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Developing a life cycle analysis framework for the microalgae biodiesel industry

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DEVELOPING A LIFE CYCLE ANALYSIS FRAMEWORK FOR THE MICROALGAE BIODIESEL INDUSTRY

by

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AUTHOR'S DECLARATION OF ORIGINALITY

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ABSTRACT

This research develops a Life Cycle Analysis framework for evaluating the sustainability performance within the microalgae industry for producing biodiesel. The industry is now so extensive that an LCA framework is needed as a guide. The microalgae biodiesel industry varies considerably in configuration design and output. The industry is rapidly developing and growing and needs an LCA tool to keep pace with assessing its benefits and impacts. Disruptive technologies in extraction and synthesis can increase the economic viability and catapult microalgae biodiesel as a true competitor in the fuel market. An assessment of environmental impacts is essential, with particular emphasis on the trade-offs of microalgae biodiesel production because of potential risks, such as when using GMO-algae. Industry trends were coupled with LCAs from literature to develop an industry benchmark and LCA framework. Industry benchmarks can act as an anchor for transparent and explicit comparison of LCAs. An LCA framework was shown to be beneficial in rapidly evaluating a design configuration for the microalgae biodiesel industry. More research is necessary in generating benchmarks for economics, water use, and other emissions as there is currently not enough data.

DEDICATION

Dedicated to Elizabeth and Sophia -- my source of constant inspiration and motivation.

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LIST OF ABBREVIATIONS

CED – Cumulative Energy Demand

CML – Universitiet Leiden Institute of Environmental Sciences

EBR – Energy Balance Ratio

GDP – Gross Domestic Product

GHG – Green House Gas

GMO – Genetically Modified Organism

GWP – Global Warming Potential

LCA – Life Cycle Analysis

LCIA – Life Cycle Inventory Analysis

LHV – Lower Heating Value

WTT – Well to Tank

Y/N – Yes or No

LIST OF NOMENCLATURE

% wt – percent weight

g e-CO_2 – equivalent grams of carbon dioxide

GJ – giga joules

ha – hectare

kg – kilogram

L – litre

mg – milligrams

MJ – mega joules

MJ_b – mega joules embedded in biodiesel

MJ_{eq} – mega joules equivalent

MJ_f – mega joules from fuel sources

t - tonne

yr – year

1.0 INTRODUCTION

In this research, a life cycle analysis (LCA) framework is developed for the microalgae biodiesel industry. Biodiesel produced from microalgae has the potential to replace crude oil diesel based on the land use and production potential (Singh and Gu (2010)). Seed oil biodiesel and waste oil biodiesel are not currently feasible (Norgueira (2011)). Microalgae can be cultivated on non-arable land, clean wastewater, clean factory emissions, and produce fuel and other useful by-products in the process. However, there are a variety of design configurations for the microalgae biodiesel production (Chen et al. (2010)), and not all variations produce the same benefits or impacts. Furthermore, life cycle assessments undertaken to date have used widely varying parameters in their protocol, resulting in outcomes that cannot be readily compared to one another. The industry would benefit significantly from having a life cycle analysis (LCA) framework that could contrast and compare the configurations against one another based on common and transparent parameters. The comparisons could be used for research, evaluative, and investment purposes.

The preferred microalgae diesel production configuration depends on local conditions and may not be suited for a different location. The location dictates the climate, nutrient availability, and microalgae survival available for microalgae biodiesel production (Hou, J. et al. (2011)). The different outcomes at different locations add to the complexity in configuration design: there is no one-size-fits-all design answer for the microalgae biodiesel industry. An LCA framework compares configurations, and accounts also for variations due to local conditions. Furthermore, multiple scenarios can be tested using the LCA framework.

In summary, life cycle analysis (LCA) is a tool used to evaluate and compare a product or service over its life from cradle to grave (Curran et al. (2006)) and is commonly used to evaluate the environmental benefits and impacts presented by an alternative. An LCA typically defines functional units, which are the common units used throughout the LCA to represent a meaningful unit flowing through the processes, and thus establish a measure for comparing different alternatives.

Current LCAs for microalgae biodiesel production are not easily consolidated or compared. Furthermore, there are currently no *benchmarks* for the microalgae biodiesel industry: without them, it is difficult to analyze the outcomes from LCAs. A configuration design can be misrepresented as exceptionally good when compared to a worst-case scenario. Instead, a benchmark would be common between all LCAs within the industry, and would reduce the ambiguity behind how to interpret individual LCA results.

Microalgae has the potential for large-scale utilization, and there are numerous businesses worldwide bringing the technology to market. The industry is rapidly developing, and needs an LCA tool that can keep pace with the rapid developments. For an analysis tool to be useful, it needs to produce meaningful insights for decision makers. Whether the outcomes are positive or negative, the results need to be accessible, transparent, and timely.

2.0 OBJECTIVES

There are five research objectives:

The first objective is to **create an LCA framework for the microalgae biodiesel production industry**. The LCA framework is to be used by LCA practitioners in executing an LCA on a particular configuration design for microalgae biodiesel production.

The second thesis objective is to **assess and prioritize the best practices and trends within the industry**. The industry trends identify what is currently working for full scale operations and within the marketplace.

The third thesis objective is to **analyze data quality, data reliability, and data gaps**. An LCA interpretation can be vastly impacted by unreliable data as the outcomes can point in different directions.

The fourth thesis objective is to **rectify discrepancies between LCAs currently available**. Current LCAs provide rich information for the microalgae biodiesel industry, especially if the discrepancies were rectified.

The fifth thesis objective is to **develop a benchmarking system for the industry**. An industry benchmark is needed for the microalgae biodiesel industry for greater transparency.

In summary, this thesis seeks to answer the following:

- Can an LCA framework be created to analyze multiple configurations of the same technology and meaningfully compare one to another?
- Can the integrity of the analyzing process be maintained where the analysis has value for the industry?
- Can the framework also supply what is needed to sufficiently give valuable feedback across the feedback loop, especially for the iterative design process?

3.0 LITERATURE REVIEW

3.1 Potential for Microalgae Biodiesel Production

A current estimate states that microalgae could produce 136,900L/hectare of biodiesel compared to 1,190 L/hectare for biodiesel produced from rapeseed oil (Singh and Gu. (2010)). Also, compared to soybean, corn, sugarcane, and rapeseed feedstocks, the land could be uncultivable: there is no land use competition for food production from agri-business. Figure 1 below uses the relative text size of the terms to graphically depict the production potential of microalgae biodiesel as compared to rapeseed oil biodiesel based on literature estimates.

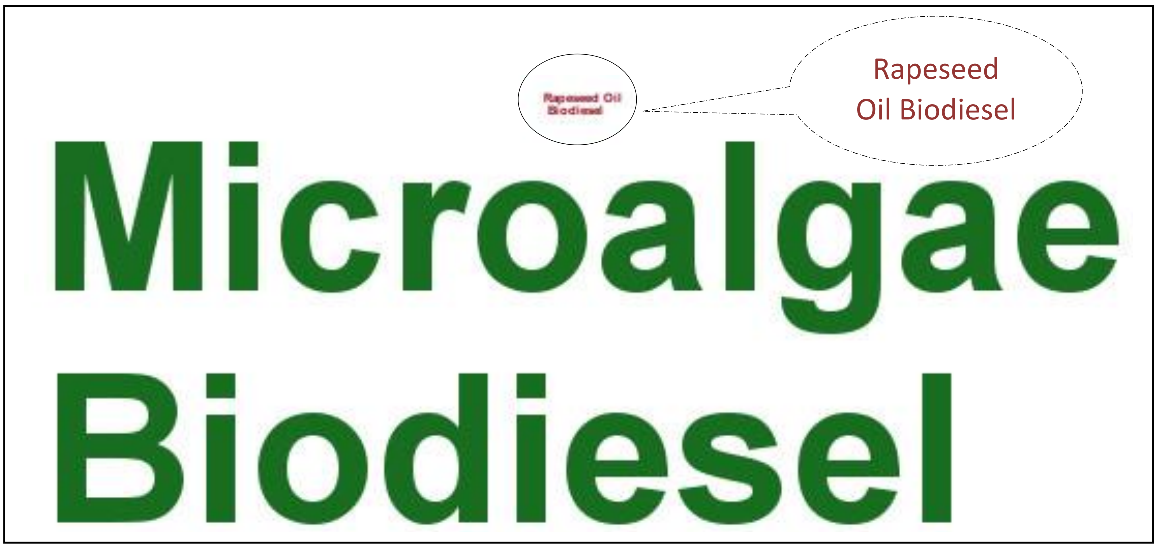


Figure 1: Comparison between Rapeseed Oil and Microalgae Biodiesel

The costs for current biodiesel processing from microalgae are too high even for large-scale production (Chen et al. (2010)). However, the trend of cost reductions coupled with a rise in the cost of a barrel of crude oil from the rapid decline in oil reserves leads to increased interest in the microalgae industry (Singh and Gu. (2010)). However, there are still other cost reductions needed in the areas of nutrient supply, algae separation, and oil extraction to make biodiesel from algae competitive (Chen et al. (2010)).

Value added by-products from algae-biodiesel production have the potential to further reduce the production costs. The by-products vary widely, and include animal feed, plastics, pharmaceuticals, and fertilizer (Singh and Gu. (2010)).

3.2 Microalgae Biodiesel Production Process

The current research surrounding microalgae biodiesel production investigates whether it is feasible to produce biodiesel from microalgae using various approaches. The various production configurations consist of the basic life stages shown in Figure 2 below.

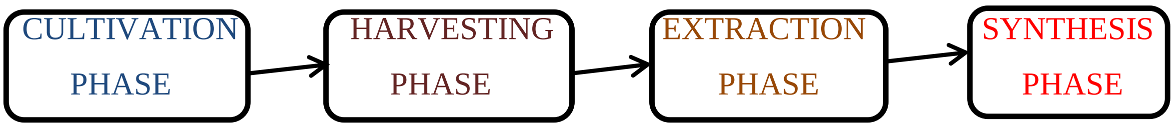


Figure 2: Life stages for biodiesel production from microalgae

An expanded life stages diagram is shown in Figure 3 below. Each life stage is broken into individual sections for greater clarity.

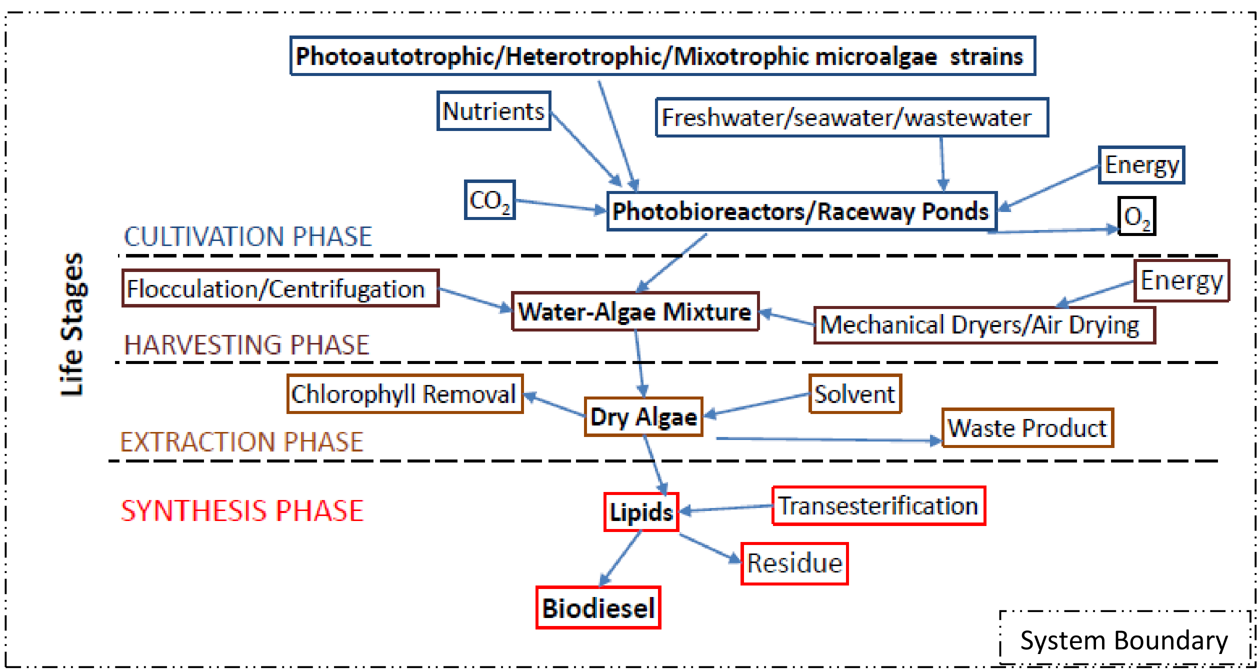


Figure 3: Expanded Life Stages Diagram

The following sections will describe in greater depth each life stage, the corresponding technologies developed for design optimization, and opportunities for innovation.

