.

- Process 2:

Ecotoxicity impacts for process 2 (base case scenario) are shown in Figure 12.

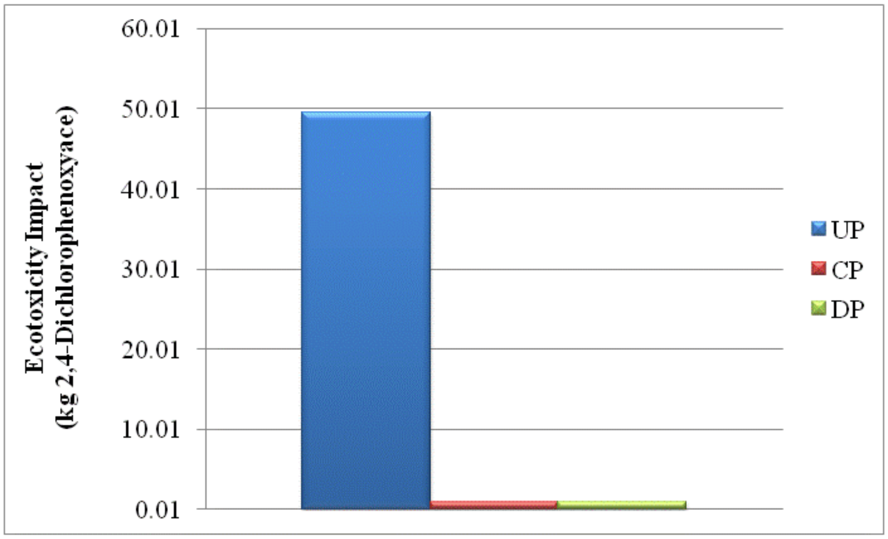

Figure 12. Ecotoxicity impacts for Process 2 (base case scenario)

From Figure 12, it is clear that upstream processes contribute primarily to the overall ecotoxicity impact. The impacts from conversion process itself and downstream processes are negligible compared with that from upstream processes. Figure 13 shows the impacts from each of the upstream processes involved in process 2.

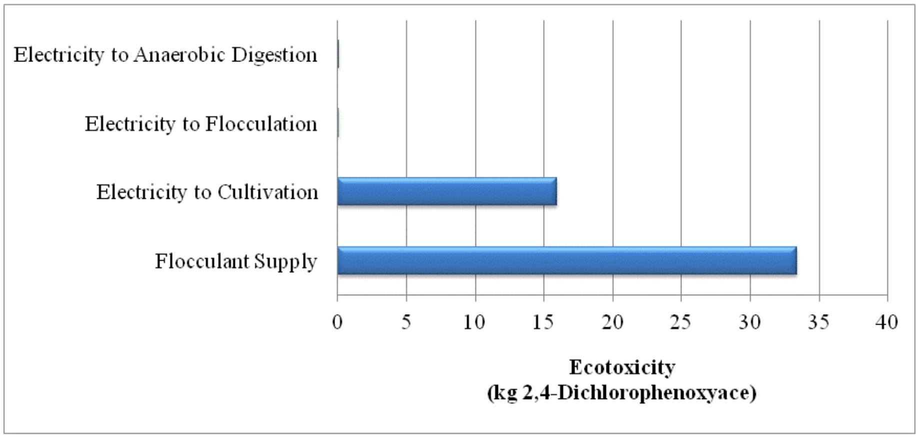

Figure 13. Upstream processes for Process 2 (base case scenario)

It is shown from Figure 13 that aluminum sulphate supply to cultivation is the major contributor to the ecotoxicity impacts from upstream processes for process 2, followed by power supply to cultivation. Other upstream processes do not show a considerable ecotoxicity potential.

As described in Table 2, the power supply processes pose ecotoxicity potential because of the emissions and waste involved in the process. Different compounds that have high ecotoxicity potential are also released in the different stages of the aluminum sulphate supply process.

3.4.2. Human Health Cancer

- Process 1:

Human health cancer impacts for process 1 (base case scenario) are shown in Figure 14.

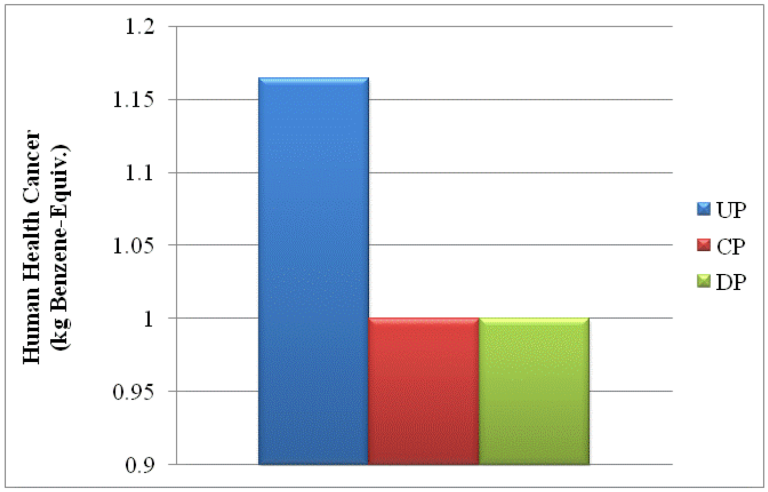

Figure 14. Human health cancer impacts for Process 1 (base case scenario)

Chemicals that cause carcinogenic toxicological responses are called carcinogens. For this impact category, the carcinogenic chemical releases to the environment are primarily from the upstream processes. The human health cancer impacts from biomass conversion process and downstream processes are negligible as shown in Figure 14. Figure 15 shows the impacts from each of the upstream processes involved in process 1 (base case scenario).

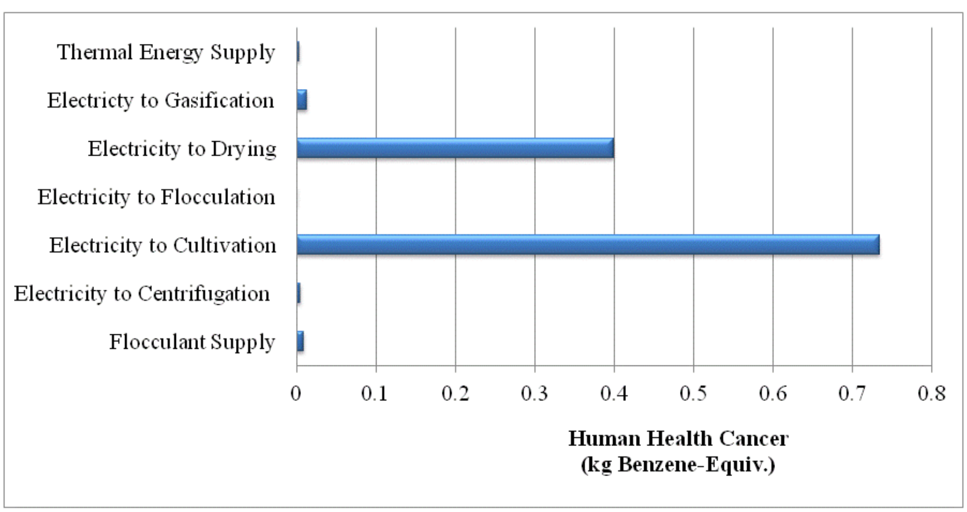

Figure 15. Upstream processes for Process 1 (base case scenario)

It is shown from Figure 15 that power supply to cultivation is the major contributor to the human health cancer impacts from upstream processes for process 1, followed by power supply to drying stage. Other upstream processes do not show a considerable human health cancer potential.

As previously discussed, the power supply process includes a series of processing stages which involve emissions and waste. Different compounds that have carcinogenic potential are released in the different stages of the power supply process. Arsenic was identified as the primary emission. Arsenic has been classified as a known carcinogen by the EPA (EPA, 2011).

- Process 2:

Human health cancer impacts for process 2 (base case scenario) are shown in Figure 16.

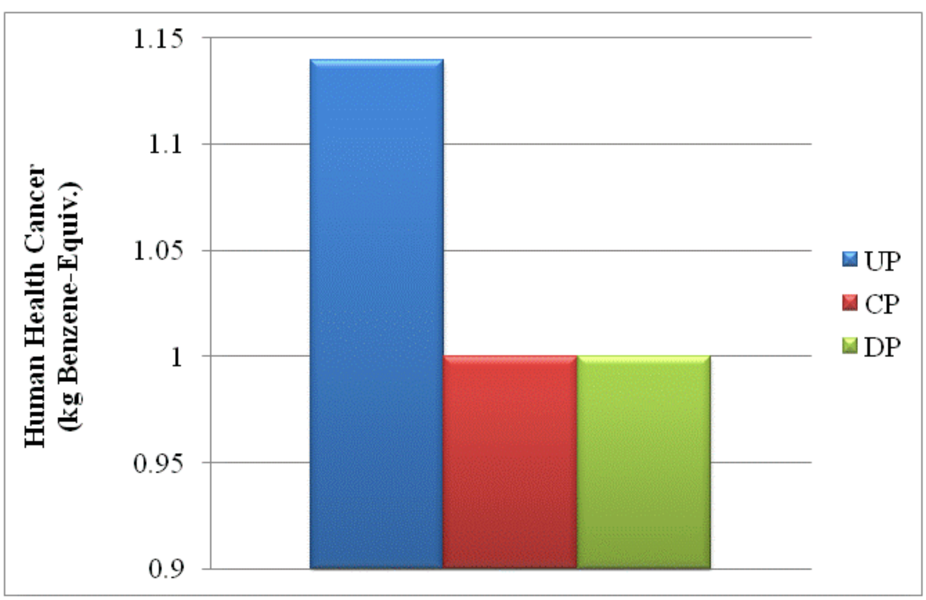

Figure 16. Human health cancer impacts for Process 2 (base case scenario)

In this case, the carcinogenic chemical releases to the environment are primarily from the upstream processes. The human health cancer impacts from biomass conversion process and downstream processes are negligible as shown in Figure 16. Figure 17 shows the impacts from each of the upstream processes involved in process 2 (base case scenario).

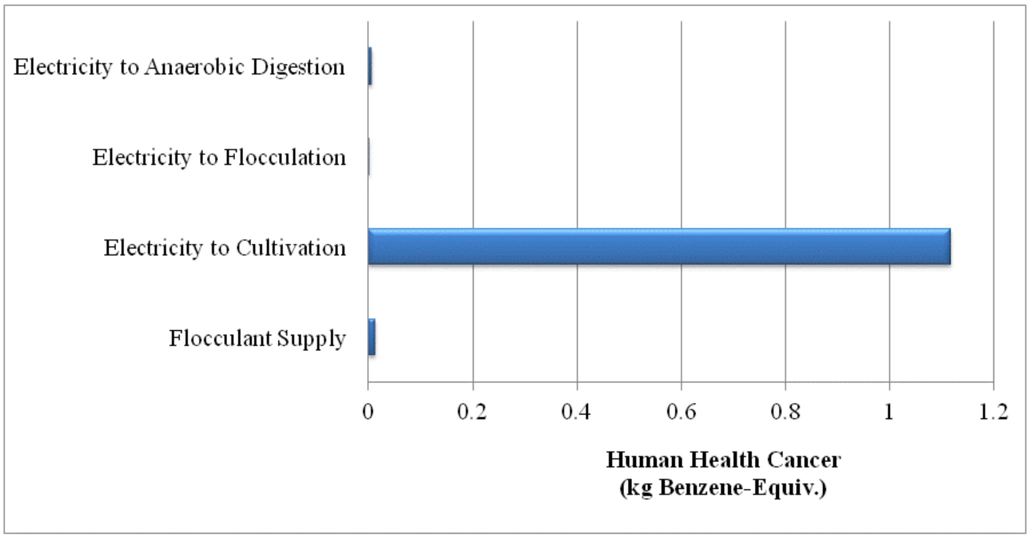

Figure 17. Upstream processes for Process 2 (base case scenario)

It is shown from Figure 17 that power supply to cultivation is the major contributor to the human health cancer impacts from upstream processes for process 2. Other upstream processes do not show a considerable human health cancer potential.

As previously discussed, the power supply process includes a series of processing stages which involve emissions and waste, these pose carcinogenic potential.

3.4.3. Human Health Non-Cancer

- Process 1:

Human health non-cancer impacts for process 1 (base case scenario) are shown in Figure 18.

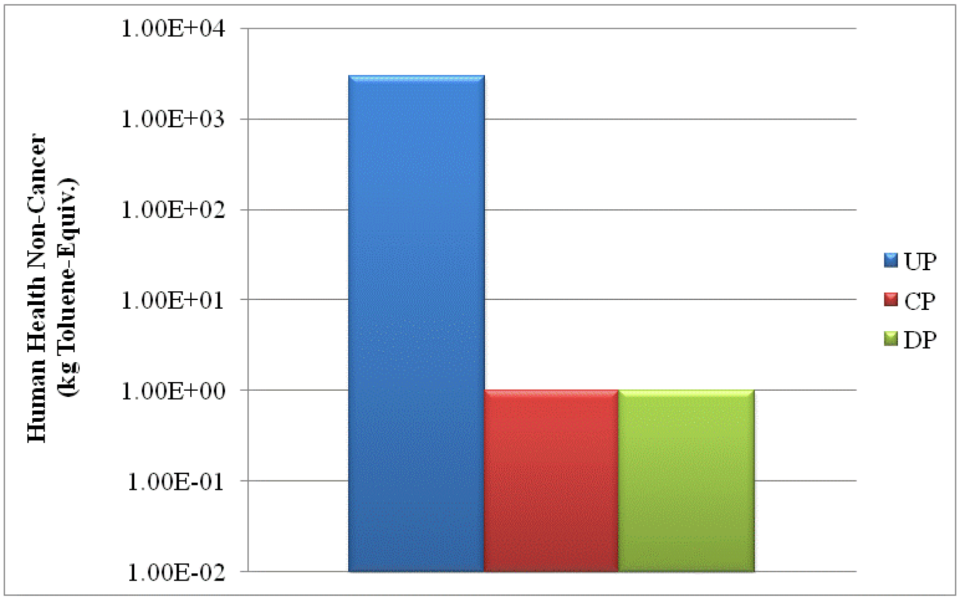

Figure 18. Human health non-cancer impacts for Process 1 (base case scenario)

Chemicals, which do not cause carcinogenic toxicological responses but pose health risks to human due to exposure, are called non-carcinogens. For this impact category, the non-carcinogenic chemical releases to the environment are primarily from the upstream processes. The human health non-cancer impacts from biomass conversion process and downstream processes are negligible as shown in Figure 18. Figure 19 shows the impacts from each of the upstream processes involved in process 1.