3.2.1 Life Stages: Cultivation Phase

The cultivation phase is associated with the production of lipids and algae growth. The variables within the cultivation phase for configurations consist of cultivation site, microalgae strain, growth mode, carbon dioxide source, nutrient source, and water source. The cultivation phase has the most diverse design options available, and the resulting production capacities vary considerably.

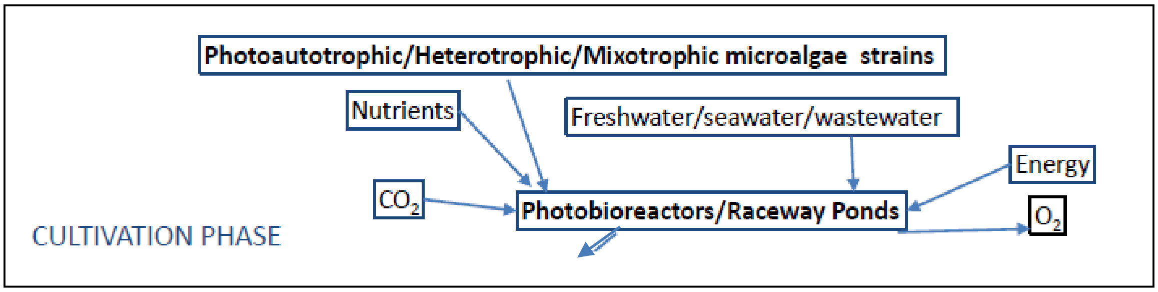


Figure 4: Cultivation Phase Diagram

The cultivation site designs are currently either raceways or photobioreactors (Gong and Jiang. (2011)). The cultivation site design depends on local conditions such as light intensity, climate conditions, available land, water availability, and surrounding industry.

Raceways are open shallow ponds where a paddle churns the microalgae-water mixture, and the mixture is exposed to the light and air. Raceways are inexpensive to build and operate, but they are susceptible to microalgae failure from contaminants (Gong and Jiang. (2011)). The shallow ponds are lined with a substrate material to prevent leaking, and require maintenance occasionally.

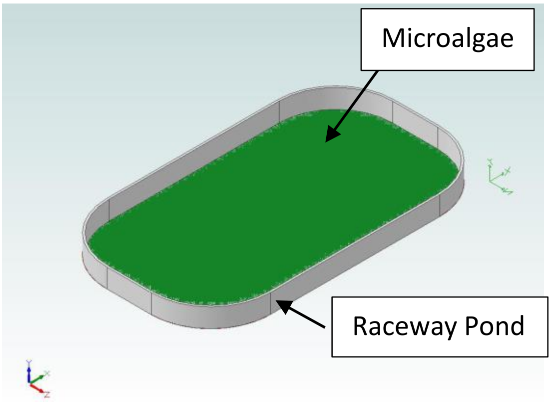


Figure 5: Raceway Ponds

Photobioreactors are enclosed structures where the optimal conditions for microalgae monoculture, necessary nutrients, CO_2, etcetera are maintained. Photobioreactors can maintain a monoculture, and can produce more biodiesel per hectare compared with raceways (Gong and Jiang. (2011)). Photobioreactors present more opportunities for alternative designs: currently, photobioreactors can be designed as tubes, bags, floating panels, and thin film membranes, in vertical or horizontal orientation.

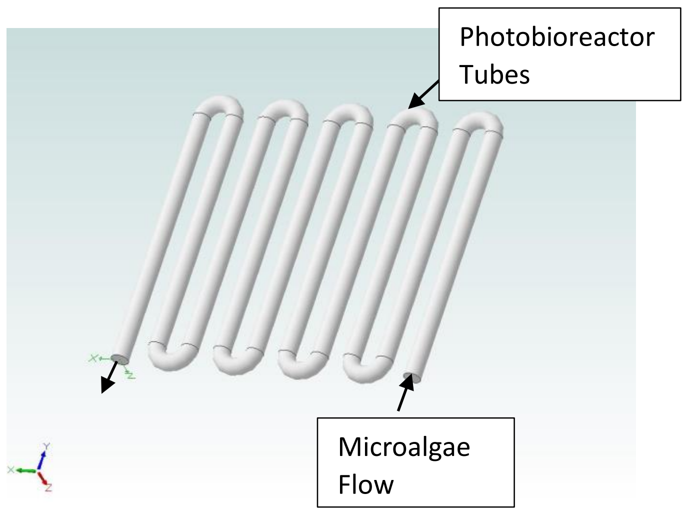


Figure 6: Photobioreactors

The lipid production is impacted from the chosen microalgae strain. There are three growth modes microalgae can undertake. Photoautotrophic microalgae undergo photosynthesis and affix CO_2 in the process. Heterotrophic microalgae grow in the absence of light, and can produce lipids 24 hours a day. The third alternative is mixotrophic microalgae which have similar properties as photoautotrophic and heterotrophic microalgae (Chen et al. (2010)). There are benefits and trade-offs for using each type of microalgae. Based on Xiong et al. (2008), the microalgae which produce the most lipids in the shortest amount of time is *Chlorella protothecoides* which produce 1209.6 – 3701.1 mg/L/day (Xiong et al. (2008)). Research is also being conducted in the area of genetically engineering microalgae to optimize lipid accumulation (Wu et al. (2010)).

Microalgae need nutrients and water to produce lipids. There are a variety of combinations currently being investigated. Using commercial fertilizer and freshwater is the most expensive option, which would greatly hamper the economic feasibility ((Jiang et al.

(2011)). Instead, using wastewater would supply water, carbon, and nitrogen to the microalgae and only phosphates would need to be supplemented (Jiang et al. (2011)). Also, seawater can be used as a water source or in combination with wastewater ((Wu et al. (2010)). In addition, instead of municipal wastewater, animal and farm runoff can be used as a nutrient source (Johnson and Wen (2010)).

There are numerous configurations possible within the cultivation phase. The cultivation phase has the greatest diversity among the life stages, but current LCAs do not account for all of the major configurations. An LCA framework could therefore contrast one configuration with another, or one configuration's LCA against another. Furthermore, benchmarking would allow decision makers to assess the merits of one configuration against another using more relevant, current criteria, because benchmarking can establish an anchor for comparison.

3.2.2 Life Stages: Harvesting Phase

Removing algae from the water during harvesting can be costly and time consuming. Usually, the algae is separated from the water and then dried in preparation for the extraction phase (Sathish. et al. (2012)). Two processes used to separate the algae are centrifugation and flocculation.

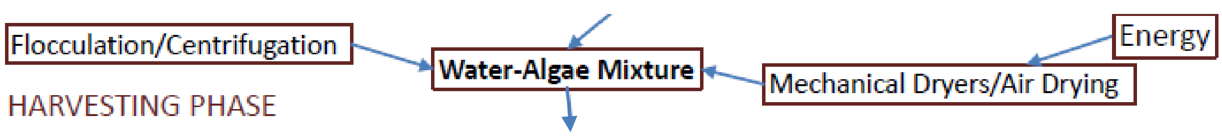


Figure 7: Harvesting Phase Diagram

Centrifugation consists of rapidly spinning the algae-water mixture and the algae clumps together and separates from the water. High shear forces due to high centrifugation speed may cause damage to the algal cell walls (Chen et al. (2010)). Centrifugation is shown to be the preferred method for small scale harvesting, but it too costly and slow for large batch harvesting (Chen et al. (2010)).

Flocculation occurs when smaller particles disperse and clump together to create larger particles of algae which would float to the surface for gathering (Chen et al. (2010)). Autoflocculation is the result of a high pH solution where the carbonate salts and algae will precipitate. Autoflocculation can be simulated by adding salts to increase the pH level (Chen et al. (2010)).

The next step in harvesting the algae is drying. The two techniques employed are solar dryers and mechanical dryers. Air drying is the most cost effective in terms of energy intensity, but the process takes a long time to complete (Sathish et al. (2012)). The drying step may soon be unnecessary as wet extraction techniques are currently being developed.

The harvesting phase can be disrupted by the development of wet extraction techniques, resulting in a net savings of time, energy, and cost. More research on wet extraction techniques from an LCA perspective could identify projected savings and increase interest in full scale implementation.

3.2.3 Life Stages: Extraction Phase

The extraction from dried algae is accomplished through processes such as solvent extraction, and direct transesterification (Sathish et al. (2012)). Super-critical fluid extraction is another method used to extract oil, but it considered too costly to effectively be used.

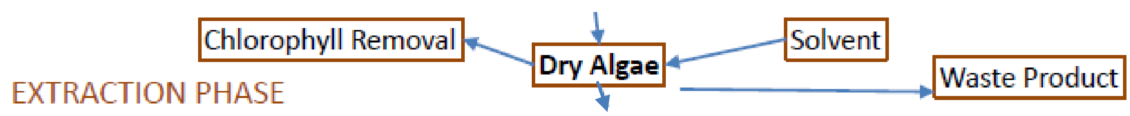


Figure 8: Extraction Phase Diagram

The solvent extraction can be accomplished using hexane. The microalga needs to be dried before the addition of hexane (Halim et al. (2010)). The mixture is agitated until separation of the lipid layer on top and non-lipid layer on the bottom occurs (Halim et al. (2010)).

Currently, research is being conducted on extracting lipids from wet algae. (Sathish et al. (2012)) Extracting directly from wet algae would eliminate the drying step and would greatly improve energy consumption and economic feasibility.

Chlorophyll contamination can reduce the quality of biodiesel production and needs to be removed (Sathish et al. (2012)). Chlorophyll and other contaminants need to be removed before synthesis.

There is potential within the extraction phase to improve the economic feasibility and competitiveness from new extraction techniques.

3.2.4 Life Stages: Synthesis Phase

Synthesis is the final step where the lipids are converted into biodiesel. The lipids undergo a process called transesterification. Either the oils are extracted first from dried algae, or can be synthesized using 'in-situ' transesterification (Ehimen et al. (2009)).

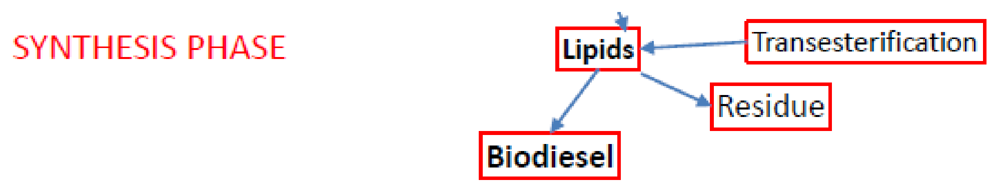


Figure 9: Synthesis Phase Diagram

The process requires a catalyst to link the Fatty Acid Methyl-Ester (FAME) chains producing biodiesel. Methanol is typically used, but it is not the only catalyst used in the industry (Ehimen et al. (2009)). The process needs to be carefully designed and monitored to prevent saponification.

Another method is the supercritical transesterification, which requires high reaction temperatures and pressures without catalysts. There are safety concerns regarding supercritical transesterification due to the high temperatures and pressures (Ehimen et al. (2009)).

'In-situ' transesterification has the potential to reduce the time and cost requirements for biodiesel synthesis (Ehimen et al. (2009)). The process would eliminate the drying and extraction phases, and is therefore attractive for further research.

Another option, instead of synthesizing the biodiesel onsite, is the extracted lipids could be transported and processed at a traditional refinery. The benefits include using already established infrastructure, machinery, and distribution systems. Also, other fuels and by-products can be synthesized from established techniques.

3.3 Microalgae Biodiesel Lower Heating Value (LHV)

Table 1 below compares the Lower Heating Value for diesel, gasoline, ethanol and biodiesel.

Table 1: Fuel Lower Heating Values			
Fuel Type	**LHV (MJ/kg)**	**Density (g/gal)**	**Source**
Low-Sulfur Diesel	42.612	3206	GREET (2010)
Conventional Gasoline	43.448	2819	GREET (2010)
Ethanol	26.952	2988	GREET (2010)
Methyl-Ester (Biodiesel)	37.528	3361	GREET (2010)
Biodiesel (Microalgae)	42	(unknown)	Batan, L. et al. (2010)

The two biodiesel ratings represent values found in literature, and are also commonly used for LCAs conducted to date. Therefore, the range in expected LHV is 37-42 MJ/kg biodiesel.

3.4 Potential By-Products

The materials left over from the extraction phase and synthesis phase can be used in other products and industries. Converting the waste materials into by-products will create value added products which further increase the feasibility for creating biodiesel from microalgae. Current by-products under investigation are plastics, animal feed, and pharmaceuticals.

Plastics can be created using the starchy materials remaining after lipid extraction. The starches would have to be separated from the proteins first, and then can be easily converted into plastics using already established methods (Singh and Gu (2010)).

Animal feed is a high demand by-product, and the remaining materials would be high in proteins and carbohydrates (Harun et al. (2009)). The animal feed would need to meet certain regulations as established by the agri-business.

Pharmaceuticals have been created from microalgae before microalgae were considered as a fuel feedstock. The quality of the residual materials would need to be monitored and maintained if pharmaceuticals are to be manufactured from the waste materials derived from producing biodiesel from microalgae (Harun et al. (2009)).

The remaining materials could also be converted into biogas and burned to produce electricity (Singh and Gu (2010)). The energy produced can then be used onsite or sold to the grid to offset electricity costs.

An analysis would need to be conducted to see which industry would generate the greatest profitability for the remaining materials.

3.5 Trade-offs Associated with Microalgae Biodiesel

There are trade-offs for producing biodiesel from microalgae. The greatest known trade-offs result from the cultivation phase and biodegradation prevention.

The accidental release of genetically modified microalgae is a potential threat to local ecosystems. The genetically modified microalgae could potentially dominate a local ecosystem similar to how invasive species have been shown to do. Microalgae is found in the wild, which is different than other GMO products within agriculture. Corn is highly domesticated and cannot grow without cultivation, while microalgae is not domesticated and grows without aid.

Utilizing waste water as a water and nutrient source can improve the economic feasibility of microalgae biodiesel. The trade-offs for using waste water may be associated with the residual chemicals in the final fuel. The quality and reliability of the wastewater may be difficult to control. More research is needed to assess the affects waste water has on the final fuel.

Biodiesel degrades quickly compared to traditional diesel. The addition of pesticides to the final fuel has been shown to increase the shelf life of biodiesel. The trade-off is the potential environmental impacts associated with burning the additional pesticides. An emissions analysis needs to be conducted on the fuel with added pesticides.

Current LCAs do not discuss trade-offs beyond the inputs and outputs of the system.

3.6 Bioengineering Microalgae

Genetic modification techniques are currently being applied to microalgae for biodiesel production. The goals typical in bioengineering microalgae is to increase yield and lipid content, increase growth rate, and decrease crop failure.

One technique used to increase the lipid content in microalgae is by increasing photosynthetic efficiency. This is accomplished by modifying the strain to increase the photosynthetic receptors' size within the cells. The receptors are like miniature umbrellas which capture the sunlight. Increasing the "umbrella" size will increase the photosynthetic uptake and efficiency (Flynn et al. (2009)).

A trade-off associated with genetically modifying microalgae is accidental release into the wild. Microalgae is an opportunistic wild organism which currently grows unaided. There are numerous strains of microalgae found in the wild, and a bioengineered microalgae could reduce the biodiversity by crowding out the other strains.

A biosecurity risk assessment was conducted by Campbell (2011) for Australia for importing microalgae strands for biodiesel production. The risk to local biodiversity by importing opportunistic species is high, and a protocol was proposed for assessing which imports to allow and which to reject. A similar protocol needs to be established for bioengineered microalgae based on regional conditions.

3.7 The Bioethanol Industry: Review

The bioethanol industry has been established for longer than the biodiesel industry. The bioethanol industry has gone through the preliminary stages of development, and has overcome obstacles inherent in the process. The microalgae biodiesel industry can leapfrog over certain obstacles by learning from the bioethanol industry. The following section will review the bioethanol industry for Brazil, United States, and Canada.

3.7.1 Brazil

The following review for Brazil's bioethanol industry is based on a journal article by Azadi et al (2012). The information reflects their research, but may not depict the entire industry nor all perspectives necessarily because the industry is complex and fluid as new technologies are developed and implemented. This discussion, however, can inform the biodiesel industry to avoid certain pitfalls.

Brazil is the largest producer of bioethanol in the world. Brazil produces approximately 32.5 billion litres of ethanol from sugarcane per year. 90% of all ethanol produced is consumed in Brazil, while 6% of production was exported to the US (Azadi et al (2012)).

There is high political drive for ethanol production in Brazil. Large corporations like BP have invested approximately a billion dollars on ethanol research with particular emphasis on Brazil.

Sugarcane is a labour intensive crop, and the bioethanol industry currently employs approximately 1 million people in Brazil. The bio-ethanol industry comprises 3.5% of the GDP for the country. The labour conditions in the bio-ethanol industry in Brazil are considered "forced labour" and are similar to slave labour. There are organizations trying to mitigate the labour conditions in Brazil (Azadi et al (2012)).

Sugarcane fields are traditionally burned for harvesting, which results in pollution to the air, water, and soil. Also, the labourers working the fields are at risk of breathing in the particulates from the burnt fields.

Also, using food crops to produce biofuels has been linked to food price increases and shortages. Brazil had a devastating food shortage in 2008, while land that could have been used for food crops or cattle were taken by biofuels.

Sugarcane fields currently compose 2.5% of arable land in Brazil. The land needs to be near water, and is not shown to be located near the Amazon rainforest. There is debate surrounding whether biofuel production is linked to deforestation, but the results are inconclusive (Azadi et al (2012)).

3.7.2 United States

The United States is the second largest producer of bioethanol behind Brazil. The main crop currently used in the US to produce bioethanol is corn (Akinci et al. (2008)).

Using corn as a feedstock to the fuel industry has been linked to rising food prices as it is competing with the food market. Even if there is enough land for corn to be cultivated, having more than one industry interested in corn crops increases the prices at market.

There is federal pressure to increase bioethanol production to replace 25% of gasoline. Corn as a feedstock is supposed to be replaced with 2nd generation feedstocks in the near future, but there is a bottleneck with the technology to convert lignocellulosic feedstock into a quality fuel (Akinci et al. (2008)).

3.7.3 Canada

The majority of bio-ethanol produced in Canada is from corn. Any benefits from converting corn into ethanol can be cancelled from the cultivation phase of production (Champagne. (2006)).

The quality of the feedstock determines the quality of the ethanol produced. Hard lignocellulose materials need to first be broken down using enzymes for efficient release of the sugars within for fermentation.

Biosolids from manure, municipal wastewater, and industrial wastewater are not quality feedstocks for ethanol production. The biosolids consists of protein which is more challenging to convert to ethanol compared with other lignocellulosic materials. The quality of the ethanol produced is compromised (Champagne. (2006)).

The industry in Canada is comprised mainly of small scale plants. Feasibility is limited based on costs in converting waste materials into ethanol due to the low yield and high cost for the hydrolysis process.

If all agricultural waste products in Canada combined were used for ethanol production it would replace 18-27% of the fossil fuel demand in Canada. Using available crop residues not currently used as soil remediation and animal bedding would replace 3.7% of the fossil fuel demand in Canada (Champagne. (2006)).

The Canadian government currently requires 2.5% of the total gasoline use in Canada to be from ethanol (Champagne, P. (2006)).

3.8 Lessons Learned from the Bioethanol Industry

The microalgae biodiesel industry can learn from the bioethanol industry by looking at their previous successes and failures. Caution is needed in applying the lessons directly as the industries have significant differences.

Government regulations and incentives helped catapult the bioethanol industry into a viable business option. The incentives and labor conditions for producing bioethanol in Brazil results in competitive price points. The microalgae biodiesel industry is cost intensive in technology and not labor intensive compared to the bioethanol industry in Brazil.

Biodiesel from microalgae does not compete directly with resources used to grow food crops, and can be marketed in those terms. The controversy of rising food prices created a blithe over the bioethanol industry and has slowed down its progression.

Quality standards for microalgae biodiesel should be established and each product meeting the criteria should be shown upfront. The LHV of biodiesel is lower than crude oil diesel and should be stated with the product so a true energy comparison can be made. The LHV varies for different biodiesel blends.

3.9 Life Cycle Analysis: Review

A life cycle analysis (LCA) is a tool used to evaluate a product or service over its life from cradle to grave. An LCA is used in decision making by designers, executives, government regulatory officials, and academics. Typical metrics used are associated with economics, energy, air, water and land emissions with particular emphasis on greenhouse gases, eutrophication, acidic depletion potential, and human toxicity. An LCA uses a functional unit particular to the product or service under investigation. There are system boundaries defined to show which flows are being accounted for, and where the process starts and ends. The outcomes from the LCA are evaluated against previous designs or other designs.

An LCA framework is used to evaluate different configurations within the same industry which perform the same function or produce equivalent products. An LCA framework would assess each configuration with the same functional units, and would define how the data would be collected and analyzed. The LCA framework streamlines the LCA process by reducing the LCA completion timeframe. Also, the LCA framework would create a consistent roadmap for users and reduce the data gaps and uncertainty surrounding individual LCA practitioners generating distinct flowcharts, boundaries, functional units, and metrics. The LCA framework allows LCA practitioners to focus on higher level analysis since the basic structure is already developed.

3.10 Life Cycle Analysis: Benchmarking

Benchmarks are established agreed upon values used for comparison within a particular industry. Benchmarks can be basic expectations for outcomes from a particular process. If an LCA were conducted, and the results are below the benchmark value for a benefit and/or above for a system cost the process would be considered poor. Without a benchmark, there would not be a transparent, explicit measure to base the merits of a process. A poor system design could hide behind their outputs by creating their own low baseline benchmark. An industry accepted benchmark would help to eliminate false representations and improve the LCA quality and credibility for a particular industry.

3.11 LCA Framework

This LCA framework is a template for LCA practitioners to use to develop an LCA for a particular industry. The LCA framework is specific to this industry, and is defined to give relevant information to the LCA practitioner. It acts as a structure to reduce LCA processing time, while also striving to improve reliability and quality of an LCA. The LCA framework is intended to be a guide which describes the control points and best practices for LCAs within this industry.

3.12 LCA Model Software: GREET

Argonne Laboratories has developed an LCA model for algal biofuels pathways for their program GREET (Frank et al. (2011)). The model describes one particular pathway with variances only within the sensitivity analysis. The model does not allow variability in configuration design.

There are several gaps within the model that can be investigated. First, photobioreactors are not considered within the model. Only raceway ponds are considered based on large scale facilities in place as of the model development (Frank et al. (2011)). There is significant potential within the literature for using photobioreactors for production.

Another gap within the GREET model is it only considers photoautotrophic growth mode. Heterotrophic and mixotrophic growth modes are not considered (Frank et al. (2011)). Research into all three growth modes is currently underway.