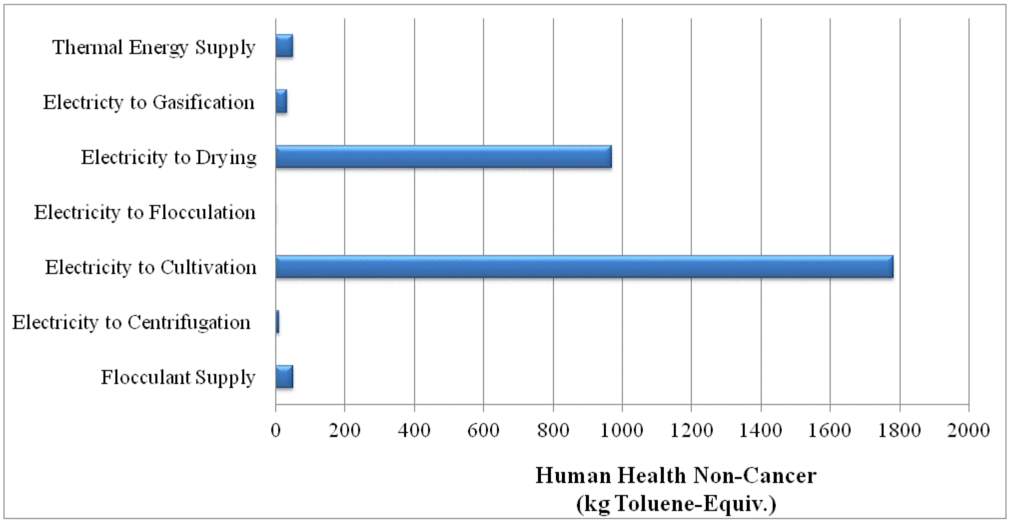

Figure 19. Upstream processes for Process 1 (base case scenario)

It is shown from Figure 19 that power supply to cultivation is the major contributor to the human health non-cancer impacts from upstream processes for process 2, followed by power supply to drying. Other upstream processes do not show a considerable ecotoxicity potential.

It was found that lead, cadmium, and aluminum were released from the power supply process and presented the highest emissions for this upstream process. Among these compounds, lead was the main emission for human health non-cancer impact. Lead is highly toxic and can affect humans' neurological capacity when severe lead exposures occur (NIEHS, 2011).

- Process 2:

Human health non-cancer impacts for process 2 (base case scenario) are shown in Figure 20.

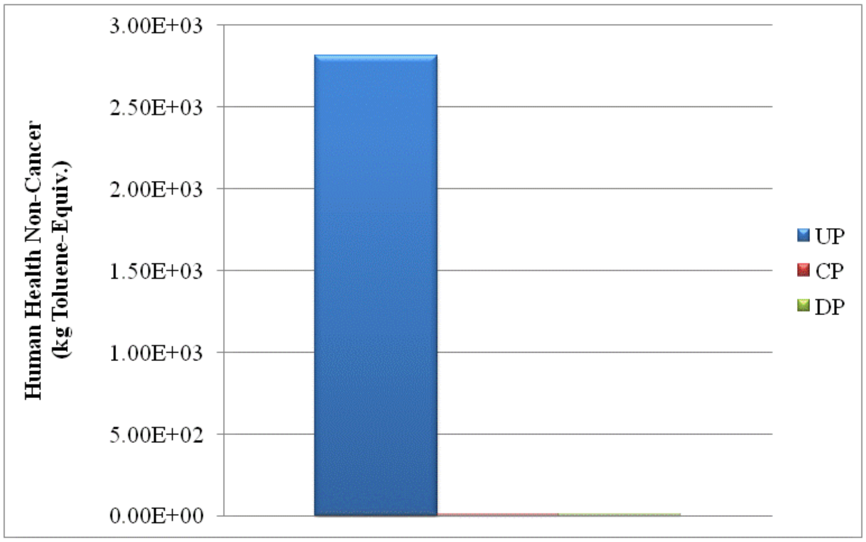

Figure 20. Human health non-cancer impacts for Process 2 (base case scenario)

For this process, the non-carcinogenic chemical releases to the environment are primarily from the upstream processes. The human health non-cancer impacts from biomass conversion process and downstream processes are negligible as shown in Figure 20. Figure 21 shows the impacts from each of the upstream processes involved in process 2.

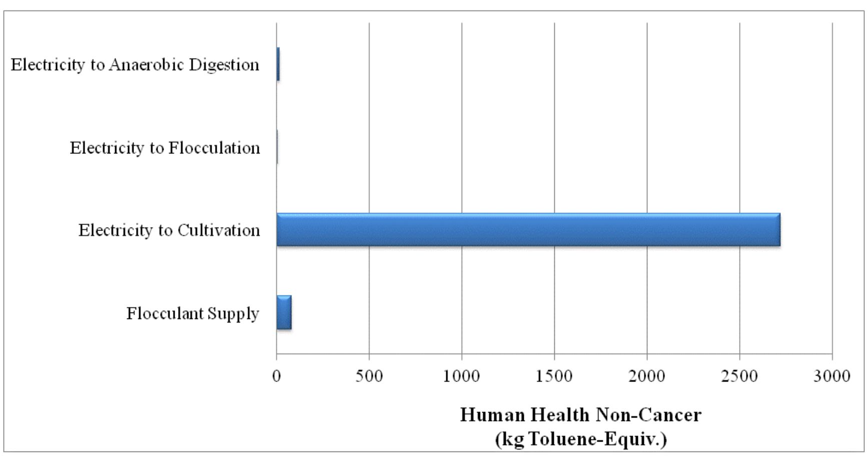

Figure 21. Upstream processes for Process 2 (base case scenario)

It is shown from Figure 21 that power supply to cultivation is the major contributor to the human health non-cancer impacts from upstream processes for process 2, followed by aluminum sulphate supply. Other upstream processes do not show a considerable ecotoxicity potential. It was found that lead, cadmium, and aluminum were released from the power supply process and presented the highest emissions for this upstream process.

3.5. Scenarios Analysis

It can also be seen that the impacts vary for each one of the scenarios studied. Table 7 shows the variation of the impact results depending on the scenarios studied.

Table 7. Impact results variation depending on scenarios[2]

Impact Categories	From 1S to 4S	From 1S to 2S	From 1S to 3S
Global Warming	514.05%	120.96%	393.09%
Acidification	105.37%	79.35%	26.02%
Eutrophication	4106.80%	4029.61%	77.19%
Ecotoxicity	2273.08%	2273.08%	0.00%
Human Health Cancer	370.99%	370.99%	0.00%
Human Health Non Cancer	1156.27%	1156.27%	0.00%
Ozone Depletion	59.10%	59.10%	0.00%
Smog Air	363.99%	245.32%	118.67%

The total percentage change in the impact results from scenario 1 to 4 reveals how much the use of fertilizers and chemical CO_2 for algae cultivation affects the impact

[2] **1S:** Wastewater is used as a source of nutrients and flue gas is used as a source of CO_2, assuming the process is co-located with a power plant; **2S:** Fertilizers are used as a source of nutrients, and Flue Gas is used as a source of CO_2; **3S:** Wastewater is used as a source of nutrients, and chemical CO_2 is used as the carbon source; **4S:** Fertilizers are used as a source of nutrients, and chemical CO_2 is used as the carbon source.

results. When analyzing the impact results from scenario 1 to 2, it can be seen from table 7 that all impact categories show a dramatic increase when using fertilizers for algae cultivation. Impact results for global warming and smog air also increase significantly from scenario 1 to 3 where chemical CO_2 is used for algae cultivation.

Thus, it can be concluded that the base case scenario, where wastewater and flue gas are used for algae cultivation is the best scenario in terms of impact results. Given that this scenario does not have emissions from chemical CO_2 or fertilizers supply. It can also be concluded that the largest negative environmental impacts are obtained when using fertilizers instead of wastewater as source of nutrients for algae cultivation.

CHAPTER 4

LIGNOCELLULOSIC BIOMASS CONVERSION LCA

The LCA in this chapter evaluates the environmental impacts associated with different lignocellulosic biomass energy products from various routes across their life cycle.

4.1. Analyzed Processes

Three production processes were evaluated in this comparative LCA. All of these processes involve the conversion of lignocellulosic biomass to energy products via thermochemical gasification. For these three processes the same type and quantity of biomass is used, as well as the same transportation process delivering biomass to the bioprocessing plant where the conversion process will take place. The differences between the three production systems are the process design and end products. Figure 22 shows a general view of the three biomass conversion processes, and their energy products.

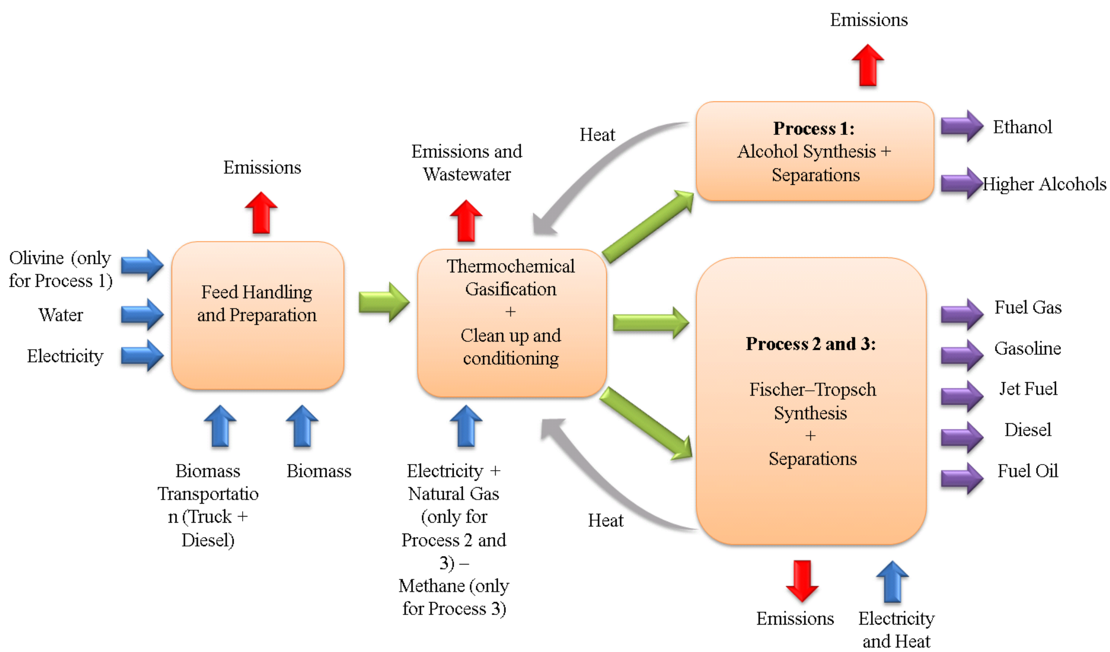

Figure 22. Lignocellulosic biomass conversion processes' general view

4.1.1. Process 1: Conversion of Lignocellulosic Biomass to Ethanol and Mixed Alcohol Synthesis via Thermochemical Gasification and Alcohol Synthesis

Process 1 is a process simulate by the National Renewable Energy Laboratory (NREL) which involves the conversion of lignocellulosic biomass to ethanol and higher alcohols through a gasification process and alcohol synthesis process (Aden et al., 2007). Figure 23 shows the first process' flow chart.

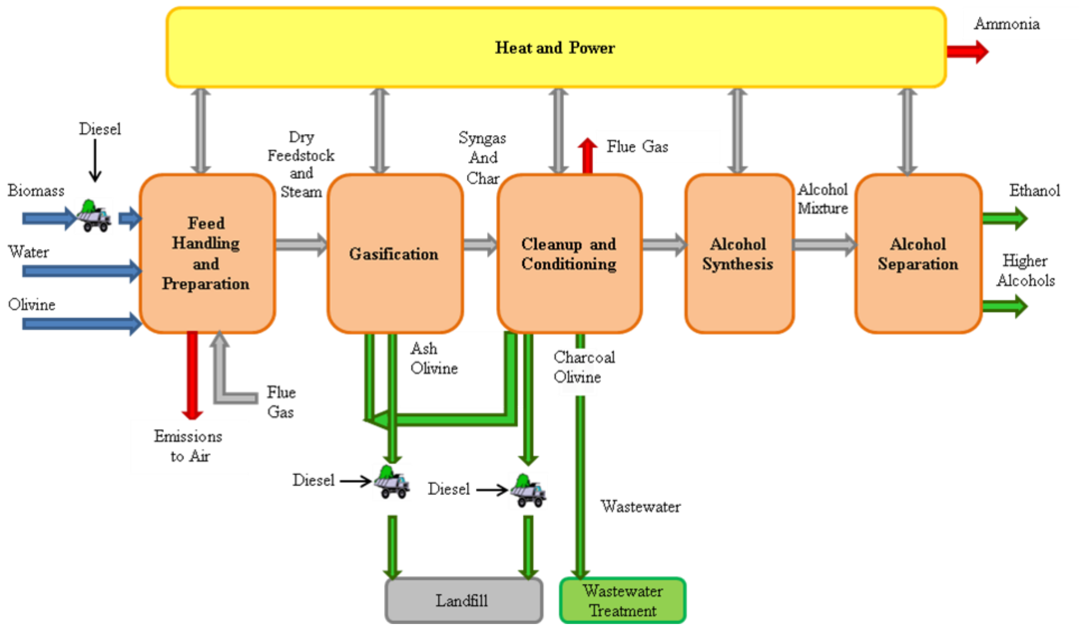

Figure 23. Lignocellulosic biomass to alcohols conversion process's flow chart

In this process biomass and water are taken to the feed handling and preparation stage, where the biomass is stored for a short period of time and dried for processing in the gasifier. Hot synthetic olivine is circulated between the gasifier and char combustor to supply heat for the endothermic gasification process. The dry feedstock and steam will feed into the gasification process. The gasification process converts the biomass into synthesis gas (syngas) and char. Char is taken to landfill for disposal. The syngas, which is a mixture of carbon monoxide and hydrogen, is then cleaned up and conditioned, to make it suitable for the alcohol synthesis process, where it is synthesized into a mixture of alcohols using a fixed bed catalyst. The mixture of alcohols is de-gassed, dried, and separated into: ethanol, butanol, isopropanol, and pentanol in the alcohol separation stage.

Process 1 has two storage tanks, one for ethanol and the second one for higher alcohols. In addition, waste is generated from the gasification and gas cleanup and conditioning stages, this waste is transported using trucks and disposed to landfill. The gas cleanup and conditioning stage generates wastewater, which has to be treated.

This process has unique energy integration design, in which a heat and power station is connected to the other stages of the process, as shown in figure 23. The integrated combined heat and power system supplies all steam and electricity needed by the plant. This eliminates the natural gas inputs for the char combustor and fuel combustor. This also eliminates the need to purchase electricity from the grid. The fuel for integrated combined heat and power system is from a slipstream of unreformed syngas. Although this design eliminates the external energy input, it lowers the ethanol yield because syngas fed into the alcohol synthesis process is reduced. Figure 24 shows an overall view of the conversion process of the lignocellulosic biomass to alcohols.