Also, the model only determines the microalgae nutrient supply from fertilizers. The fertilizer data is taken from previous investigations for seed oil biodiesel (Frank et al. (2011)).

There are fixed parameters given for the microalgae strain, which would mean only one strain of microalgae is considered (Frank et al. (2011)). There are numerous microalgae strains being identified as potential biodiesel feedstock. Also, genetic engineering techniques are being applied to microalgae to increase the lipid production (Tabatabaei et al. (2010)).

Another gap within the model is its exclusion of wastewater. The water source within the model is freshwater (Frank et al. (2011)). Using freshwater in the model can greatly skew the end results away from determining if microalgae were sustainable. Seawater and wastewater have been shown to work as a water source for microalgae production. Also, the wastewater would supply nutrients to the microalgae (Pittman et al. (2010)).

Finally, the model assumes the conversion facility from lipids to biodiesel is 600mi away and would require transportation. The figure was chosen based on transportation distance from the production of soybean oil biodiesel and not from algae facilities (Frank et al. (2011)).

The model could be used as a framework, but if additional LCAs were built from the model, the inherent flaws of the model would be perpetuated. Also, without defining what the functional units would be for the LCAs extrapolated from the model, one could not compare and contrast the results.

3.13 Current Commercial Operations

There are multiple microalgae biodiesel production facilities in North America. Table 2 below highlights 11 companies currently employing microalgae for fuel production.

Table 2: Microalgae Biodiesel Production Companies		
Company	**Description**	**Challenges/Differences**
Algenol Biofuels[1]	• 2,300 algae strains • Flexible plastic film photobioreactor • No harvest no kill strategy to produce ethanol • Ethanol and water evaporate and is collected once it condenses from the sides	• How to compare ethanol and diesel production from microalgae?
Solix Biofuels[2]	• Develops algae growth systems for the algae industry • The demonstration plant uses waste water generated during coal bed methane production • Floating photobioreactor panel • Integrated cleaning system	• How to assess the microalgae contaminants from the coal waste water?
Sapphire Energy[3]	• Power generation/factory emissions are inserted into opens ponds with algae and non-potable water • The algae is harvested and the oil extracted • The oil is then refined at a traditional refinery	• How to assess the microalgae contaminants from factory emissions? • How to assess the contaminants in final oil refined offsite?
Solazyme[4]	• Heterotrophic microalgae strains • Flexible input such as sugarcane, corn and stover, miscanthus, switchgrass, forest residue, waste streams • Uses standard industrial fermentation equipment	• How would the oil yield be impacted by the flexible input? • What percentage accounts for each input?

	• Looking to sell oil directly to refiners to access their distribution infrastructure	
Heliae[5]	• Different strains for different applications • Open to fully closed photobioreactors • Solvent extraction process • Harvesting and dewatering selected based on needs including centrifugation, membrane filtration, flocculation, and additional solids separation technology	• What configuration do you choose based on local conditions given the configuration complexity?
Synthetic Genomics[6]	• Genetically modified strains available for licensing	• What are the impacts of using genetically modified strains? • What are the unintended outcomes in the event of a mishap?
Algae Systems[7]	• Floating offshore growth systems • Municipal wastewater • Factory emissions • non-GMO algae • Algae harvested, and the biomass is converted into biodiesel.	• How to assess the microalgae contaminants from municipal wastewater and factory emissions? • How would pharmaceuticals from the municipal wastewater impact the final product?
Pond Biofuels (Canada)[8]	• Converts raw smokestack emissions from heavy industry into algae biomass (St. Mary's cement kiln) • Strains chosen based on southern Ontario environmental conditions • Enclosed reactors	• How to assess the microalgae contaminants from the smokestack emissions?

	• Harvested biomass is processed using mechanical, drying, and chemicals steps to yield the final biofuel	
Cellana[9]	• Algae grown in photobioreactors and open ponds • Algae strains taken locally in Hawaii. • Algae are concentrated by gravitation, excess water removed, and then dried	• What impacts to the configuration design are associated with the local conditions?
Aquatic Energy[10]	• Open pond farm in Louisiana using a proprietary strain of algae • The algal oil is promoted as a "drop-in" feedstock for existing energy infrastructure	• What impact would the genetically engineered algae have on the local biosphere?
Inventure[11]	• Developed a Direct Extraction Technology to convert algae directly into biodiesel without extracting the oil first	• How would the technology deal with impurities from using waste streams as system inputs?

[1] Algenol Biofuels. (2011). In *Direct to Ethanol Technology.* Retrieved August 7, 2012. www.algenolbiofuels.com/direct-to-ethanol/direct-to-ethanol.

[2] Solix. (2011). In *Our Products.* Retrieved August 7, 2012. www.solixbiofuels.com/content/products.

[3] Sapphire Energy. (2012). Sapphire Energy. In *What is Green Crude.* Retrieved August 7, 2012. www.sapphireenergy.com/green-crude/.

[4] Solazyme. (2012). In *Biotechnology that Creates Renewable Oils from Microalgae.* Retrieved August 7, 2012. www.solazyme.com/technology.

[5] Heliae. (2012). In *Algae Production Systems.* Retrieved August 7, 2012. www.heliae.com/technology/?page=algae-production.

[6] Synthetic Genomics. (2012). In *Products.* Retrieved August 7, 2012. www.syntheticgenomics.com/products/.

[7] Algae Systems. (2011). In *Our Platform*. Retrieved August 7, 2012. www.algaesystems.com/technology/integrated-platform/.

[8] Pond Biofuels. (2011). In *Technology.* Retrieved August 7, 2012. www.pondbiofuels.com/Technology/Technology.html.

[9]). Cellana (2012). In *Technology Alduo Patented Hybrid Hybrid Algae Production System.* Retrieved August 7, 2012. www.cellana.com/our-technology/.

[10] Aquatic Energy. (2010). In *Algae Technology Algae: The Super Organism.* Retrieved August 7, 2012. www.aquaticenergy.com/algae-the-super-organism.

[11] Inventure. (2010). In *Direct Extraction Technology.* Retrieved August 7, 2012. www.inventurechem.com/direct_extraction_technology.html.

Each company approaches biodiesel production from microalgae differently. The downsides of poor comparisons are:

- Incompatible units, such as mass/time compared with mass/area/time
- Boundary conditions are different, therefore results are not comparable
- False positive or negative design decisions
- No meaningful insights

Comparing and contrasting one company to another could be facilitated using a well-structured LCA framework. The LCA framework would offset the downsides of poor comparisons by defining the starting point and set-up for LCAs developed from the framework.

3.14 GaBi LCA Software

PE International developed GaBi, an LCA implementation software, for LCA practitioners. GaBi uses common internationally recognized databases and engineering metrics to evaluate a product or service as defined by the LCA practitioner (PE International. (2013)).

GaBi was developed to support business applications for life cycle assessment, life cycle costing, life cycle reporting, and life cycle working environment. GaBi models every element from a life cycle perspective, and looks at the impacts from alternative manufacturing, energy sources, distribution, recyclability, and sustainability. GaBi helps protect brands to deliver more sustainable products to better meet customer expectations. The LCA tool can also be used to give feedback to customers about sustainability for a product or service (PE International. (2013)).

GaBi uses a flowchart method and can be readily used for developing an LCA framework. Once the framework is developed using GaBi, the flowchart can be adapted for other configurations, locations, and other parameters.

3.15 LCAs Currently Available

There are numerous LCAs available within the literature which evaluate one or two forms of microalgae production or compare microalgae biodiesel to seed oil biodiesel, jatropha derived biodiesel, and crude oil.

The issue with current LCA studies is they are not comparable from one LCA to the next. There are no common functional units, and what is measured is measured differently from one LCA to the next. Therefore, the conclusions made cannot be directly compared. Table 3 on the following page reviews 7 example LCAs conducted on microalgae biodiesel production.

Table 3: Example LCAs for Microalgae Biodiesel Production

LCA	Description	Problems/Issues
Batan et al. (2010)	• Based on GREET model • Photobioreactor • Nanochloropsis microalgae • Centrifugation harvesting • Extraction process based on soybeans • Transesterification synthesis • Functional units based on total GHG emissions.	• Problem A: The errors in the GREET model are carried over into the LCA.
Frank et al. (2012)	• Based on GREET model • Open ponds • Bio-flocculation harvesting • Hexane extraction • Anaerobic digestion • Biogas conversion to electricity • Functional units based on total GHG emissions.	• Same as problem A
Hou et al. (2011).	• Basic LCA methodology supplemented with Gabi 4.3 • System design for microalgae biodiesel is not defined	• Problem B: System design is not defined and LCA cannot be repeated.

	• Functional units based on abiotic depletion potential (ADP), global warming potential (GWP), and ozone depletion potential (ODP).	
Yang et al. (2010).	• Basic LCA methodology • Open pond, freshwater, and fertilizer • Harvested and dried • Extraction and synthesis based on soybean • Functional units based on freshwater usage in kg/kg biodiesel, and nutrient usage in kg/kg biodiesel.	• Problem C: Basic configuration, but does not represent industry.
Lardon et al. (2009).	• LCA study of a virtual facility • Open pond • Centrifugation harvesting • Hexane extraction • Transesterification synthesis • Functional units based on global warming potential (GWP), Ozone, Eutro, AbD, Acid, Human Tox, Marine Tox, Land, Rad, and Photo.	• Same as problem C
Campbell et al. (2010).	• LCA study of a system designed for Australian conditions • Open pond, CO2 from power station or ammonia plant, fertilizer, and seawater from nearby coast	• Problem D: Results are only applicable to local conditions, and cannot be compared to results from elsewhere.

	• Harvested using diesel tractor after chemical flocculation • Transesterified using methanol • Functional units based on GHG emissions and cost.	
Khoo et al. (2011).	• Hypothetical LCA for Singapore • Photobioreactor and raceway ponds • Harvested and dried • Lipids are extracted and filtered • Transesterification synthesis • Functional units based on MJ energy demand/MJ biodiesel, and life cycle CO2 in kg/MJ biodiesel.	• Same as problem D

In summary, the LCA framework would rectify discrepancies in LCAs, and bring order to the chaotic mix of LCAs currently available. The uniform LCA base approach would assess the most sustainable technology and benchmarking. The benefits of comparison between LCAs are:

- Contrast economic viability
- Uncover realistic expectations
- Identify outliers for further investigation
- Define regulatory conditions and incentives
- Contrast environmental impacts

An LCA framework would further increase the ease of comparison as the LCAs would not have disparate outcomes as seen currently within the LCA literature.

4.0 METHODOLOGY

The LCA framework is developed for rapid LCA execution by LCA practitioners using established benchmarks, functional units, default settings, and a data acquisition rubric. Creating a life cycle analysis (LCA) framework consists of identifying the life stages based on current academic and industry information, conducting a data gap analysis, prioritizing LCA focus, defining the functional units, and testing the framework using industry and academic data.

The following list summarizes the key steps undertaken in this research:

1. Identify life stages common to all configurations
2. Identify industry trends for configuration design
3. Create word arrays visually depicting the trends for each life stage
4. Compile LCA data from literature, and convert into common units
5. Conduct a data gap analysis for data quality and data reliability using LCAs found from literature
6. Prioritize the LCA focus
7. Define the functional units to be used across all configurations
8. Develop and define a benchmark for industry
9. Identify the process flow options for configuration design
10. Develop and define the default case for the LCA framework
11. Create a data acquisition rubric for the LCA framework
12. Recreate the LCA framework in GaBi using objects, flows, and parameters
13. Test the LCA framework in GaBi against two case studies found in Appendices A and B
14. Compile framework in Appendix E

4.1 Methodology: Industry Trends

Table 4 on the following page lists the companies used for identifying industry trends, creating word arrays, and generating the default configuration design settings. The LCA framework uses a default case to streamline the LCA process. Basing the default case on industry trends reflects actual industry circumstances rather than arbitrarily chosen configurations. When using the LCA framework, the default settings would decrease the time and resources spent on creating the process flowchart. The framework should be generically applicable, and only processes unique to the current configuration would need to be customized.