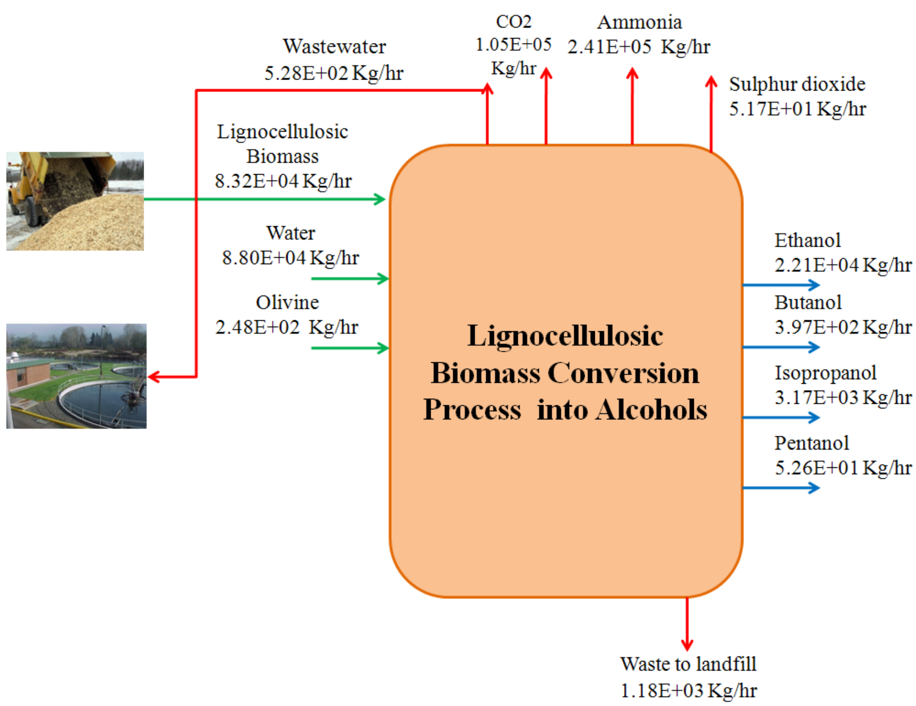

Figure 24. Overall conversion process of lignocellulosic biomass conversion to alcohols

4.1.2. Process 2: Thermochemical Gasification and Conversion of Lignocellulosic Biomass to Hydrocarbons

Process 2 is designed by the Department of Chemical Engineering at University of South Florida, which involves the conversion of lignocellulosic biomass to hydrocarbons through a gasification process and FTS process. Figure 25 shows the second process' flow chart (Joseph, 2011).

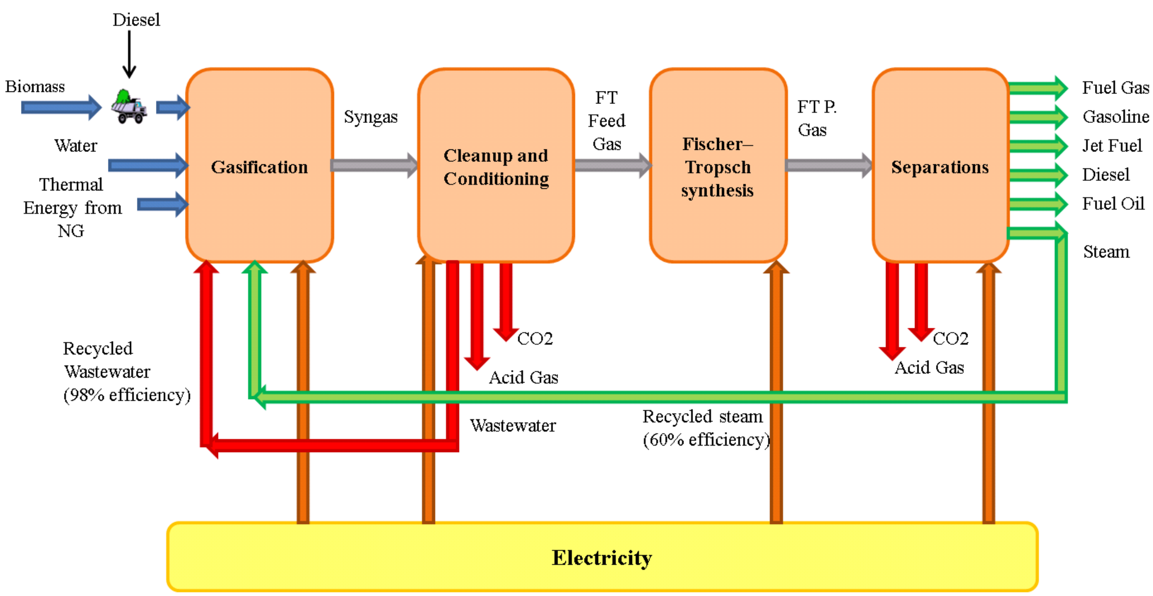

Figure 25. Lignocellulosic biomass to hydrocarbons conversion process's flow chart

In this process, biomass and water are fed into to the gasification process where biomass is converted to syngas. The syngas is cleaned up and conditioned and then converted to liquid hydrocarbons via the FTS process. The mixture of hydrocarbons is separated into fuel gas, gasoline, jet fuel, diesel, and fuel oil based on their molecular weights in a separation process.

Process 2 has five storage tanks, one for each energy product obtained. This process also generates wastewater from the biomass conversion. This stream of wastewater is recycled back to the process with an assumed efficiency of 98%, to supply part of the process water requirement. Carbon dioxide and acid gases are also generated by this conversion process, as shown in Figure 25.

This process requires external natural gas to provide the steam, and grid electricity as an energy source. Steam generated in the biomass conversion process is recycled back to the process with an assumed efficiency of 60%, to supply part of the process heat requirement.

Figure 26 shows an overall view of the conversion process of lignocellulosic biomass to hydrocarbons.

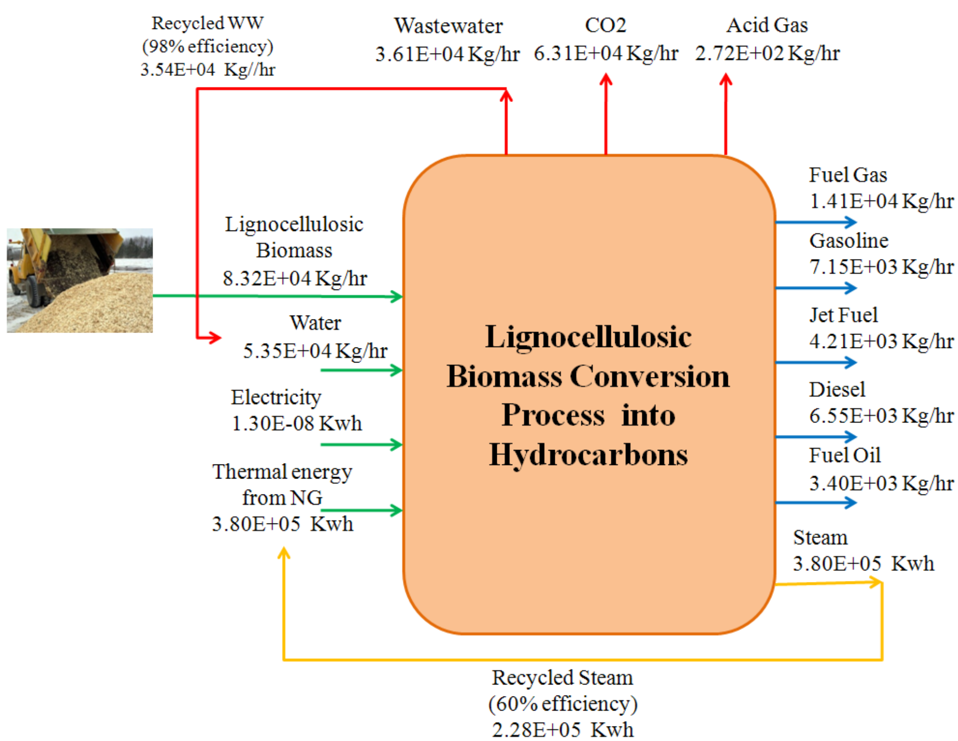

Figure 26. Overall conversion process of lignocellulosic biomass to hydrocarbons

4.1.3. Process 3: Thermochemical Gasification and Conversion of Lignocellulosic Biomass to Hydrocarbons with Methane

Process 3 is also designed by the Department of Chemical Engineering at University of South Florida, similar as Process 2 involving gasification and FTS processes with an additional input of methane to the gasification process (Joseph, 2011). The purpose of using methane is to increase the efficiency of the process in terms of energy production. Figure 27 shows the third process' flow chart.

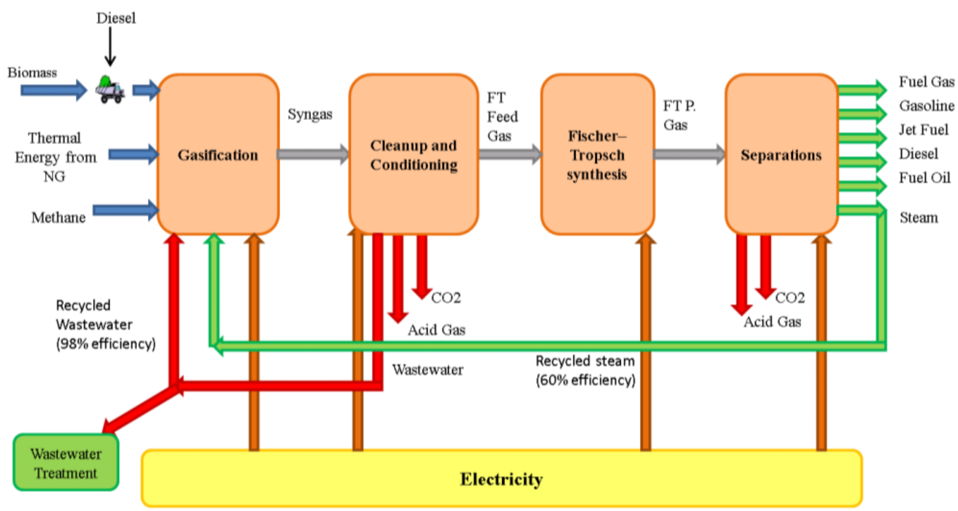

Figure 27. Lignocellulosic biomass to hydrocarbons (using methane) conversion process' flow chart

Process 3 has five storage tanks, one for each energy product obtained (fuel gas, gasoline, jet fuel, diesel, and fuel oil). This process also generates wastewater from the biomass conversion. This stream of wastewater is recycled back to the process, with an assumed efficiency of 98%, to supply the process water requirement. Wastewater generated can meet the water requirement and the remaining wastewater needs to be treated. Carbon dioxide and acid gases are also generated by this conversion process, as shown in Figure 27.

This process requires external natural gas to provide steam, and grid electricity as an energy source. Steam generated from the biomass conversion process is recycled back to the process with an assumed efficiency of 60%, to supply part of the heat requirements for the process. Figure 28 shows an overall view of the conversion process of lignocellulosic biomass to hydrocarbons using methane.

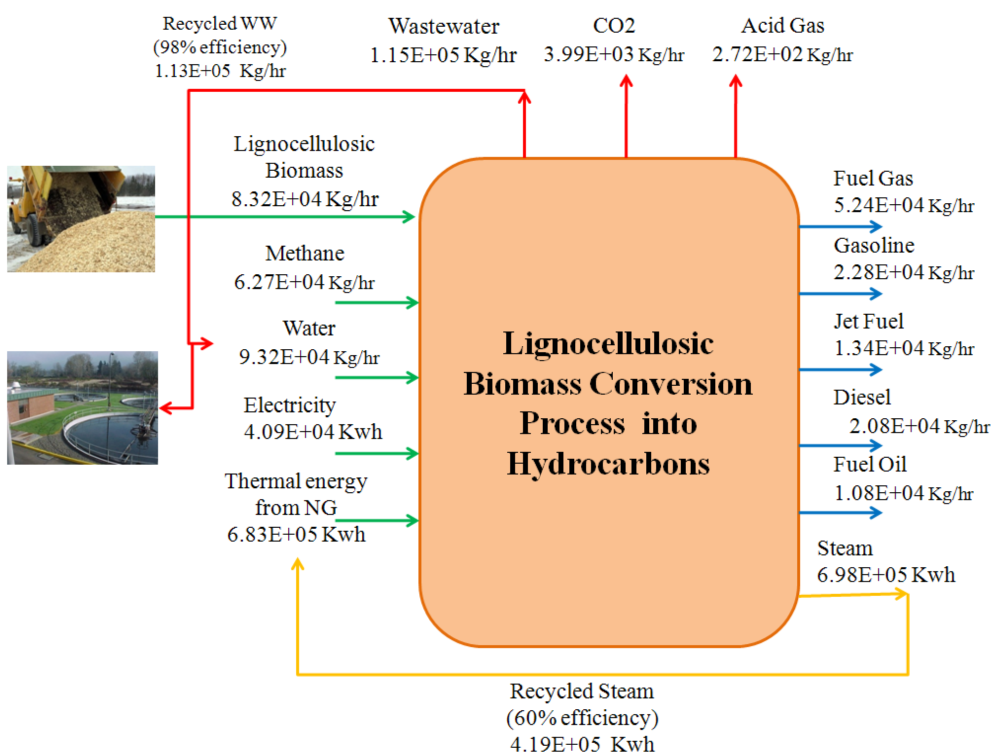

Figure 28. Overall conversion process (using methane) of lignocellulosic biomass to hydrocarbons

4.2. Goal and Scope

The goal of this study is to compare the environmental impacts involved in the three processes of converting lignocellulosic biomass to different energy products and identify the major contributors to the impacts for each process.

The system boundary of this study is considered to be “cradle to gate”. This includes the extraction/production and transportation of all raw materials used in the process, the conversion of biomass to liquid fuels, and storage of the fuels. The infrastructure of the conversion processes, such as buildings, materials for constructions, equipment, is not included. It does not include as well the transportation of the liquid fuels to the customers, nor the use stage. Figure 29 depicts this study’s system boundaries.

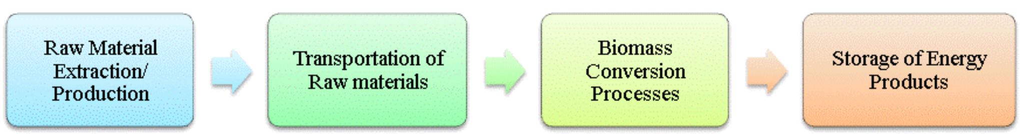

Figure 29. Lignocellulosic biomass conversion LCAs’ system boundaries

The function of liquid fuel is to provide the energy for different applications. Since the use phase is not considered in this study, the functional unit is chosen to be 1 million BTU. This functional unit allows a fair comparison to be made between the three conversion processes with different energy products.

4.3. Life Cycle Inventory

Relevant data was gathered from various sources and organized to develop the LCA as discussed in this section. Data to develop this LCA's inventory is classified into foreground and background data.

4.3.1. Foreground Data

Foreground data includes all of the mass and energy flows that are part of the process.

4.3.1.1. Process 1: Thermochemical Gasification and Conversion of Lignocellulosic Biomass to Ethanol and Mixed Alcohol Synthesis

Foreground data for the lignocellulosic biomass conversion process into ethanol and higher alcohols was obtained from the NREL report "*Thermochemical Ethanol via Indirect Gasification and Mixed Alcohol Synthesis of Lignocellulosic Biomass*" (Aden et al., 2007). This report provided mass and energy balances, as well as emissions for each one of the biomass conversion stages. Table 8 summarizes the mass and energy flows for process 1.

Table 8. Process 1's mass and energy flows

Input	Amount	Units
Lignocellulosic Biomass	8.32E+04	Kg/hr
Water	8.80E+04	
Olivine	2.48E+02	
Output	**Amount**	**Units**
Wastewater	5.28E+02	Kg/hr
Carbon Dioxide	1.05E+05	
Ammonia	2.41E+05	
Sulphur Dioxide	5.17E+01	
Waste to landfill	1.18E+03	
Ethanol	2.21E+04	
Butanol	3.97E+02	
Isopropanol	3.17E+03	
Pentanol	5.26E+01	

4.3.1.2. Process 2: Thermochemical Gasification and Conversion of Lignocellulosic Biomass to Hydrocarbons

Foreground data for the lignocellulosic biomass conversion process to hydrocarbons was obtained from a production process model developed by University of South Florida. This model provided mass and energy balances, as well as emissions for each one of the biomass conversion stages. Table 9 summarizes the mass and energy flows for process 2.

Table 9. Process 2's mass and energy flows

Input	Amount	Units
Lignocellulosic Biomass	8.32E+04	Kg/hr
Water	5.35E+04	
Electricity	1.30E-08	Kwh
Thermal energy from Natural Gas	3.80E+05	
Output	**Amount**	**Units**
Wastewater	3.61E+04	Kg/hr
Carbon Dioxide	6.31E+04	
Acid gas	2.72E+02	
Fuel gas	1.41E+04	
Gasoline	7.15E+03	
Jet fuel	4.21E+03	
Diesel	6.55E+03	
Fuel oil	3.40E+03	
Steam	3.80E+05	Kwh

4.3.1.3. Process 3: Thermochemical Gasification and Conversion of Lignocellulosic Biomass to Hydrocarbons with Methane

Foreground data for the lignocellulosic biomass conversion process to hydrocarbons using methane was obtained from a production process model developed by University of South Florida (Joseph, 2011). This model provided mass and energy balances, as well as emissions for each one of the biomass conversion stages. Table 10 summarizes the mass and energy flows for process 3.

Table 10. Process 3's mass and energy flows

Input	Amount	Units
Lignocellulosic Biomass	8.32E+04	Kg/hr
Water	9.32E+04	
Methane	6.27E+04	
Electricity	4.09E+04	Kwh
Thermal energy from Natural Gas	6.83E+05	
Output	**Amount**	**Units**
Wastewater	1.15E+05	Kg/hr
Carbon Dioxide	3.99E+03	
Acid gas	2.72E+02	
Fuel gas	5.24E+04	
Gasoline	2.28E+04	
Jet fuel	1.34E+04	
Diesel	2.08E+04	
Fuel oil	1.08E+04	
Steam	6.98E+05	Kwh

4.3.2. Background Data

Background data includes the upstream and downstream processes that are part of a process, and that supply the energy and materials for the foreground data.

Background data for upstream and downstream processes for this comparative LCA was found in various databases and literature. Table 11 and 12 compile all background data, upstream and downstream processes respectively, used by processes 1, 2, and 3.

Table 11. Upstream processes data

Processes	Used by	Source	Description
Biomass Supply	Process 1, 2 and 3	Simapro	This upstream process includes the transportation of the urban and demolition wood waste to the facility where the biomass will be chopped, the infrastructure, the chopping process, the water consumption by the process, and the disposal of wastes and effluents generated during the biomass sorting process.
Transportation	Process 1, 2 and 3	Gabi 4	Diesel trailer with a 45,000 lb capacity. This process includes all of the emissions associated with driving the trailer for the specified distances (50 miles average), and efficiency (90%).
Diesel Supply	Process 1, 2 and 3	Gabi 4	This process includes the emissions and waste generated in the process of diesel production, supply, and burning.
Water Supply	Process 1 and 2	Simapro	This process includes the infrastructure and energy use for water treatment and transportation to the end user. It does not include any emissions from water treatment.
Olivine Supply	Process 1	Gabi 4	This process includes the emissions and waste associated with the olivine's excavation, processing, and supply.
Power Supply	Process 2 and 3	Gabi	This process includes the emissions and waste generated in the process of electricity production and supply.
Thermal Energy from Natural Gas	Process 2 and 3	Gabi	This process includes the emissions and waste generated in the process of thermal energy production and supply.
Methane Supply	Process 3	Gabi	This process includes the emissions and waste associated with the methane's processing and supply.

Table 12. Downstream processes data

Processes	Used by	Source	Description
Wastewater Treatment	Process 1 and 3	(Vlasopoulos et al., 2006; & Kohler et al., 2007)	This process was adapted from literature, and it is considered a granular activated carbon (GAC) wastewater treatment process. It includes the emissions and waste associated with the energy required to treat a specific amount of wastewater. It also includes the waste generated (spent carbon) from the process, and the treatment of this waste in landfills. This process does not include any chemicals added for treatment or any other processes not already mentioned in this description.
Landfill	Process 1 and 3	Gabi 4	This process is described as the disposal of commercial waste to landfills. It includes all emissions and waste generated by the handling, decomposition and treatment of the waste. This process produces electricity.

4.4. Impact Assessment

Impact categories results were normalized as explained in section 3.5. The overall normalized impacts of producing 1 million BTU of energy products via three different conversion processes using lignocellulosic biomass feedstock are shown in Figure 30.

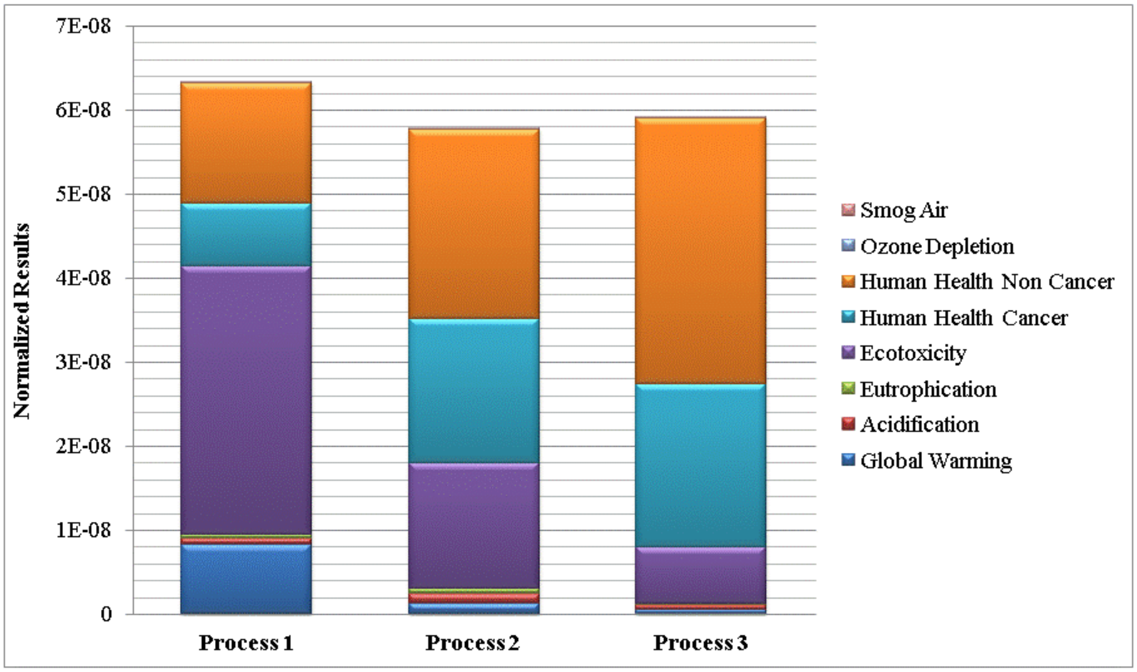

Figure 30. Overall results from the comparative lignocellulosic biomass conversion LCA

As can be seen from Figure 30, process 1 has the highest overall impact assuming the same weight for each impact category. The results also showed that the categories that appear to have the largest impacts are ecotoxicity, human health non-cancer, human health cancer, and global warming. For those categories, the impacts vary for each of the three processes studied. The following sections explain the impact results obtained for each process. Results will not be discussed for acidification, eutrophication, ozone depletion, and smog air, since these categories do not have significant impacts as shown in Figure 30.

4.4.1. Ecotoxicity

From Figure 30, it can be seen that the process that shows the largest ecotoxicity impact is process 1, followed by process 2 and 3, respectively. The contributing factors for high ecotoxicity impact for each process are discussed below.

- Process 1:

Ecotoxicity impacts contributed from upstream processes (UP), conversion processes (CP), and downstream processes (DP) for process 1 are shown in Figure 31.

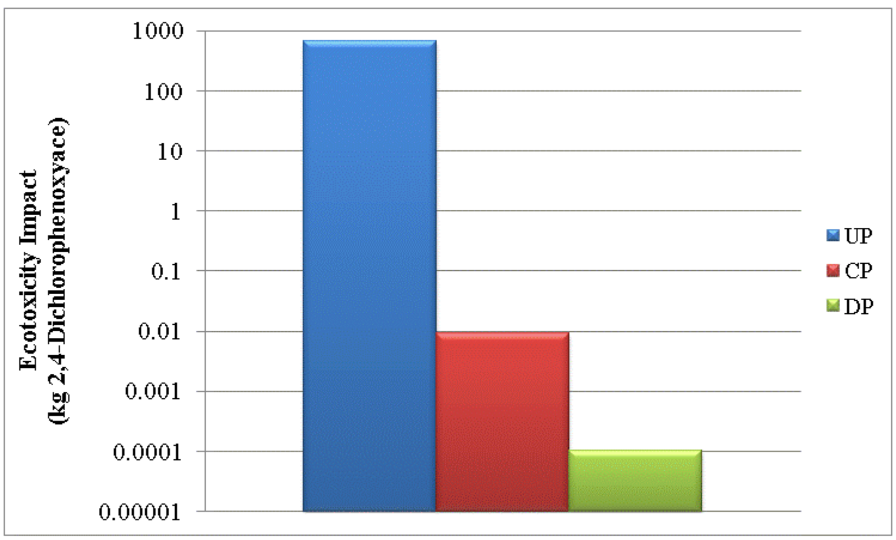

Figure 31. Ecotoxicity impacts for Process 1

From Figure 31, it is clear that upstream processes contribute primarily to the overall ecotoxicity impact. The impacts from conversion process itself and downstream processes are negligible compared with that from upstream processes. Figure 32 shows the impacts from each of the upstream processes involved in process 1.

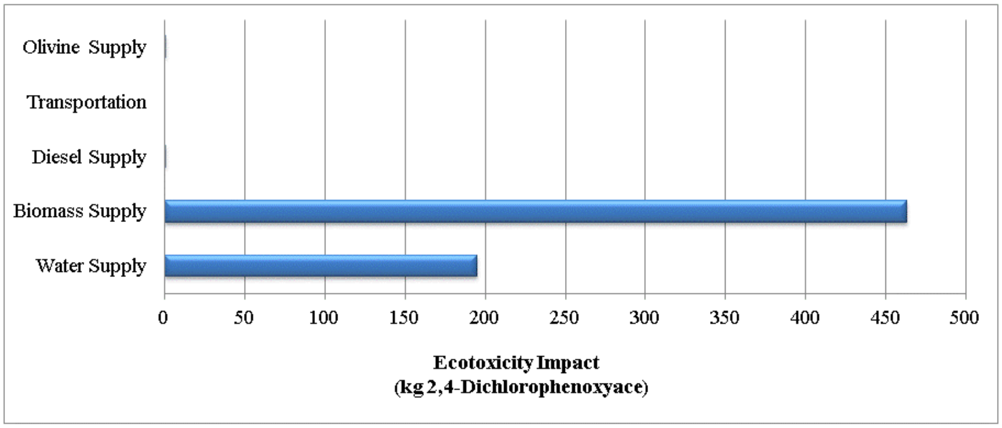

Figure 32. Upstream processes for Process 1

It is shown from Figure 32 that biomass supply is the major contributor to the ecotoxicity impacts from upstream processes for process 1, followed by water supply. Other upstream processes do not show a considerable ecotoxicity potential.

As described in Table 11, biomass supply process includes the transportation of the biomass to the conversion facility, the pre-processing of the biomass (e.g., chopping), and the water consumption and the disposal of wastes and effluents generated during the biomass sorting process. Different compounds that have high ecotoxicity potential are released in the different stages of the biomass supply process. The water supply process includes the infrastructure and energy use for water treatment and distribution to the end user. Emissions and waste associated with materials and energy use for water treatment and distribution pose ecotoxicity potential.

- Process 2:

Ecotoxicity impacts for process 2 are shown in Figure 33.

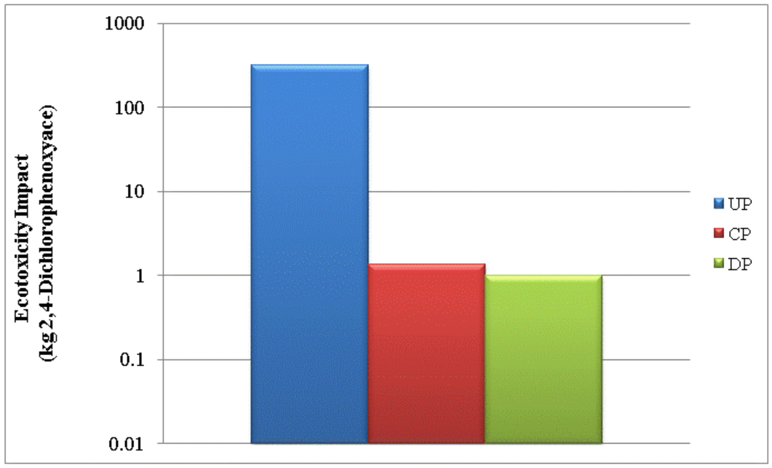

Figure 33. Ecotoxicity impacts for Process 2

From Figure 33, it can be seen that upstream processes contribute primarily to the overall ecotoxicity impact. The impacts from conversion process itself and downstream processes are negligible compared with that from upstream processes. Figure 34 shows the impacts from each of the upstream processes involved in process 2.

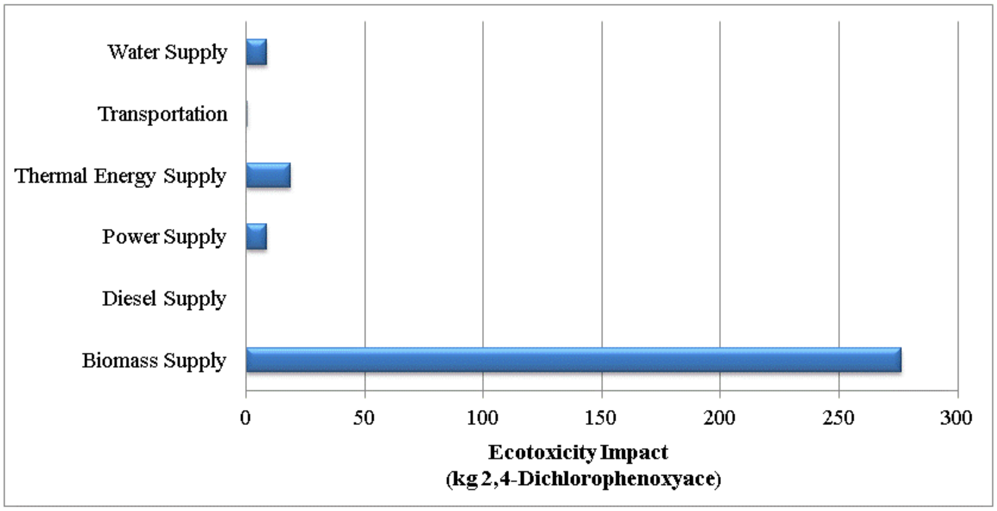

Figure 34. Upstream processes for Process 2

It is shown from Figure 34 that biomass supply is the major contributor to the ecotoxicity impacts from upstream processes for process 2, followed by thermal energy, power, and water supply.