Table 4: Microalgae Biodiesel Industry Company List		
Company Name	**Location**	**Established**
Algae Floating Systems	San Francisco, CA, USA	2007
AlgaeLink	Yerseke, Netherlands	2007
Algae Production Systems	Houston, TX, USA	2008
Algae Systems	USA	2011
Aquaflow	New Zealand	2010
Aquatic Energy	Lake Charles, LA, USA	2006
Alvigor	Ueberstorf, Switzerland	2012
Aurora Algae	Hayward, CA, USA	2007
Cellana	Kona, HI, USA	2009
Diversified Energy	Gilbert, AZ, USA	2005
Heliae	Gilbert, AZ, USA	2008
Lgem B.V.	Netherlands	2007
Live Fuels	San Carlos, CA, USA	2006
Photon8	Texas, USA	--
Phycal	Highland Heights, OH, USA	2006
Pond Biofuels	Markham, ON, Canada	2007
Sapphire Energy	San Diego, CA, USA	2007
Seambiotic	Tel Aviv, Israel	2003
Solazyme	San Francisco, CA, USA	2003
Solix Biofuels	Fort Collins, CO, USA	2006

4.1.1 Rationale for Choosing Companies

The companies chosen for inclusion in designing the LCA framework were based on the following two criteria.

1. Each company has information posted on website for each process/life stage
2. Each company has at least a demonstration site for a complete configuration

The relevant information as described by the criteria above is used to identify industry trends in configuration design.

4.2 Methodology: LCAs from Literature Analysis

LCAs were taken from literature for analysis with respect to functional units, boundary conditions, average input and output values, and benchmark creation. The methodology for benchmark creation can be found in section 4.5. Table 5 on the following pages lists all LCAs considered for utilization in creating the LCA framework. The LCAs were evaluated with respect to the following criteria:

- Depth of LCA as compared to the LCA framework scope
- Full configuration analysis
- Convertible functional units
- Measurements with respect to algae production, biodiesel production, energy requirements, and emissions
- Data relevant to the LCA framework scope

LCAs were eliminated by not having sufficient data or not evaluating a complete configuration. The LCAs chosen for utilization were then compiled into a chart for comparison. Values needing to be converted to common units were then converted. There were issues in converting data, and data gaps were then discovered from the chosen LCAs. Details on how the data was converted and all equations can be found in section 5.3.1. A data gap analysis methodology can be found in section 4.3, and the results and discussions can be found in section 5.3.4.

Table 5: Rationale for Choosing LCAs from Literature			
	Keep	**Omit**	**Explanations**
Amin, et al. (2009)		x	Overview of technology and future potential. No quantifiable data.
Anthony, et al. (2013)		x	Review of harvesting stage. Not a full LCA including all life stages.
Azadi, et al. (2013)	x		Full system LCA with relevant data.
Batan, et al. (2010)	x		Full system LCA with relevant data.
Batten, et al. (2013)		x	Full system overview from an economic perspective. No other LCA data available.
Borkowski, et al. (2013)	x		Full system LCA with relevant data.
Brentner, et al. (2011)	x		Full system LCA with relevant data.
Campbell, et al. (2010)	x		Full system LCA with relevant data.
Collet, et al. (2011)		x	Full LCA system with data, but it represents anaerobic digestion and no biodiesel is produced.
Frank, et al. (2012)	x		Full system LCA with relevant data.
Franz, et al. (2012)		x	Review of variability due to algae strain and location from an LCA perspective. Not a full LCA including all life stages.
Greenwell et al. (2013)		x	Overview of technology and future potential. No quantifiable data.
Ho, et al. (2013)		x	Review of variability due to algae strain from an LCA perspective. Not a full LCA including all life stages.
Holma, et al. (2013)	x		Full system LCA with relevant data.
Hou, et al. (2011)	x		Full system LCA with relevant data.
Jorquera, et al. (2010)	x		Full system LCA with relevant data.
Khoo, et al. (2011)	x		Full system LCA with relevant data.
Lam, et al. (2012)		x	CO2 balance for different algae strains. No other variables considered. Not a full LCA including all life stages.
Lardon, et al. (2009)	x		Full system LCA with relevant data.
Liu, et al. (2011)		x	Analyzes the biodiesel yield under photoautotrophic and heterotrophic growth modes. No data for other life stages. Not a full LCA including all life stages.
Mata, et al. (2011)		x	Reviewed various fuels and compared metrics. The data was taken from another LCA. No unique data.

Table 5: Rationale for Choosing LCAs from Literature (cont'd)			
	Keep	**Omit**	**Explanations**
Murillo-Alvarado, et al. (2013)		x	Pareto analysis for biorefineries. The configuration design is not clearly defined. Not a full LCA including all life stages.
Murphy et al. (2012)		x	Analysis focuses only on water use and energy associated with water use. Not a full LCA including all life stages.
O'Connell, et al. (2013)	x		Full system LCA with relevant data.
Olguin, et al. (2012)		x	Focuses on the cultivation stage from an LCA perspective. Not a full LCA including all life stages.
Peccia, et al. (2013)		x	Analysis focuses only on nitrogen transfer. Not a full LCA including all life stages.
Powell, et al. (2009)		x	LCA based on creating bioethanol and biodiesel at the same plant. Not representative of a microalgae biodiesel LCA.
Razon, et al. (2011)	x		Full system LCA with relevant data.
Rosch, et al. (2012)		x	Focuses on nutrient recycling. No other data presented. Not a full LCA including all life stages.
Sander, et al. (2010)	x		Full system LCA with relevant data.
Sevigne Itoiz, et al. (2012)	x		Full system LCA with relevant data.
Shirvani, et al. (2011)	x		Full system LCA with relevant data.
Singh, et al. (2010)		x	Full system overview from an economic perspective. No other LCA data available.
Soh, et al. (2014)		x	No biodiesel produced in LCA. Does not include the synthesis phase. Not a full LCA including all life stages.
Soratana, et al. (2012)		x	Data taken from other LCAs. No unique data.
Stephenson, et al. (2010)	x		Full system LCA with relevant data.
Sudhakar, et al. (2012)		x	Location specific LCA. Concentrates on cultivation phase. Not a full LCA including all life stages.
Torres, et al. (2013)	x		Full system LCA with relevant data.
Ventura, et al. (2013)	x		Full system LCA with relevant data.

Table 5: Rationale for Choosing LCAs from Literature (cont'd)			
	Keep	**Omit**	**Explanations**
Wang, et al. (2013)		x	Focuses on biogas creation. No biodiesel is produced. Not a full LCA including all life stages.
Williams, et al. (2010)		x	Review of technology from a biochemistry perspective and economics. No energy data. Not a full LCA including all life stages.
Woo, et al. (2012)		x	Focuses on lipid content from algae grown on wastewater. Not a full LCA including all life stages.
Xu, et al. (2013)		x	Bibliometric evaluation on research output. Not a full LCA including all life stages.
Yanfen, et al. (2012)		x	Information taken from other LCAs. No unique data.
Zaimes, et al. (2013)	x		Full system LCA with relevant data.
Zhang, et al. (2013)		x	Data includes elements outside the system boundaries for the LCA framework. Not representative of the LCAs used for creating the benchmarks.

Table 6 on the following page lists the LCAs found from literature that are utilized for creating the benchmarks. The benchmark values are available in the LCA framework as comparisons to then evaluate the outcomes of an individual LCA.

Table 6: LCAs from Literature Utilized for LCA Framework	
Author/Citation	**Journal Title**
Azadi, et al. (2013)	The carbon footprint and non-renewable energy demand of algae-derived biodiesel
Batan, L. et al. (2010)	Net Energy and Greenhouse Gas Emission Evaluation of Biodiesel Derived from Microalgae
Borkowski, et al. (2013)	Integrating LCA and Thermodynamic Analysis for Sustainability Assessment of Algal Biofuels: Comparison of Renewable Diesel vs. Biodiesel
Brentner, et al. (2011)	Combinatorial Life Cycle Assessment to Inform Process Design of Industrial Production of Algal Biodiesel
Campbell, P.K. et al. (2010)	Life cycle assessment of biodiesel production from microalgae in ponds
Frank, E.D. et al. (2012)	Methane and nitrous oxide emissions affect the life-cycle analysis of algal biofuels
Holma, et al. (2013)	Current limits of life cycle assessment framework in evaluating environmental sustainability - case of two evolving biofuel technologies
Hou, J. et al. (2011)	Life cycle assessment of biodiesel from soybean, jatropha, and microalgae in China conditions
Jorquera, et al. (2010)	Comparative energy life-cycle analyses of microalgal biomass production in open ponds and photobioreactors
Khoo, H.H. et al. (2011)	Life cycle energy and CO_2 analysis of microalgae-to-biodiesel: Preliminary results and comparisons
Lardon, L. et al. (2009)	Life-Cycle Assessment of Biodisel Production from Microalgae
O'Connell, et al. (2013)	Life cycle assessment of dewatering routes for algae derived biodiesel processes
Razon, et al. (2011)	Net energy analysis of the production of biodiesel and biogas from the microalgae *Haematococcus pluvialis* and *Nannochloropsis*
Sander, et al. (2010)	Life cycle analysis of algae biodiesel
Sevigne Itoiz, et al. (2012)	Energy balance and environmental impact analysis of marine microalgal biomass production for biodiesel generation in a photobioreactor pilot plant
Shirvani, et al. (2011)	Life cycle energy and greenhouse has analysis for algae-derived biodiesel
Stephenson, et al. (2010)	Life-Cycle Assessment of Potential Algal Biodiesel Production in the United Kingdom: A Comparison of Raceways and Air-Lift Tubular Bioreactors
Torres, et al. (2013)	Microalgae-based biodiesel: A multicriteria analysis of the production process using realistic scenarios
Ventura, et al. (2013)	Life cycle analyses of CO_2, energy, and cost for four different routes of microalgal bioenergy conversion
Zaimes, et al. (2013)	Microalgal biomass production pathways: evaluation of life cycle environmental impacts

The LCA data from literature is compiled in Table 8 in section 5.3, and then converted to common units for future analysis with respect to a data gap analysis and benchmarking. The calculations can be found proceeding Table 8. The assumptions used for the calculations are:

- One year has 300 production days, unless otherwise stated.
- Assume the lower heating value (LHV) of biodiesel is 42MJ/kg

All unit conversion factors are stated within the calculations. There were significant data gaps identified, and an analysis of data gaps was considered. The following section will describe the methodology in analyzing the data gaps.

4.3 Methodology: Data Gap Analysis

The data gap analysis was conducted based on the LCA literature data as shown in Table 8. There are numerous LCA metrics, and ideally, the most relevant metrics to the particular LCA should be chosen. Furthermore, the metrics chosen should be informed by the quality of data supplied by literature. Potential LCA metrics are economics, water use, lipid content, algae production, biodiesel production, energy balance ratio, global warming potential, eutrophication, acidification, resource consumption, and social conditions. However, based on the availability and quality of the data of the studies reviewed previously, the metrics measured from the LCA literature for this particular research are:

- Lipid Content
- Algae Production
- Biodiesel Production
- Energy Balance Ratio (EBR)
- Global Warming Potential (GWP)

Average values and standard deviations were then calculated for each metric based on values that were found in the existing literature. These values were used for evaluating the data quality and reliability. The data gaps discovered were also analyzed.

Average: $$\bar{X} = \frac{\sum_{i=1}^{n}(X_i)}{n}$$

Standard Deviation: $$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(X_i - \overline{X})^2}{n-1}}$$

$\overline{X} = average\ metric\ value$

$X_i = metric\ value\ at\ LCA\ i$

$n = total\ number\ of\ measureable\ LCAs\ for\ a\ particular\ metric$

$\sigma = standard\ deviation$

The analysis is considered to be a data gap analysis because a true uncertainty analysis is not possible due to the small sample size of 20 LCAs and because the studies reviewed were not intended to be related to one another in any meaningful way. Also, each LCA data point represents one measurement and each LCA is not measuring the same data from the same configuration. Therefore, the data gap analysis is accomplished by evaluating the sample size standard deviations coupled with a qualitative analysis of Literature LCAs and Industry Trends.

4.4 Methodology: Functional Units

The functional units were chosen based on a qualitative analysis of functional units found in LCA Literature and relevance to industry. The units were also chosen based on convertibility to:

- Different unit sizes
- Different time frames
- Total values derived from algae and biodiesel quantity

The qualitative analysis consisted of evaluating the most commonly used units currently utilized within the LCA literature for microalgae biodiesel production. Also, the ease of conversion to other metrics and units for comparison were considered.

4.5 Methodology: Benchmarks

The benchmark represents the minimal value for each metric that must be obtained for a configuration to be considered. The benchmark must represent current industry and academic values. Having a benchmark within the LCA framework would replace the need to establish a new baseline for each LCA, increasing transparency within the industry. The benchmark is developed by analyzing the average and standard deviations from the LCA literature data and the industry trends, and also the mode, 25th percentile, 50th percentile, and 75th percentile for each metric. The metrics used for the Benchmark are:

- Lipid Content
- Algae Production
- Biodiesel Production
- Energy Balance Ratio (EBR)
- Global Warming Potential (GWP)

The metrics were chosen based on relevance to the industry, and the inherent beneficial quality obtained from each metric. Benchmarks with respect to water consumption, nutrient consumption, CO_2 uptake, and economics should be established. Due to the lack of quality data from literature and time constraints, these other metrics are scoped out of the thesis, and are relegated to future work.

Studies from literature which focused only on one parameter, such as lipid content, were not included in developing the benchmarks. Even though the information would indicate a possible lipid content value, without data on impacts or other variables considered in the representative LCA studies reviewed here, such information was excluded because it may skew the assessment and benchmarking efforts due to the lack of context.

Each metric's data was analyzed individually with respect to the data gaps, range, and quality. For example, certain metrics might use a modal value as the benchmark, while others might use another value. The calculations and development of each benchmark metric is discussed in the results and discussion section of the report, along with difficulties, rationale, and benchmark outcomes.

4.6 Methodology: Developing Default Case for LCA Framework

The LCA Framework is developed for rapid LCA execution using established benchmarks, functional units, default settings, and data acquisition rubric.

The default settings streamline the LCA process by requiring only differing elements to be altered. Also, default settings illustrate the system boundaries and LCA scope. LCA practitioners benefit from having the system boundaries and LCA scope predefined.

The default settings were determined from the industry trends analysis, and the LCA literature data analysis. The names for processes and flows are chosen carefully to represent the overall function the process has instead of a specific process design. The four process life stages where the algae is transported and processed are:

- Growth Mode
- Harvesting Mode
- Extraction Mode
- Synthesis Mode

The life stages were referred to as phases and are now referred to as modes for modelling purposes. Using default settings therefore only require changing a few values since the other values are common. The default settings are also expanded where certain elements require more steps: the LCA practitioner does not need to add other process flows or options. Therefore, elements can be set to zero when they are not required, but generally no new elements need to be added to the default settings as they are already accounted for within the default settings.

The algae flows through the system and is converted into biodiesel as the final output. A detailed description of process flows in the default case can be found in the results and discussion section.

4.7 Methodology: Selecting Case Studies

To test the LCA framework and benchmarking, two case studies were developed using documented scenarios based on their relevance to industry, complete configuration system boundary, LCA scope, and completeness in data. The LCA must be representative of both industry and literature circumstances in order to evaluate how well the framework functioned.

The first Case Study data can be found in Appendix A. Case study #1 is based on the article "Combinatorial Life Cycle Assessment to Inform Process Design of Industrial Production of Algal Biodiesel" by Laura B. Brentner et al. (2011) from the journal *Environmental Science and Technology 2011 vol. 45*.

The second Case Study data can be found in Appendix B. Case study #2 is based on the article "Net Energy and Greenhouse Gas Emission of Biodiesel Derived from Microalgae" by Batan, L et al. (2010) from the journal *Environmental Science and Technology 2011 vol. 44*.

The case studies were chosen based on the following criteria. The LCA's quality was assessed as compared to other available LCAs and the "best" LCAs were chosen as the case studies.

- *Relevance to Industry*

The case study must be of a configuration common in industry to better represent and validate the LCA framework.

- *Complete Configuration System Boundary*

The case study must be robust and a complete system boundary for the LCA production phase to do justice to the case study analysis.

- *LCA Scope*

The scope must be in common with the LCA framework.

- *Completeness in Data*

The data presented in the LCA must be complete and outlined in the LCA or supporting materials and not just the results. If only the results are available, the LCA could not be repeated.

The case studies are further discussed in the results and discussions section.

4.8 Methodology: GaBi Testing

Figure 10 below is a screenshot of the Growth Mode process database for Case #2. The inputs are described with the units, factors, and origin information. There are parameters used to describe the flows into and out of the process. The parameters make it easier to change a flowchart to test a different configuration. Changing one parameter would adjust all other parameters built from it within the process database.

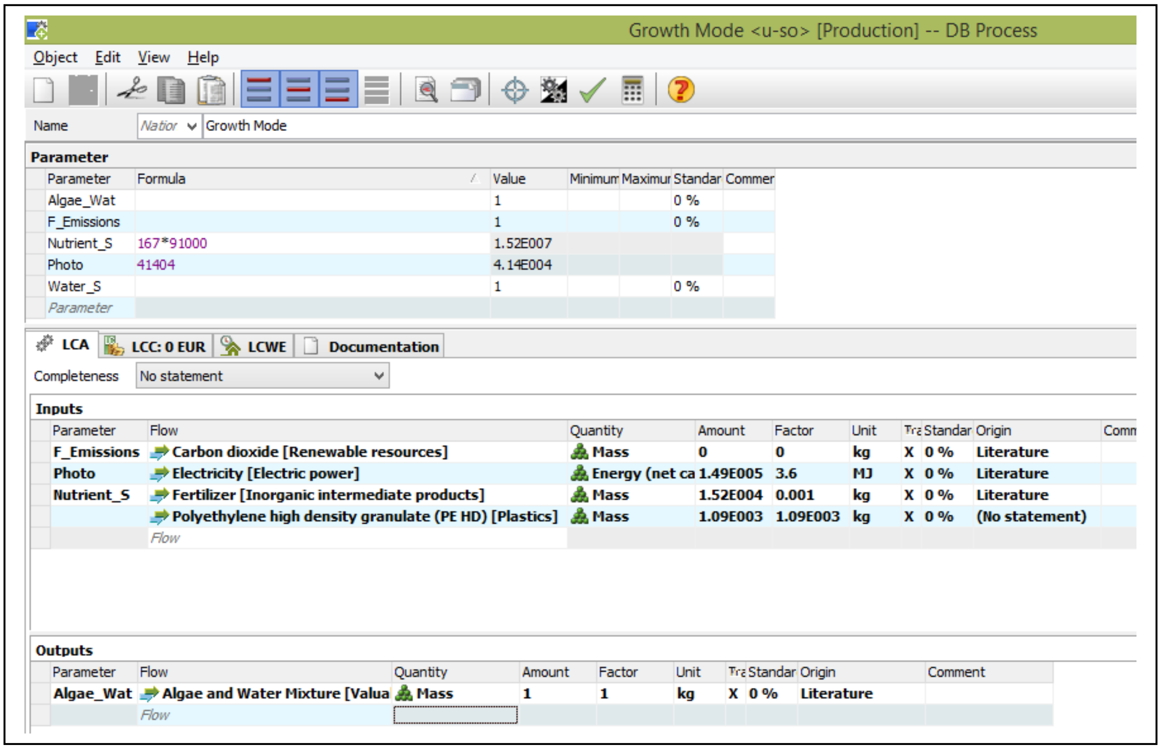


Figure 10 Example Process Database in GaBi for Growth Mode for Appendix B

For instance, the parameter 'Nutrient_S' represents the nutrient flow into the system process. The nutrients are supplied by fertilizer. The parameter is set to the value given in the LCA. The 'Photo' parameter is the total electricity input for the cultivation phase of the life stages. The value is given in the LCA data, and is also compiled in the data acquisition rubric. The data acquisition rubric is used for supplying the data for the parameters in GaBi.

Figure 11 below is a screenshot from the process database for US: Electricity grid mix. The electricity grid mix is connected to the system processes using flows. The flow would show as electricity. The same output in 'US: Electricity grid mix' would appear as the input for the system process. The parameter only needs to be changed in the system process and not the ‘US: Electricity grid mix’ process.

Once GaBi has generated raw data for each metric, then the data is compiled for comparison to the original LCA and the benchmarks. An analysis is then conducted for the results of using the LCA framework and where the framework can be improved.

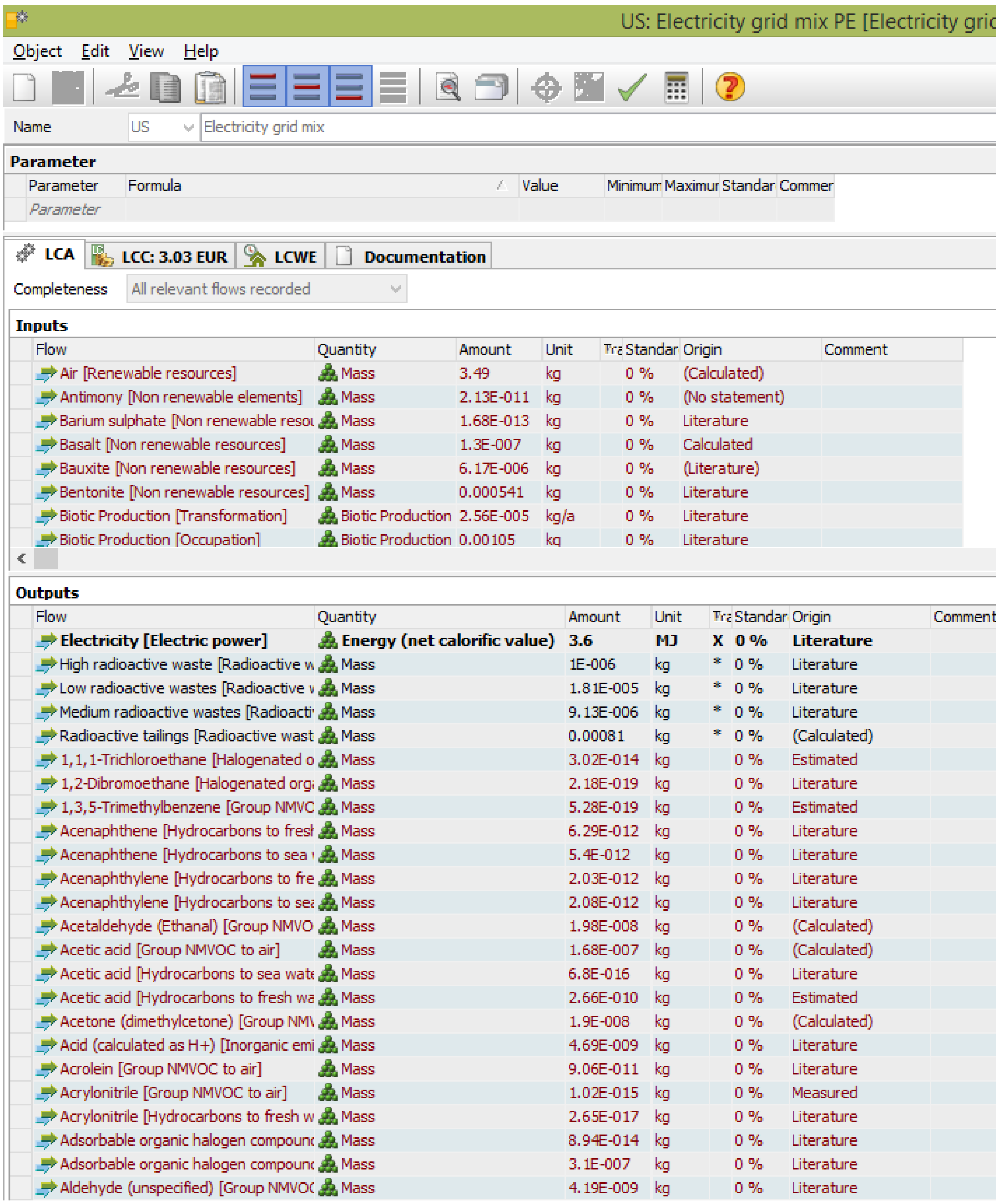


Figure 11 GaBi Process for US Electricity Grid Mix

4.9 Compile LCA Framework

The LCA framework is compiled in Appendix E for reference purposes. The charts and graphs found in Appendix E are compiled from the results and discussion section of the thesis. The information contained within Appendix E can be used to facilitate the creation of an LCA. The major elements of the framework are itemized below, and the information included in Appendix E are:

- Flowchart with boundaries, scope, and flows defined
- Functional units
- Benchmarks
- Default case based on industry trends
- All process configuration design options
- Data acquisition rubric
- GaBi flowchart

The LCA practitioner can use Appendix E to implement the LCA framework using their own design and data.