As described in Table 11, biomass and supply processes release different compounds that have high ecotoxicity potential throughout the different stages of their processes. The thermal energy and power supply processes include the emissions and waste generated in the process of energy production and distribution to the end user. These emissions and waste pose ecotoxicity potential.

- Process 3:

Ecotoxicity impacts for process 3 are shown in Figure 35.

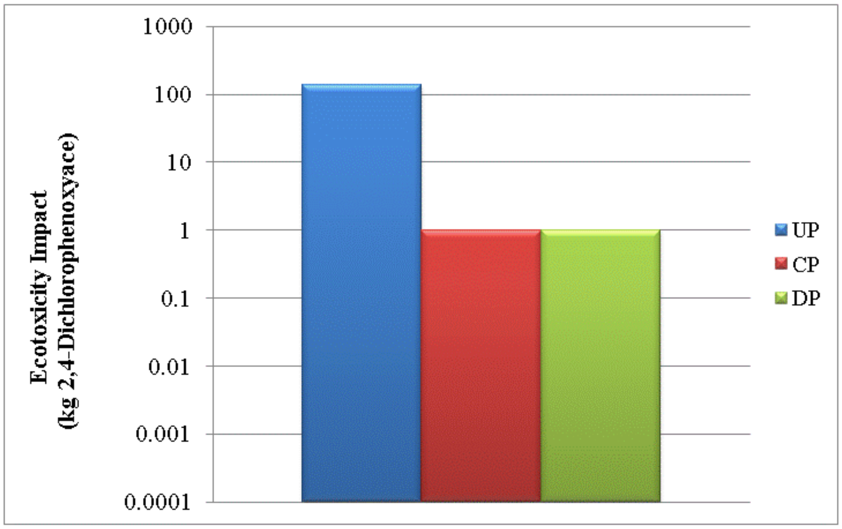

Figure 35. Ecotoxicity impacts for Process 3

From Figure 35, it can be seen that upstream processes contribute primarily to the overall ecotoxicity impact. The impacts from conversion process itself and downstream processes are negligible compared with that from upstream processes. Figure 36 shows the impacts from each of the upstream processes involved in process 3.

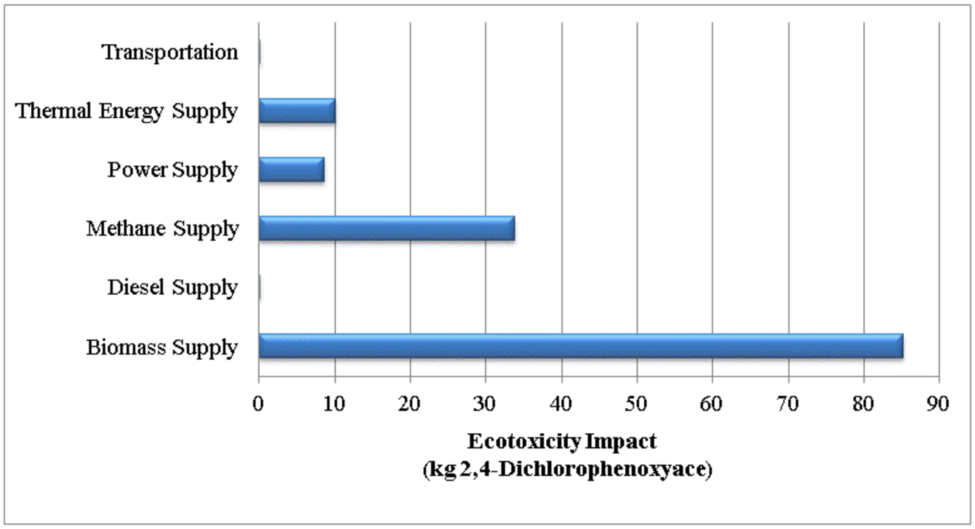

Figure 36. Upstream processes for Process 2

It is shown from Figure 36 that biomass supply is the major contributor to the ecotoxicity impacts from upstream processes for process 3, followed by methane, thermal energy and power supply. Other upstream processes do not show a considerable ecotoxicity potential.

As described in Table 11, biomass, thermal energy and power supply processes pose ecotoxicity potential. The methane supply process includes the emissions and waste generated in the process of production and distribution to the end user. These emissions and waste have ecotoxicity potential.

4.4.2. Human Health Non-Cancer

From Figure 30, it can be seen that the process that shows the largest human health non-cancer impact is process 3, followed by process 2 and 1, respectively. The contributing factors for high human health non-cancer impact for each process are discussed below.

- Process 1:

Human health non-cancer impacts for process 1 are shown in Figure 37.

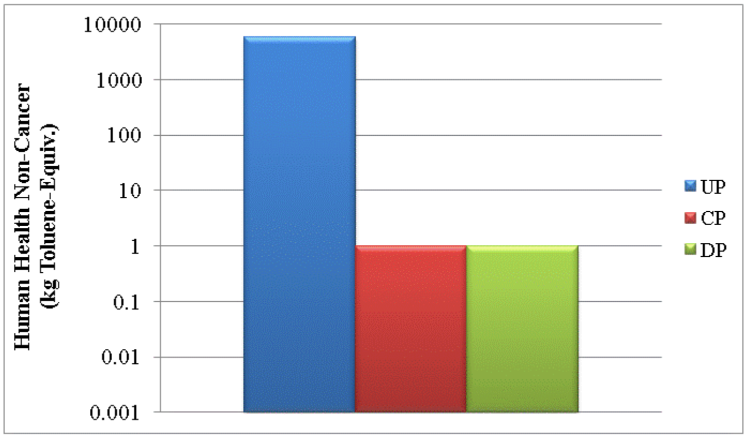

Figure 37. Human health non-cancer impacts for Process 1

Chemicals, which do not cause carcinogenic toxicological responses but pose health risks to human due to exposure, are called non-carcinogens. For this impact category, the non-carcinogenic chemical releases to the environment are primarily from the upstream processes. The human health non-cancer impacts from biomass conversion process and downstream processes are negligible as shown in Figure 37. Figure 38 shows the impacts from each of the upstream processes involved in process 1.

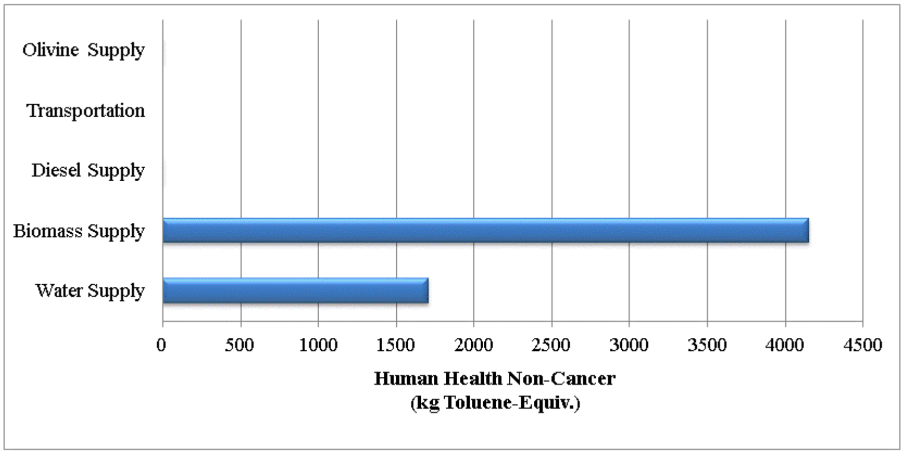

Figure 38. Upstream processes for Process 1

It is shown from Figure 38 that biomass supply is the major contributor to the human health non-cancer impacts from upstream processes for process 1, followed by water supply. Other upstream processes do not show a considerable ecotoxicity potential. It was found that lead, cadmium, and aluminum were released from the biomass supply process and presented the highest emissions for this upstream process. Among these compounds, lead was the main emission for human health non-cancer impact. Lead is highly toxic and can affect humans' neurological capacity when severe lead exposures occur (NIEHS, 2011). The water supply process includes the infrastructure and energy use for water treatment and distribution to the end user. Emissions and waste associated with materials and energy use for water treatment and distribution pose human health non-cancer potential. Along with this process, non-carcinogenic compounds are released to the environment, which mainly includes lead.

- Process 2:

Human health non-cancer impacts for process 2 are shown in Figure 39.

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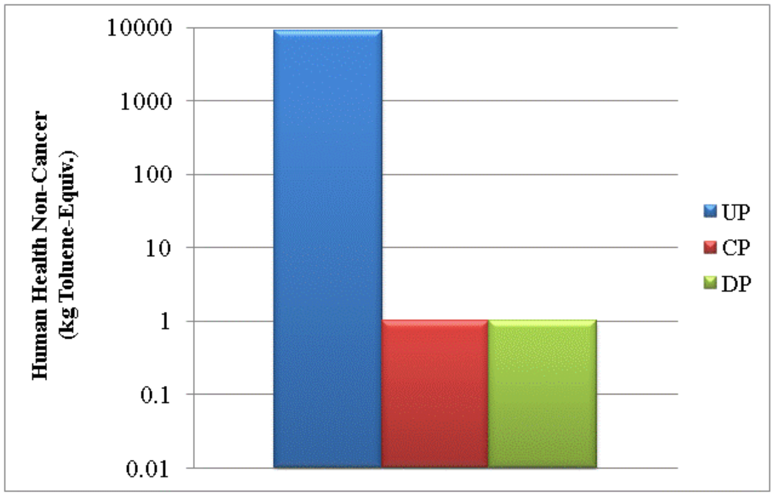

Figure 39. Human health non-cancer impacts for Process 2

From Figure 39 it can be seen that for this impact category, the non-carcinogenic chemical releases to the environment are primarily from the upstream processes. The impacts from conversion process itself and downstream processes are negligible compared with that from upstream processes. Figure 40 shows the impacts from each of the upstream processes involved in process 2.

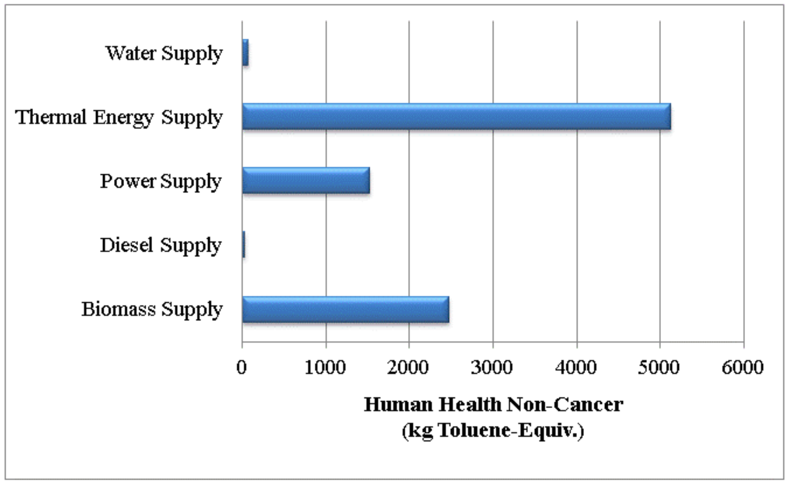

Figure 40. Upstream processes for Process 2

It is shown from Figure 40 that thermal energy supply is the major contributor to the human health non-cancer impacts from upstream processes for process 2, followed by biomass, power, and water supply. Other upstream processes do not show a considerable ecotoxicity potential.

As described in Table 11, thermal energy and power supply processes include the emissions and waste generated in the energy production and distribution to the end user. Different compounds that have non-carcinogenic potential are released in the different stages of the supply processes. These releases were identified to be for the most part lead. As it was mentioned before, non-carcinogenic compounds are released by the biomass and water supply processes. The supply process includes the emissions and waste generated in the process of production and distribution to the end user. These emissions and waste pose human health non-cancer potential.

- Process 3:

Human health non-cancer impacts for process 3 are shown in Figure 41.

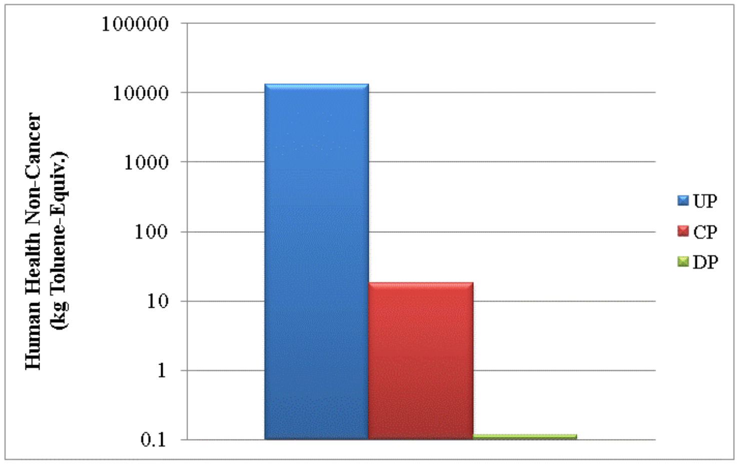

Figure 41. Human health non-cancer impacts for Process 3

For this impact category, the non-carcinogenic chemical releases to the environment are primarily from the upstream processes. The human health non-cancer impacts from biomass conversion process and downstream processes are negligible as shown in Figure 41. Figure 42 shows the impacts from each of the upstream processes involved in process 3.

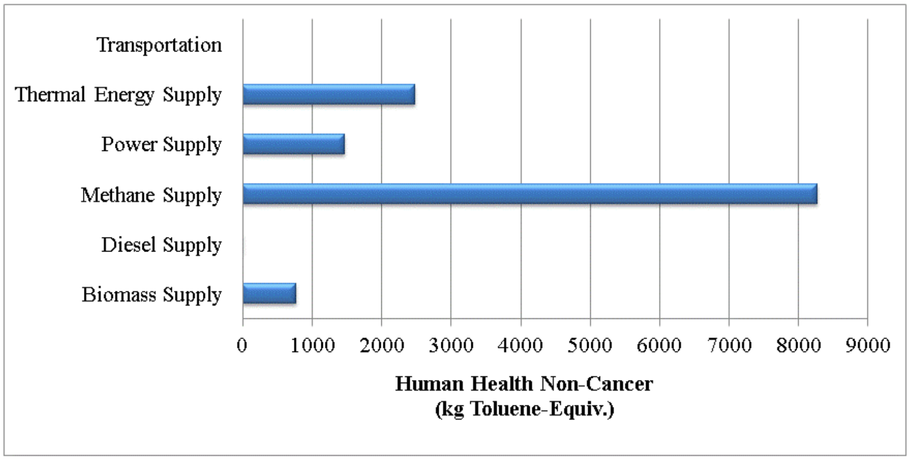

Figure 42. Upstream processes for Process 3

It is shown from Figure 42 that methane supply is the major contributor to the human health non-cancer impacts from upstream processes for process 3, followed by thermal energy, power and biomass supply. Other upstream processes do not show a considerable human health non-cancer potential.

As described in Table 11, methane supply process includes the emissions and waste generated in the methane production and distribution to the end user. Different compounds that have non-carcinogenic potential are released in the different stages of the methane supply process. These releases were identified to be primarily lead. As it was mentioned before, non-carcinogenic compounds are released by the thermal energy, power and biomass supply processes. These emissions and waste pose human health non-cancer potential.

4.4.3. Human Health Cancer

From Figure 30, it can be seen that the process that shows the largest human health cancer impact is process 3, followed by process 2 and 1, respectively. The contributing factors for high human health cancer impact for each process are discussed below.

- Process 1:

Human health cancer impacts for process 1 are shown in Figure 43.

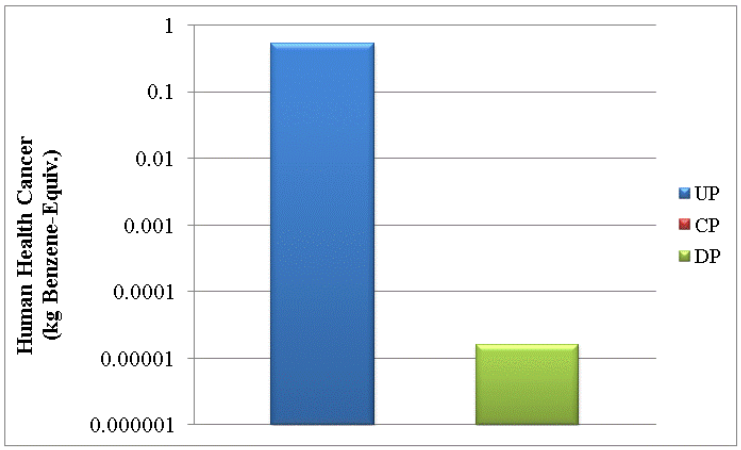

Figure 43. Human health cancer impacts for Process 1

Chemicals that cause carcinogenic toxicological responses are called carcinogens. For this impact category, the carcinogenic chemical releases to the environment are primarily from the upstream processes. The human health cancer impacts from biomass conversion process and downstream processes are negligible as shown in Figure 43. Figure 44 shows the impacts from each of the upstream processes involved in process 1.

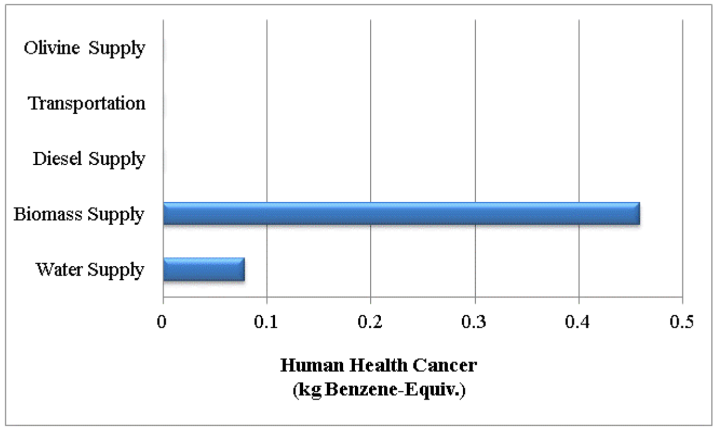

Figure 44. Upstream processes for Process 1

It is shown from Figure 44 that biomass supply is the major contributor to the human health cancer impacts from upstream processes for process 1, followed by water supply process. Other upstream processes do not show a considerable human health cancer potential.

As described in Table 11, the biomass and water supply processes include a series of processing stages which involve emissions and waste. Different compounds that have carcinogenic potential are released in the different stages of the biomass and water supply processes. Arsenic was identified as the primary emission.

- Process 2:

Human health cancer impacts for process 2 are shown in Figure 45.

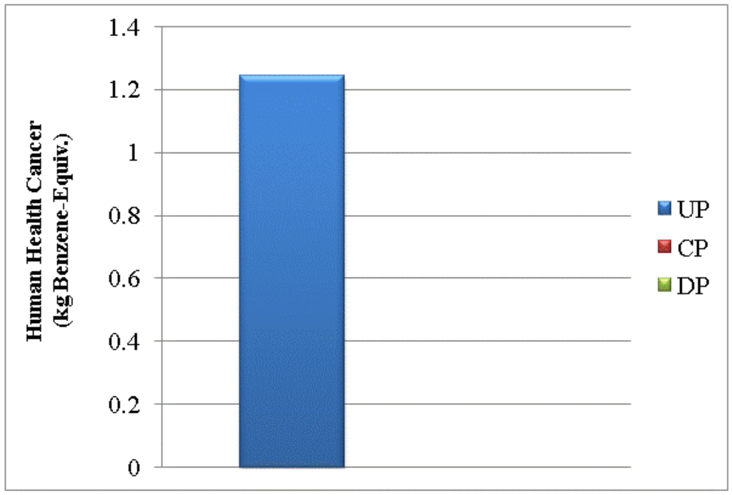

Figure 45. Human health cancer impacts for Process 2

For this impact category, the carcinogenic chemical releases to the environment are primarily from the upstream processes. The human health cancer impacts from biomass conversion process and downstream processes are negligible as shown in Figure 45. Figure 46 shows the impacts from each of the upstream processes involved in process 2.

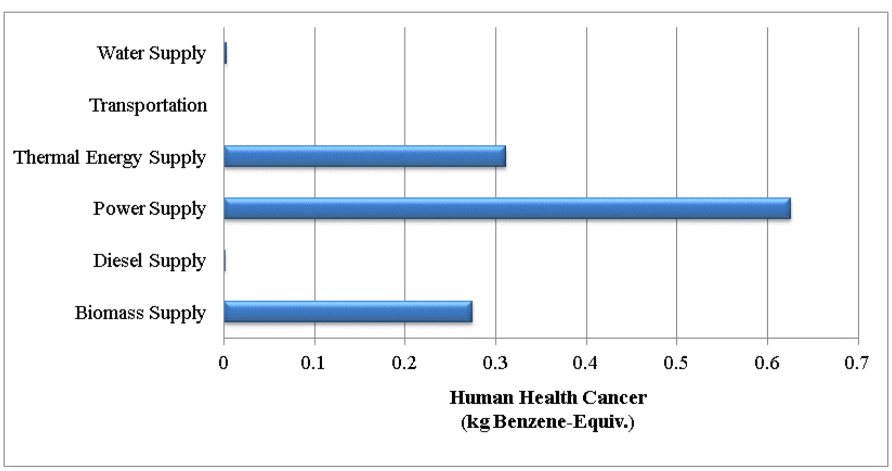

Figure 46. Upstream processes for Process 2

It is shown from Figure 46 that power supply process is the major contributor to the human health cancer impacts from upstream processes for process 2, followed by thermal energy, and biomass supply processes. Other upstream processes do not show a considerable human health cancer potential.

As described in Table 11, thermal energy and power supply processes have high human health cancer potential because these processes include a series of stages which involve emissions and waste. Different compounds that have carcinogenic potential are released in the different stages of these processes. Biomass supply process, as it was mentioned before, also releases carcinogenic chemicals throughout the process' stages. Heavy metals and organic emissions are being emitted to the air by these processes. These heavy metals are being emitted in the form of arsenic.

- Process 3:

Human health cancer impacts for process 3 are shown in Figure 47.

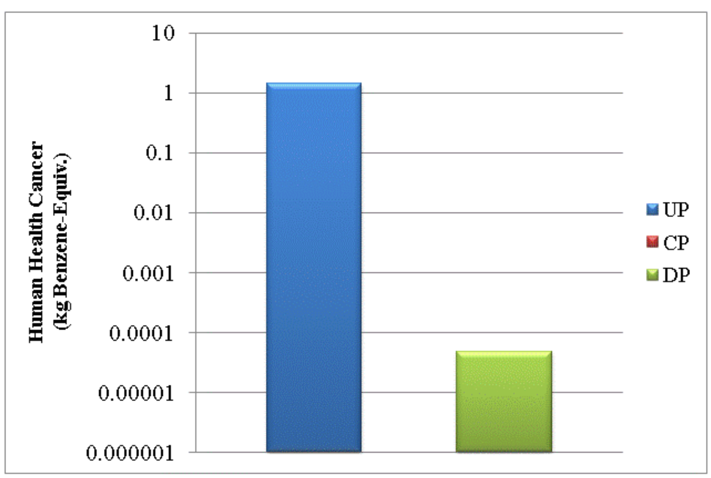

Figure 47. Human health cancer impacts for Process 3

For this impact category, the carcinogenic chemical releases to the environment are primarily from the upstream processes. The human health cancer impacts from biomass conversion process and downstream processes are negligible as shown in Figure 47. Figure 48 shows the impacts from each of the upstream processes involved in process 3.

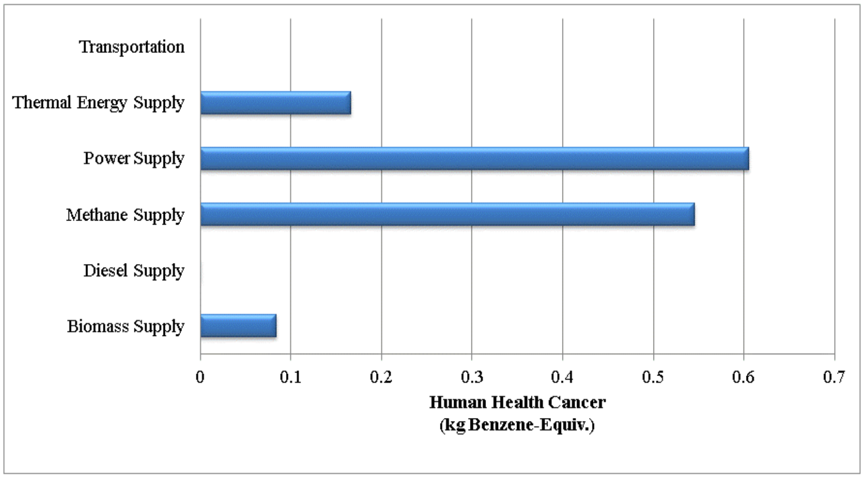

Figure 48. Upstream processes for Process 3

It is shown from Figure 48 that power supply process is the major contributor to the human health cancer impacts from upstream processes for process 3, followed by methane, thermal energy, and biomass supply processes. Other upstream processes do not show a considerable human health cancer potential.

As it was mentioned before, the power, thermal energy, and biomass supply processes have high human health cancer potential because of the carcinogenic chemicals released during their production and supply. The methane supply process releases carcinogenic chemicals throughout the methane production and distribution to end user process. These chemicals have been identified to be primarily arsenic.

4.4.4. Global Warming

From Figure 30, it can be seen that the three processes show very low global warming potential. The contributing factors for global warming potential for each process are discussed below.

- Process 1:

Global warming impacts for process 1 are shown in Figure 49.

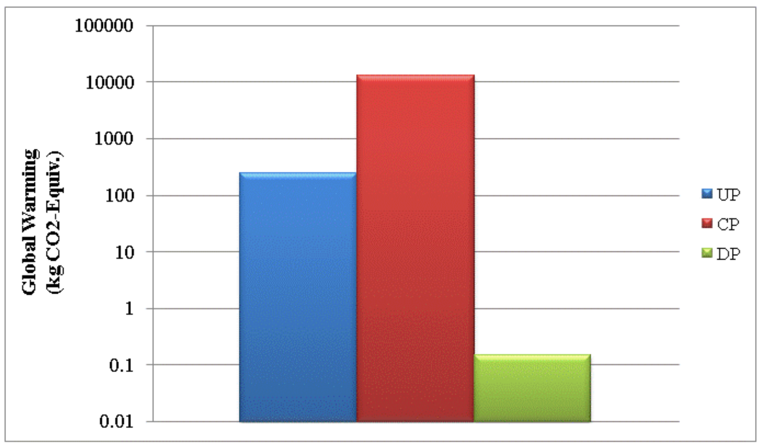

Figure 49. Global warming impacts for Process 1

For global warming impact category, the primary contributor is the biomass conversion process itself. The global warming potential from upstream and downstream processes is minor compared with the conversion process.

The major greenhouse gas emitted by the conversion process is CO_2. Carbon dioxide is emitted during the feed handling and preparation stage where the biomass is dried to a desired the moisture content of 5wt%. The biomass drying is performed through the direct contact with recycled hot flue gas from the combustors. During this process, CO_2 is generated and released to the atmosphere (Aden et al., 2007). CO_2 is also emitted during the syngas cleanup and conditioning stage. The catalysts used in the following alcohols synthesis process require low concentrations of sulphur and carbon dioxide. Therefore, the syngas produced from the gasification process has to be conditioned to achieve desired concentrations of the compounds in the syngas. An amine system was used for removing the acids present in the syngas followed by a liquid phase oxidation process for the removal of sulphur and CO_2. Carbon dioxide is emitted to the atmosphere by this cleanup and conditioning process.

- Process 2:

Global warming impacts for process 2 are shown in Figure 50.

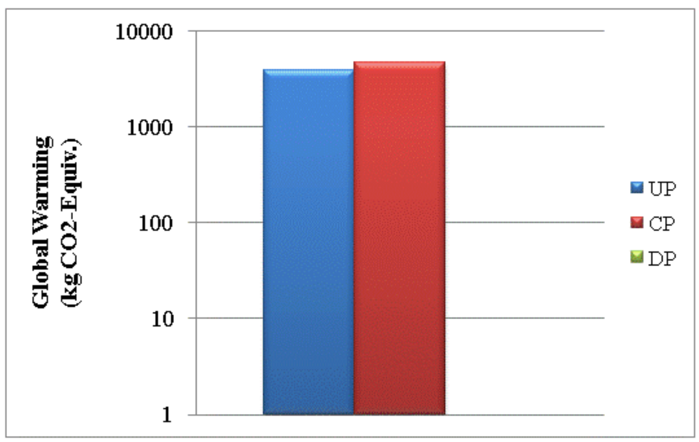

Figure 50. Global warming impacts for Process 2

From Figure 50 it can be seen that for process 2's global warming impact potential, the primary contributor is the biomass conversion process itself. The global warming potential from upstream processes also shows considerable global warming impacts, while downstream processes impacts are negligible when compared to that from upstream and conversion processes.

As mentioned before, regarding the biomass conversion process high global warming impacts, CO_2 is emitted during the feed handling and preparation stage where the biomass is dried, and during the cleanup and conditioning stage. Figure 51 shows the impacts from each of the upstream processes involved in process 2.