5.0 RESULTS AND DISCUSSION

5.1 Life Stages Common to All Configurations

Microalgae biodiesel production consists of 4 main life stages with multiple sub stages within each main stage. If the life stages are appropriately identified with the inputs and outputs clearly defined, it will help create a more efficient life cycle analysis. An example is shown in Figure 12 below.

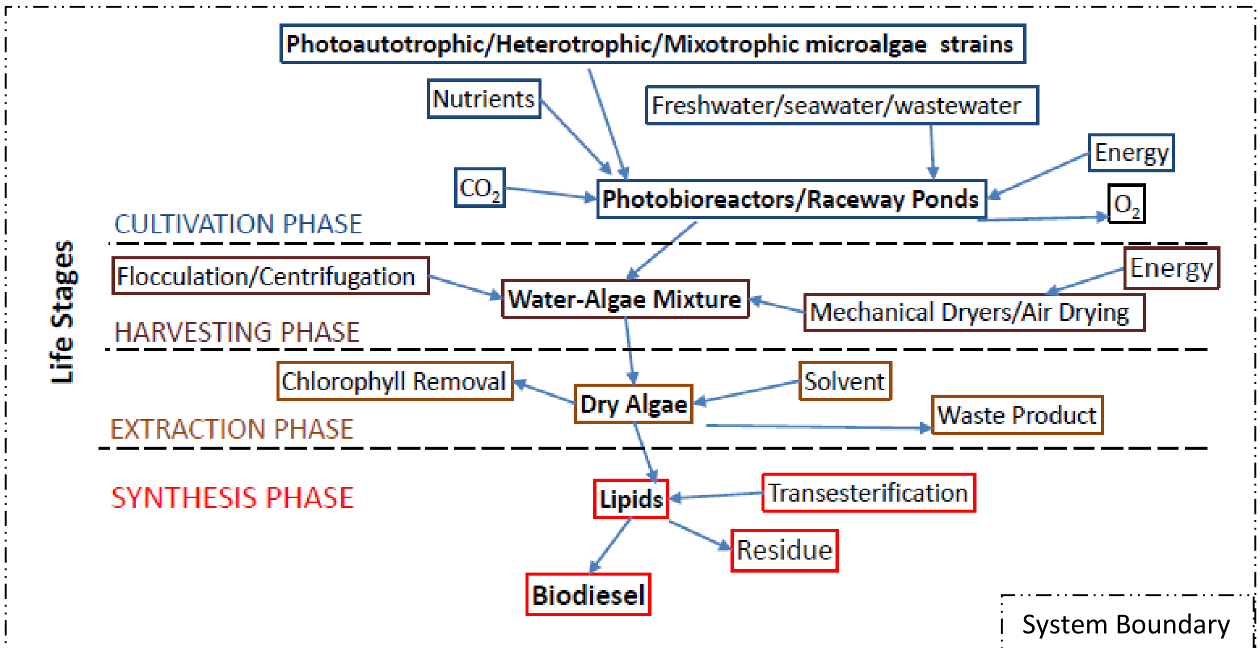


Figure 12: Example life stages for biodiesel production

5.2 Industry Trends: Configuration Design

Table 4 on the following page evaluates 20 configurations from the industry for producing biodiesel. The information found in table 4 is used to identify common pathways and trends within the industry, and create word arrays as a quick visual guide to the trends for each life stage.

Table 7: LCIA Microalgae Biodiesel Industry Configuration Chart

	CULTIVATION PHASE															HARVESTING PHASE				EXTRACTION PHASE					SYNTHESIS PHASE		
Company Name	Photoautotrophic	Heterotrophic	Non-GMO Algae	GMO Algae	Fermenters	Raceway Ponds	Photobioreators – Floating Systems	Photobioreactors – Tubes	Freshwater	Wastewater	Non-potable Water	Seawater	Starchy waste products	Fertilizer	Factory Emissions	Centrifugation	Flocculation	Membrane Filtration	Additional Solids Separation	Mechanical Dryers	Solar dryers	Dry Extraction	Hexane Extraction	Wet Extraction	Transesterification	Super Critical Transesterificaiton	Traditional Refinery
Algae Floating Systems	x		x				x		x					x	x		x							x			x
AlgaeLink	x		x					x	x					x			x				x				x		
Algae Production Systems	x		x					x	x					x		x				x							x
Algae Systems	x		x				x			x					x		x						x		x		
Aquaflow		x	x							x			x			x				x		x					x
Aquatic Energy	x			x		x																	x				x
Alvigor	x		x					x	x					x	x		x			x			x		x		
Aurora Algae	x			x		x						x		x	x		x				x		x				x
Cellana	x		x			x		x									x						x		x		
Diversified Energy	x			x			x		x					x	x		x				x		x				x
Heliae				x		x		x								x	x	x	x				x		x		
Lgem B.V.	x		x					x	x					x			x						x				x
Live Fuels	x		x			x						x					x				x		x				x
Photon8	x			x			x		x					x	x		x							x	x		
Phycal	x			x		x			x					x			x				x		x				x
Pond Biofuels	x		x					x							x		x			x			x		x		
Sapphire Energy	x					x					x				x		x			x			x				x
Seambiotic	x		x			x			x					x	x		x			x			x		x		
Solazyme		x		x	x				x				x												x		
Solix Biofuels	x		x				x			x					x		x			x			x		x		

Word arrays for each life stage are shown in figures 13-16 below.

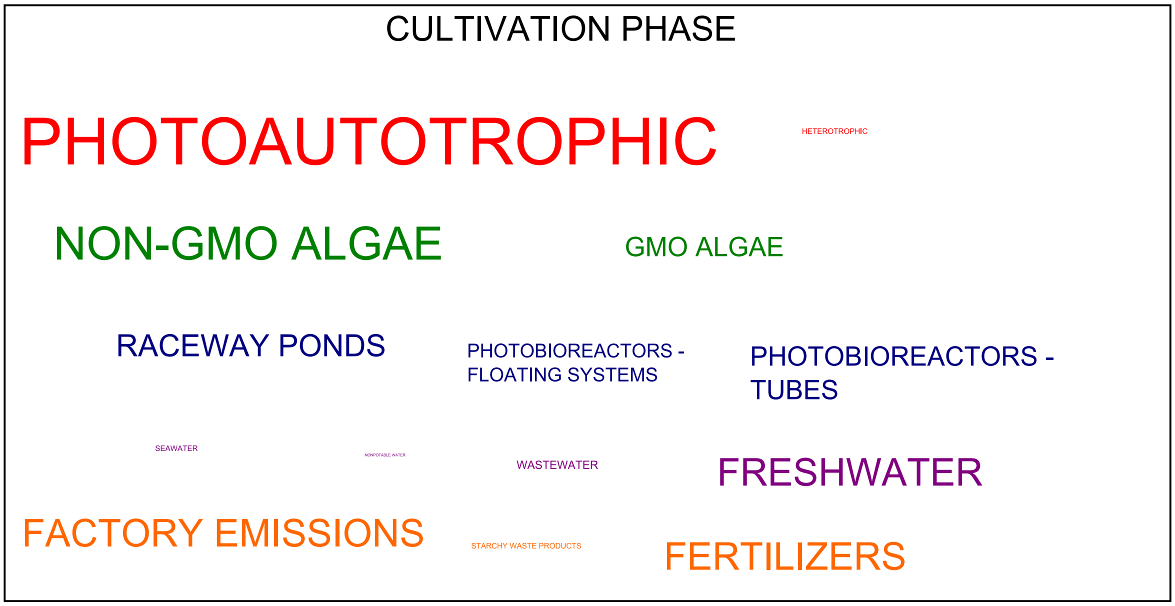


Figure 13: Cultivation phase

The first life stage, the cultivation phase, has the greatest diversity in viable technology. Based on figure 13 above, photoautotrophic microalgae is currently the most popular in industry. Non-GMO algae is currently in the lead, and yet the GMO algae is growing in market share. Photobioreactors make up the majority in growth media, but raceways are still popular because of their low cost. Photobioreactors' design consists of variances which lead to multiple design configurations. Even though there is interest in using other water sources, freshwater still dominates the industry. Factory emissions and fertilizers are used together to supply CO_2 and nutrients to the microalgae.

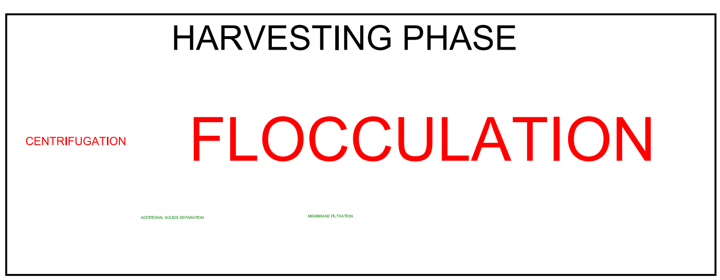


Figure 14: Harvesting Phase

The harvesting phase word array is shown in figure 14 above. Flocculation is the predominant technique used for harvesting microalgae. Additional separation techniques are not currently employed in industry beyond the initial separation.

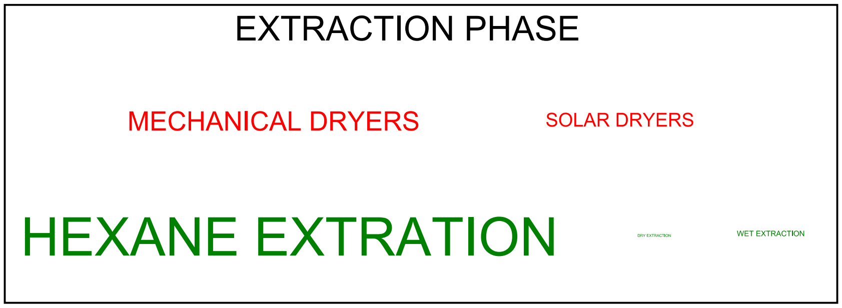


Figure 15: Extraction Phase

For the extraction phase, shown in figure 15 above, mechanical dryers and solar dryers are both used in industry. Hexane extraction is the predominant extraction technique, even though wet extraction has shown great promise in the future, which would eliminate the drying step in the process.