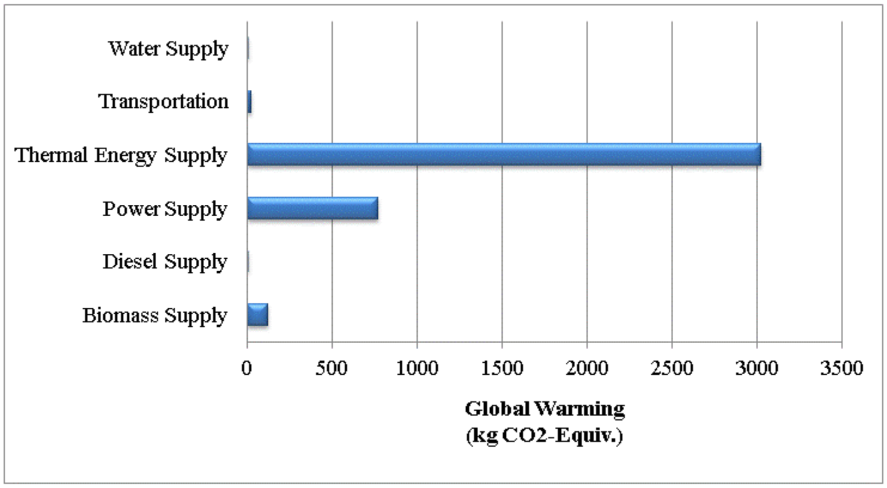

Figure 51. Upstream processes for Process 2

It is shown from Figure 51 that thermal energy supply process is the major contributor to the global warming impacts from upstream processes for process 2, followed by power and biomass supply processes. Other upstream processes do not show a considerable global warming potential.

As described in Table 11, the thermal energy, power and biomass supply processes show high global warming potential because of the carbon dioxide emissions throughout their production and supply.

- Process 3:

Global warming impacts for process 3 are shown in Figure 52.

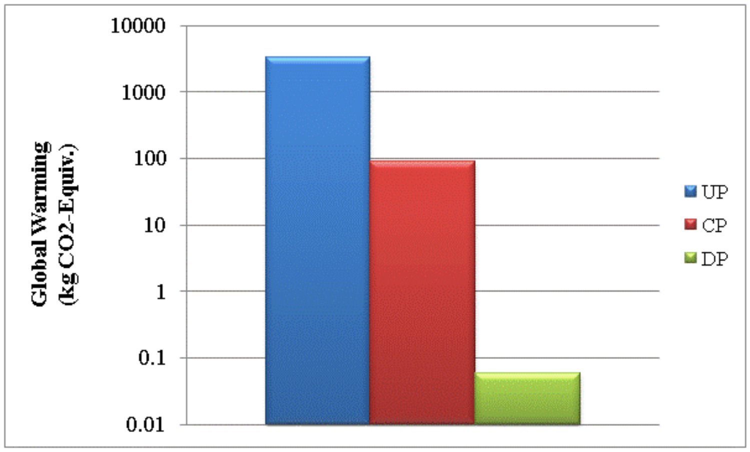

Figure 52. Global warming impacts for Process 2

Figure 52 exposes that for process 3's global warming impact potential, the primary contributor is the upstream processes. It can also be seen that impacts for conversion and downstream processes are negligible when compared to that from upstream processes. Figure 53 shows the impacts from each of the upstream processes involved in process 3.

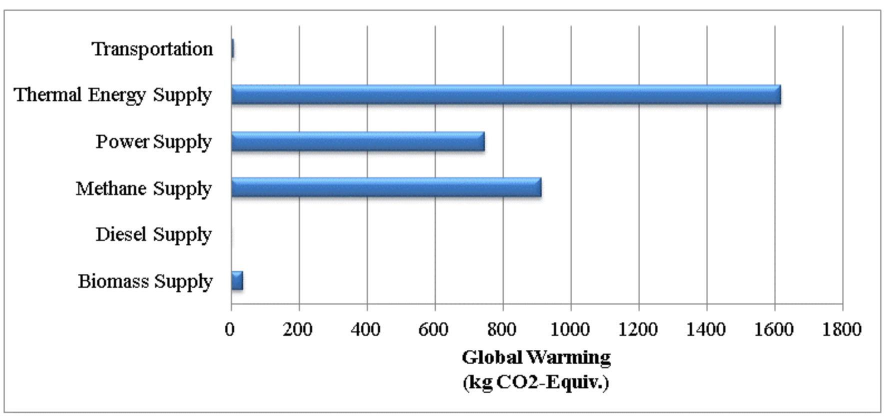

Figure 53. Upstream processes for Process 3

It is shown from Figure 53 that thermal energy supply process is the major contributor to the global warming impacts from upstream processes for process 3, followed by methane, power and biomass supply processes. Other upstream processes do not show a considerable global warming potential.

As described in Table 11, the methane, thermal energy, power and biomass supply processes show high global warming potential because of the carbon dioxide emissions throughout their production and supply.

4.5. Summary of Overall Results and Conclusions

Among three processes evaluated for the conversion of lignocellulosic biomass to various energy products, process 1 has the highest overall environmental impacts if all impact categories are weighted equally. Out of the eight impact categories, four present considerable impacts - ecotoxicity, human health non-cancer, human health cancer, and global warming. Table 13 summarizes the results for these four impact categories and the processes studied. For each, the processes are ordered based on their impact.

Table 13. Impact assessment results summary.
(1 represents the highest impact and 3 represents the lowest impact among three processes)

Impact Category	Process 1	Process 2	Process 3
Ecotoxicity	1	2	3
Human Health Non Cancer	3	2	1
Human Health Cancer	3	2	1
Global Warming	1	2	3

The major contributors to each of four impact categories for three processes are summarized in Table 14.

Table 14. Identification of impacts

Impact Categories	Process 1			Process 2			Process 3		
	UP	CP	DP	UP	CP	DP	UP	CP	DP
Ecotoxicity	X			X			X		
Human Health Non Cancer	X			X			X		
Human Health Cancer	X			X			X		
Global Warming		X			X		X		

From Table 14, it can be seen that for the three processes studied in this chapter, most of the environmental impacts are from the upstream processes. It is also important to mention that process 1 and 2 are the only processes for which the biomass conversion process is the primary contributor to the global warming impact.

CHAPTER 5

COMPARISON BETWEEN LCAS OF ALGAE AND LIGNOCELLULOSIC BIOENERGY

5.1. Comparative Analysis on Feedstock Type

As it was previously mentioned, algae and lignocellulosic biomass have been presented as promising feedstocks for bioenergy production. The supply process for these two feedstocks is analyzed in this Chapter to determine environmental impacts associated with feedstock supply alone. The feedstocks evaluated in Chapters 3 and 4 have very different supply processes, which can be seen in Figure 54.

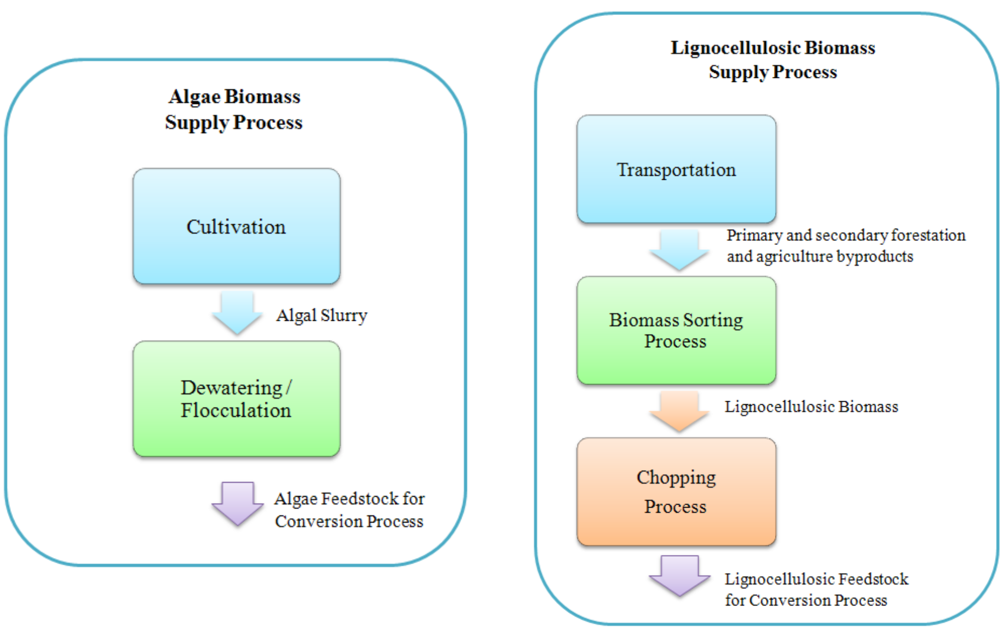

Figure 54. Algae and lignocellulosic biomass supply processes' flow chart

The lignocellulosic biomass supply process evaluated in this study includes the transportation of the biomass to the facility, the biomass sorting process, and the chopping process. The biomass cultivation is not considered because primary and secondary forestation and agriculture byproducts such as corn stalks and waste wood, are used in the analysis.

The algae biomass supply process evaluated in this study includes two stages. During the first stage, algae are cultivated in photobioreactors, which use centrate from municipal wastewater as the nutrient source and power plant flue gas as the CO_2 source. In the second stage, algae are harvested through flocculation using aluminum sulphate and dewatering process when the algal biomass has reached a desired density.

These two supply processes are compared on the same basis of supplying 1 Kg of biomass to identify the process with lower environmental impacts. Normalized results of this analysis are shown in Figure 55.

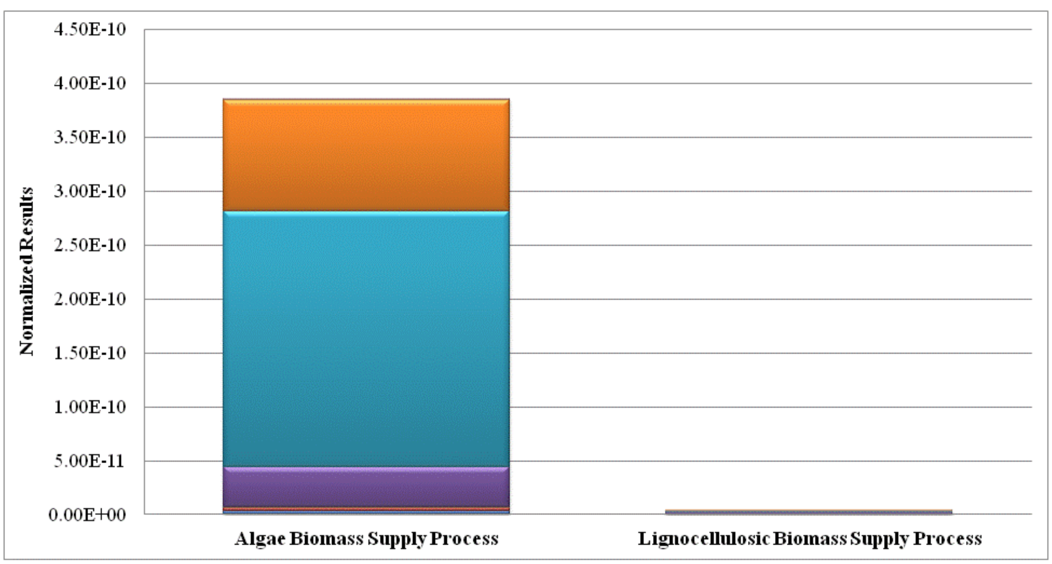

Figure 55. Overall results for comparative analysis on feedstock type

As seen in Figure 55, the algae biomass supply process has much higher environmental impacts compared with lignocellulosic biomass feedstock.

The large impacts from the algae biomass supply process are mainly due to the electricity consumed in the entire process. The cultivation stage has the largest electricity requirement for pumping flue gas containing CO_2 into photobioreactors and pumping algae slurry for further flocculation and dewatering stage.

From these results, lignocellulosic feedstock from forestation and agriculture byproducts demonstrates better environmental performance compared with cultivated algae feedstock.

5.2. Comparative Analysis on Conversion Technology

In the development of this study five different conversion technologies were used. It is important to understand the environmental impacts associated with conversion process alone. Therefore, two algae biomass conversion technologies are compared in this section, as well as three lignocellulosic biomass conversion technologies.

5.2.1. Algae Biomass Conversion Technologies Comparison

Two algae biomass conversion technologies are compared in this section, which are described below.

- Technology A: Algae anaerobic digestion process and CHP, which produces electricity and heat.
- Technology B: Algae thermochemical gasification and FTS process, which produces a variety of hydrocarbon biofuels.

These two technologies are compared on the same basis of converting 1 Kg of biomass to bioenergy. Normalized results of this analysis are shown in Figure 56.

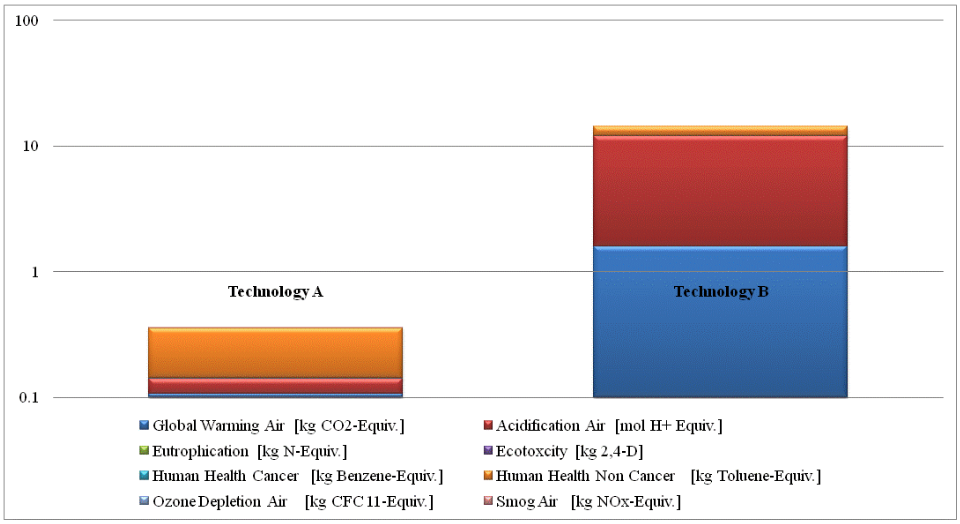

Figure 56. Comparison of algae biomass conversion technologies when converting 1 Kg of biomass to bioenergy

In addition, these two technologies are compared on the same basis of obtaining 1 BTU biomass-derived energy. Normalized results of this analysis are shown in Figure 57.

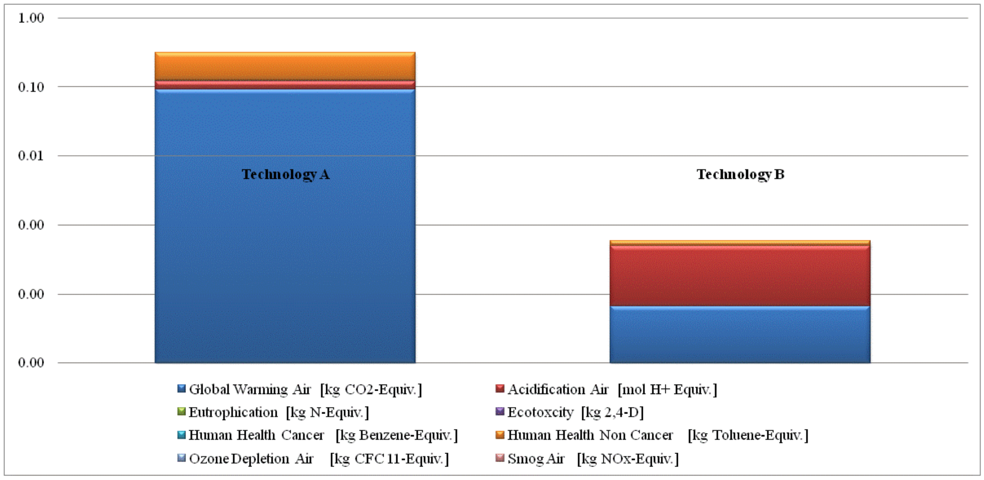

Figure 57. Comparison of algae biomass conversion technologies when producing 1 BTU algae biomass-derived energy

From Figure 56, it can be seen that gasification with FTS process (Technology B) has the higher environmental impacts compared with anaerobic digestion with combined heat and power process (Technology A) to convert the same amount of algae biomass to end energy products. However, if these two processes are evaluated based on the energy product (to produce the same amount of energy), technology B poses lower environmental impacts than technology A, as seen in Figure 57. This means technology B is more efficient to convert biomass to bioenergy.

5.2.2. Lignocellulosic Biomass Conversion Technologies Comparison

Three lignocellulosic biomass conversion technologies are compared in this section, which are described below.

- Technology C: Lignocellulosic biomass thermochemical gasification and alcohol synthesis process, which produces ethanol and higher alcohols.

- Technology D: Lignocellulosic biomass thermochemical gasification and FTS process, which produces hydrocarbons.
- Technology E: Lignocellulosic biomass thermochemical gasification and FTS process that uses methane as one of its inputs, which produces hydrocarbons.

These three technologies are compared on the same basis of converting 1 Kg of biomass to bioenergy. Normalized results of this analysis are shown in Figure 58.

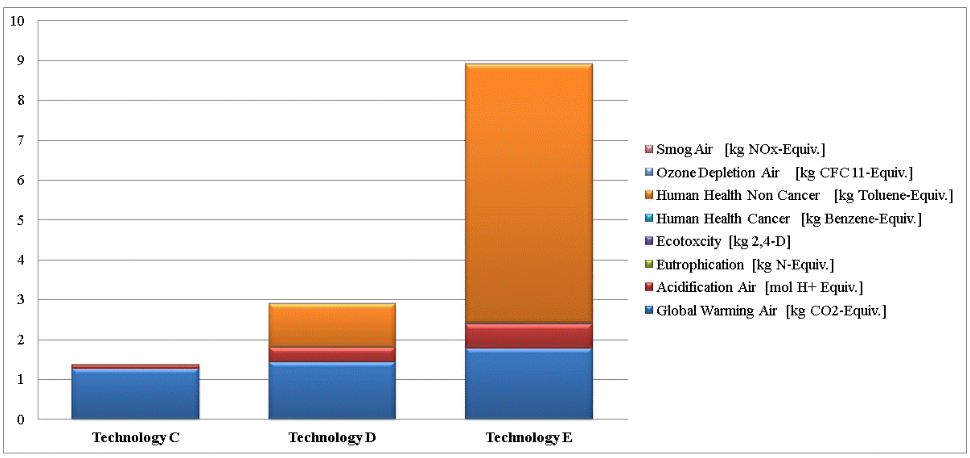

Figure 58. Comparison of lignocellulosic biomass conversion technologies when converting 1 Kg of biomass to bioenergy

In addition, these three technologies are compared on the same basis of obtaining 1BTU biomass-derived energy. Normalized results of this analysis are shown in Figure 53.

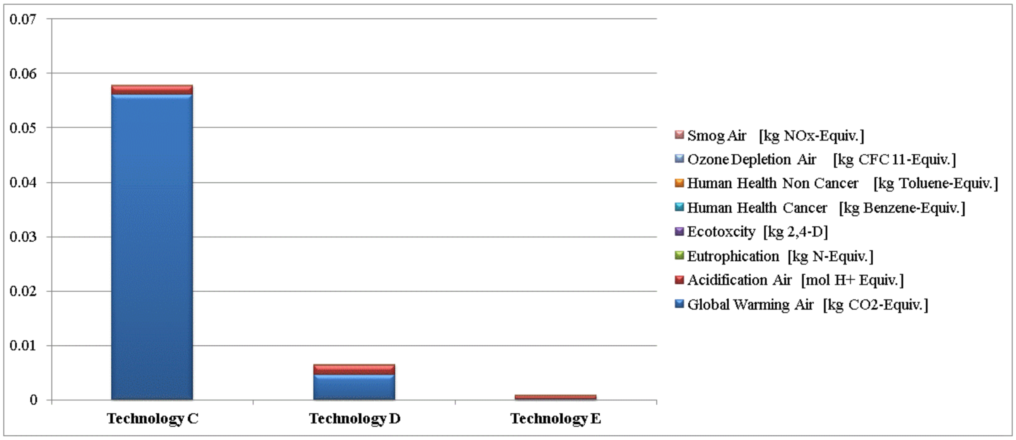

Figure 59. Comparison of lignocellulosic biomass conversion technologies when producing 1 BTU algae biomass-derived energy

From Figure 58, it can be seen that gasification with FTS process that uses methane as one of its inputs (Technology E) has the highest environmental impacts when compared to technologies C and D to convert the same amount of lignocellulosic biomass to end energy products. If these three technologies are evaluated based on the energy product, to produce the same amount of energy, technology E poses lowest environmental impacts than technologies C and D, as seen in Figure 59. This means that technology E is more efficient to convert biomass to bioenergy.

5.3. Comparative Analysis on Overall Bioenergy Pathway

Since both of the comparative LCAs developed in this study assumed the same system boundaries (cradle to gate) and same functional unit (1 million BTU bioenergy derived), it is possible to compare algae bioenergy pathways with lignocellulosic bioenergy pathways. Overall results for comparative LCA of algae and lignocellulosic bioenergy are shown in Figure 60.

When five pathways are compared, it can be seen from Figure 60 that the pathway with lignocellulosic biomass (feedstock) & thermochemical gasification and alcohol synthesis process (conversion process) & ethanol and higher alcohols (energy products) has the largest environmental impacts.

This pathway is followed by the one with lignocellulosic biomass (feedstock) & thermochemical gasification and FTS process that uses methane as one of its inputs (conversion process) & diesel, jet fuel, gasoline, fuel gas, and fuel oil (energy products).

The pathways with algae biomass as feedstock have lower environmental impacts compared with lignocellulosic bioenergy pathways.

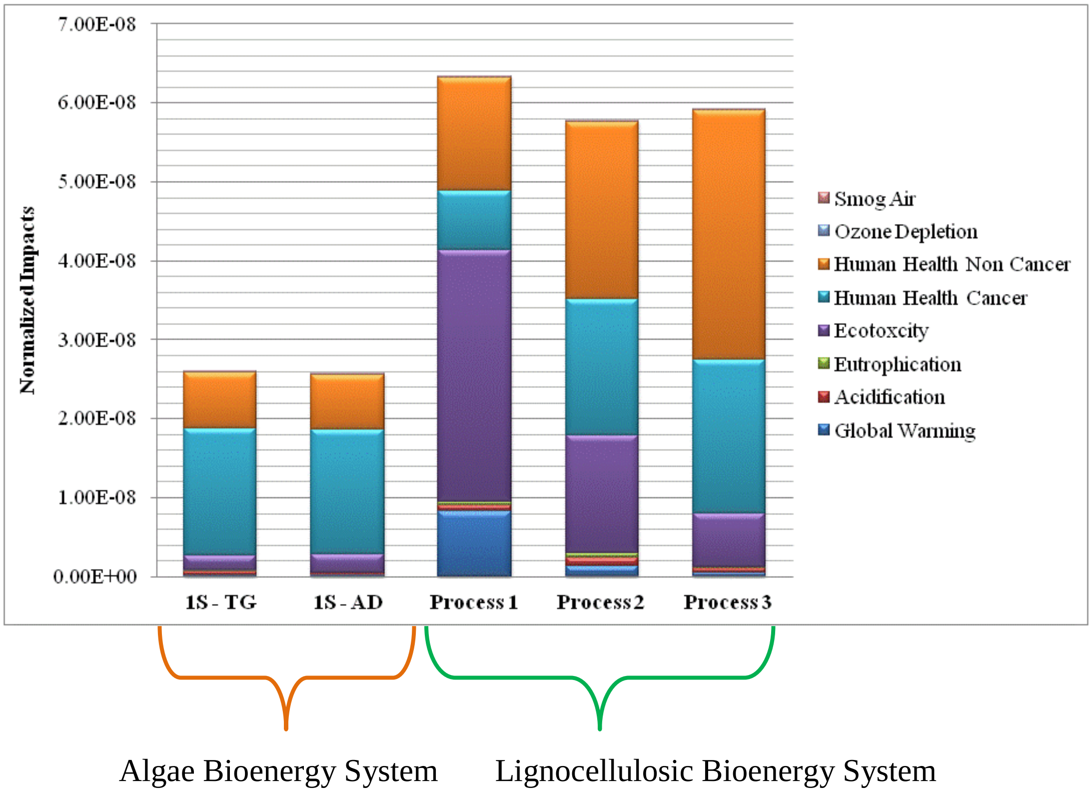

Figure 60. Overall results for comparative LCA of algae and lignocellulosic biomass conversion processes

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1. Algae Biomass Conversion LCA

In algae biomass conversion LCA study, two processes used to convert algal biomass to energy products – to liquid biofuels via a thermochemical gasification and FTS (Process 1), and to electricity and heat via anaerobic digestion and CHP (Process 2) were evaluated.

Overall results showed that in the production of 1 million BTU of energy products, processes 1 and 2 had the comparable overall environmental impact. Results also showed that the impact categories that appear to contribute the most to the overall impacts are ecotoxicity, human health non-cancer, and human health cancer.

It was also found that most of environmental impacts were generated in the upstream processes. In this case, the algae biomass supply process showed the largest impacts due to the amount of electricity used in cultivation, flocculation/dewatering, and centrifugation processes.

In addition, four different scenarios for the algae biomass supply process were analyzed. Impact assessment results showed variations for each of the scenarios studied. These variations were examined for process 2, given that this process is the one that showed the largest environmental impacts. It was concluded that the base case scenario, where wastewater and flue gas are used for algae cultivation, has the lowest environmental impact because this scenario does not have impacts from chemical CO_2 or fertilizers supply. It can also be concluded that the largest negative environmental impacts are obtained when using fertilizers instead of wastewater as source of nutrients for algae cultivation.

6.2. Lignocellulosic Biomass Conversion LCA

In lignocellulosic biomass conversion LCA, three processes that involve the conversion of lignocellulosic biomass to energy products – to ethanol and higher alcohols through thermochemical gasification and alcohols synthesis process (Process 1); to hydrocarbon biofuels through thermochemical gasification and FTS process (Process 2); and to hydrocarbon biofuels using methane through thermochemical gasification and FTS process (Process 3), were evaluated.

Overall results showed that to produce 1 million BTU of energy products process 1 has the highest overall environmental impact. This is because process 1 produces less energy than processes 2 and 3 per kg of lignocellulosic biomass input. Results also showed that the impact categories that appear to contribute the most to the overall impacts are ecotoxicity, human health non-cancer, human health cancer, and global warming.

It was also found that most of environmental impacts were generated in the upstream processes. In this case, the lignocellulosic biomass supply process showed the largest impacts due to of the transportation and the pre-processing of the biomass.

Process 1 and 2's global warming impacts were found to be mainly contributed by biomass conversion process rather than upstream processes.

6.3. Comparative Analysis on Feedstock Type

Given that algae and lignocellulosic biomass have been presented as promising feedstocks for bioenergy production, this study analyzed the supply process for these two feedstocks to determine environmental impacts associated with feedstock supply alone. Results showed that cultivated algae biomass feedstock has much higher environmental impacts compared with lignocellulosic biomass feedstock from forestation and agriculture byproducts.

It was found that the large impacts associated with the algae biomass supply process are mainly due to the electricity consumed in the entire process. The cultivation stage has the largest electricity requirement for pumping flue gas containing CO_2 into photobioreactors and pumping algae slurry for further flocculation and dewatering stage. Thus, it is concluded that lignocellulosic feedstock from forestation and agriculture byproducts demonstrates better environmental performance compared with cultivated algae feedstock. However, algae feedstock has other benefits, such as reducing nutrient loading, mitigation of flue gas and NOx.

6.4. Comparative Analysis on Conversion Technology

This study analyzed five different biomass conversion technologies to understand the environmental impacts associated with conversion process alone.

6.4.1. Algae Biomass Conversion Technologies Comparison

Two algae biomass conversion technologies were compared. Technology A includes an anaerobic digestion process and CHP, which produces electricity and heat. Technology B includes thermochemical gasification and FTS process, which produces a variety of hydrocarbon biofuels.

It was found that Technology B has the higher environmental impacts to convert 1 Kg of biomass to bioenergy compared to Technology A. However, if these two processes are evaluated based on the energy product (to produce the same amount of energy), technology B poses lower environmental impacts than technology A. This means technology B is more efficient to convert biomass to bioenergy. However, technology A is easy to integrate into the existing wastewater infrastructure. While producing energy, it also reduces nutrient loading for the wastewater plant and augments anaerobic digestion.

6.4.2. Lignocellulosic Biomass Conversion Technologies Comparison

Three lignocellulosic biomass conversion technologies were compared. Technology C includes a thermochemical gasification and alcohol synthesis process, which produces ethanol and higher alcohols. Technology D includes a thermochemical gasification and FTS process, which produces hydrocarbons. Technology E includes a thermochemical gasification and FTS process that uses methane as one of its inputs, which produces hydrocarbons.

It was found that Technology E has the higher environmental impacts to convert 1 Kg of biomass to bioenergy when compared to Technologies C and D. However, if these three technologies are evaluated based on the energy product (to produce the same amount of energy), technology C poses higher environmental impacts than technologies D and E. This means that technology E is more efficient to convert biomass to bioenergy.

6.5. Comparative Analysis on Overall Bioenergy Pathway

As previously mentioned, two pathways for converting algae biomass and three pathways for converting lignocellulosic biomass to bioenergy were analyzed in this study.

The overall results showed that the pathway with lignocellulosic biomass (feedstock) & thermochemical gasification and alcohol synthesis process (conversion process) & ethanol and higher alcohols (energy products) has the largest environmental impacts. This pathway is followed by the one with lignocellulosic biomass (feedstock) & thermochemical gasification and FTS process that uses methane as one of its inputs (conversion process) & diesel, jet fuel, gasoline, fuel gas, and fuel oil (energy products). The pathways with algae biomass as feedstock have lower environmental impacts compared with lignocellulosic bioenergy pathways.

6.6. Recommendations

This study identifies opportunities for improvement as described below:

- Regarding the algae biomass supply process, one improvement that would have large benefits to the overall algae to bioenergy process is to decrease the electricity consumption of the process. More specifically, the electricity used in the algae cultivation stage. This could be achieved by using high-end technologies that require less electricity to cultivate algae. In addition, sources of renewable energy such as wind energy or solar panels could be used to supply some or the entire electricity requirement of the process.

- Regarding the lignocellulosic biomass supply process, improvements could be made by reducing transportation distance from where the waste is located to biomass conversion facility, reducing the water and electricity consumption of the process, and having better waste disposal and effluent management policies during the biomass sorting process.
- To make the overall algae and lignocellul.osic biomass conversion to bioenergy processes environmental friendly, technologies should use waste streams (e.g., wastewater, flue gas, waste wood) for biomass supply, apply high energy and heat integration for biomass conversion processes, and produce energy products with high energy content.

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