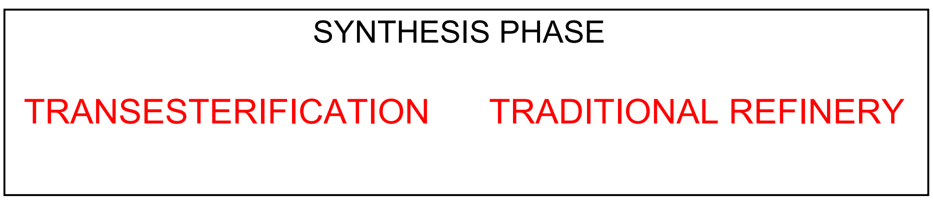


Figure 16: Synthesis Phase

Transesterification and traditional refinery are used equally within industry for the synthesis phase, as shown in figure 16 above. Transesterification would be conducted on site at the microalgae plant, while traditional refinery techniques would require the extracted algal oil to be transported elsewhere. The transportation distance would vary.

5.3 Data Quality of LCAs Reviewed

Data quality is taken to be the overall data accuracy, reliability, relevance, and completeness. When conducting an LCA, it is important to establish data quality standards: the value gained from an LCA can be negated by poor data quality. For instance, using two different measurement instruments, or two different measurement schematics, can result in dramatically different results. In such cases, if the results were compared to one another, the outcomes can be different, and whether or not the results of a particular LCA are meaningful is then uncertain. Therefore, it is important to understand that if prior LCAs were deemed inadequate, what were the “root causes” that contributed to these inadequacies? For example, were the data used in the LCA incomplete; was the LCA model inappropriate; or some combination of the two? The following section analyzes data completeness, availability, and model flexibility using 20 LCAs found from the literature. Of the many available LCA studies, these chosen LCAs were determined to be robust, relevant, and represent industry.

Table 8 on the following page converts the data from the LCAs into common units for comparison. The calculations used to convert the units are shown following the chart.

Table 8: Data Compiled from LCA Literature

	DATA FROM LITERATURE										CONVERTED DATA TO COMMON UNITS									
	Lipid Content		Algae Production		Biodiesel Production		Energy Balance Ratio		GWP		Lipid Content		Algae Production		Biodiesel Production		Energy Balance Ratio		Global Warming Potential	
LCA	QTY	Units	QTY	Units	QTY	Units	QTY	Units	QTY	Units	QTY	Units	QTY	Units	QTY	Units	QTY	Units	QTY	Units
Azadi, et al. (2013)	30	wt %	80	t/ha/yr	--	--	1.12	MJf/MJb	80.00	g e-CO2/MJ	30	wt %	80	t/ha/yr	0.00	t/ha/yr	1.12	MJf/MJb	80.00	g e-CO2/MJ
Batan, L. et al. (2010)	50	wt %	91000	kg/ha/yr	43009	L/ha/yr	0.93	MJf/MJb	75.00	g e-CO2/MJ	50	wt %	91	t/ha/yr	43.00	t/ha/yr	0.93	MJf/MJb	75.00	g e-CO2/MJ
Borkowski, et al. (2013)	20	wt %	--	--	1.00	lb/lb-algae oil	3.90	MJf/MJb	82.00	g e-CO2/MJ	20	wt %	--	t/ha/yr	--	t/ha/yr	3.90	MJf/MJb	82.00	g e-CO2/MJ
Brentner, et al. (2011)	25	wt %	4	kg/m^3/yr	95.00	% algae oil	10800	MJf/10^4 MJb	805.00	kg e-CO2/ 10^4 MJ	25	wt %	40	t/ha/yr	10.00	t/ha/yr	1.08	MJf/MJb	80.50	g e-CO2/MJ
Campbell, P.K. et al. (2010)	30	wt %	30	g/m^2/day	95.00	% algae oil	--	--	62.00	g e-CO2/MJ	30	wt %	90	t/ha/yr	25.65	t/ha/yr	--	MJf/MJb	62.00	g e-CO2/MJ
Frank, E.D. et al. (2012)	25	wt %	25	g/m^2/day	26.40	kg lipids/ MMBTU-BD	19450	BTU/ kg lipid	62000.00	g e-CO2/ MMBTU-BD	25	wt %	75	t/ha/yr	18.75	t/ha/yr	--	MJf/MJb	58.71	g e-CO2/MJ
Holma, et al. (2013)	25	wt %	3480	t/80 ha/yr	--	--	1.31	MJf/MJb	83.80	g e-CO2/MJ	25	wt %	44	t/ha/yr	--	t/ha/yr	1.31	MJf/MJb	83.80	g e-CO2/MJ
Hou, J. et al. (2011)	45	wt %	30	g/m^2/day	1000	t/1018 kg algae oil	--	--	1.6* 10^(-2)	kg e-CO2/MJ	45	wt %	90	t/ha/yr	39.78	t/ha/yr	--	MJf/MJb	16.20	g e-CO2/MJ
Jorquera, et al. (2010)	30	wt %	100000	kg/yr	207.00	Barrels/yr	699	GJ/year	--	--	30	wt %	--	t/ha/yr	--	t/ha/yr	--	MJf/MJb	--	g e-CO2/MJ
Khoo, H.H. et al. (2011)	45	wt %	25	g/m^2/day	90.00	% algae oil	3.60	MJf/MJb	--	--	45	wt %	75	t/ha/yr	33.75	t/ha/yr	3.60	MJf/MJb	--	g e-CO2/MJ
Lardon, L. et al. (2009)	20	wt %	20	t/ha/yr	90.00	% algae oil	3.84	MJf/MJb	--	--	20	wt %	20	t/ha/yr	4.00	t/ha/yr	3.84	MJf/MJb	--	g e-CO2/MJ
O'Connell, et al. (2013)	60	wt %	--	--	52300	t/yr	6.40	kWh/t biodiesel	663.00	kg e-CO2/ tonne BD	60	wt %	--	t/ha/yr	--	t/ha/yr	--	MJf/MJb	--	g e-CO2/MJ
Razon, et al. (2011)	30	wt %	16	g/m^2/day	1.00	kg / kg algae oil	4.30	MJf/MJb	--	--	30	wt %	48	t/ha/yr	14.40	t/ha/yr	4.30	MJf/MJb	--	g e-CO2/MJ
Sander, et al. (2010)	30	wt %	--	--	96.00	% algae oil	3.20	MJf/MJb	400.00	kg e-CO2/ 10000MJ	30	wt %	--	t/ha/yr	--	t/ha/yr	3.20	MJf/MJb	40.00	g e-CO2/MJ
Sevigne Itoiz, et al. (2012)	25	wt %	--	--	95.00	% algae oil	139.00	MJf/kg	23.80	kg e-CO2/kg biodiesel	25	wt %	--	t/ha/yr	--	t/ha/yr	3.31	MJf/MJb	--	g e-CO2/MJ
Shirvani, et al. (2011)	30	wt %	75	t/ha/yr	22.50	t/ha/yr	3.22	MJf/MJb	85.00	g e-CO2/MJ	30	wt %	75	t/ha/yr	22.50	t/ha/yr	3.22	MJf/MJb	85.00	g e-CO2/MJ
Stephenson, et al. (2010)	40	wt %	40	t/ha/yr	250000	t/yr	200.00	GJ/t biodiesel	4 * 10^ (-3)	kg e-CO2/MJ	40	wt %	40	t/ha/yr	16.00	t/ha/yr	4.76	MJf/MJb	4.00	g e-CO2/MJ
Torres, et al. (2013)	50	wt %	30	g/m^2/day	40000	t/yr	--	--	--	--	50	wt %	90	t/ha/yr	45.00	t/ha/yr	--	MJf/MJb	--	g e-CO2/MJ
Ventura, et al. (2013)	30	wt %	1000	t/yr	178.00	t/yr	500.00	MWh/yr	663.00	t e-CO2/yr	30	wt %	--	t/ha/yr	--	t/ha/yr	--	MJf/MJb	--	g e-CO2/MJ
Zaimes, et al. (2013)	50	wt %	35	g/m^2/day	--	--	1.80	MJf/MJb	50.00	g e-CO2/MJ	50	wt %	105	t/ha/yr	--	t/ha/yr	1.80	MJf/MJb	50.00	g e-CO2/MJ

* Cells marked with '--' do not have enough data

5.3.1 Data Compilation and Conversion Description

The following section describes how the data compiled from Literature LCAs were converted into common units. The common units (/ha/yr and /MJ_b) were later chosen as the common functional units for the LCA framework.

The metrics used for data collection and analysis are:

- Lipid Content
- Algae Production
- Biodiesel Production
- Energy Balance Ratio (EBR)
- Global Warming Potential (GWP)

The LCA data was first compiled into a chart stating the original units. All data gaps in the literature LCAs were indicated using '—'. The original units were then analyzed to see whether they could be converted properly. There were cases where the units were not convertible based on available information within the LCA. For instance, if an original unit was t/yr and the total land area was not given, it could not be converted into t/ha/yr. Instances where data could not be converted are stated within each calculation section below.

5.3.2 Calculations for Converting Data to Common Units

5.3.2.1 Assumptions

1. One year has 300 production days unless otherwise stated.
2. Assume the Lower Heating Value of biodiesel is 42 MJ/kg.

5.3.2.2 Lipid Content Calculations

No calculations necessary

5.3.2.3 Algae Production Calculations

<u>Batan et al. (2010)</u>

AP_NEW = (AP_OLD kg/ha/yr) / (1000 kg/tonne)

Brentner et al. (2011)

(AP_NEW t/ha/yr) = (AP_OLD kg/m^3/yr) * (10000 m^3/ha) / (1000 kg/tonne)

Campbell et al. (2010); Frank et al. (2012); Hou et al. (2011); Khoo et al. (2011); Razon et al. (2011); Torres et al. (2013); Zaimes et al. (2013)

(AP_NEW t/ha/yr) = (AP_OLD g/m^2/day) * (10000 m^2/ha) * (300 days/year) / (1000 g/kg * 1000 kg/tonne)

Holma et al. (2013)

(AP_NEW t/ha/yr) = (AP_OLD t/80ha/yr) / (80 ha/ha)

Jorquera et al. (2010)

The data for algae production was stated in kg/yr and the total land area used was not stated. The value could not be converted into common units.

Ventura et al. (2013)

Data for algae production was stated in t/yr and the total land area used was not stated. The value could not be converted into common units.

Missing Data: Borkowski et al. (2013); O'Connell et al. (2013); Sander et al. (2013); Sevigne Itoiz et al. (2012)

5.3.2.4 Biodiesel Production

Batan et al. (2010)

(BP_NEW t/ha/yr) = (BP_OLD L/ha/yr) / (10000L/tonne)

Brentner et al (2011); Campbell et al. (2010); Khoo et al. (2011); Lardon et al. (2009); Sander et al. (2010); Sevigne Itoiz et al. (2012)

(BP_NEW t/ha/yr) = [(LC_NEW %) / (100%)]*[(AP_NEW t/ha/yr) * [(BP_OLD %) / (100 %)]

Borkowshi et al. 2013); Frank et al. (2012); Razon et al. (2011); Stephenson et al. (2010); Torres et al. (2013)

(BP_NEW t/ha/yr) = (AP_NEW t/ha/yr) * [(LC_NEW %) / (100%)]

Borkowski et al. (2013)

Data for biodiesel production could not be converted into t/ha/yr as the original units were stated in lb/lb-algae without information on algae production quantity, land area, and timeframe.

Jorquera et al. (2010)

Data for biodiesel production was originally stated in terms of barrels/yr without the cultivation land size and therefore cannot be converted into the unit t/ha/yr.

O'Connell et al. (2013); Ventura et al. (2013)

The biodiesel production data was originally stated as t/yr without information on the cultivation land size. Therefore, the data was unable to be converted into t/ha/yr units.

Missing Data: Azadi et al. (2013); Holma et al. (2013); Zaimes et al (2013

5.3.2.5 Energy Balance Ratio (EBR)

Brentner et al. (2011)

(EBR_NEW MJ_f/MJ_b) = (EBR_OLD MJ_f/10^4MJ_b) / (10^4 MJ_b/MJ_b)

Sevigne Itoiz et al. (2012)

(EBR_NEW MJ_f/MJ_b) = (EBR_OLD MJ_f/kg) / (42 $MJ_b/kg_{biodiesel}$)

Stephenson et al. (2010)

(EBR_NEW MJ_f/MJ_b) = (EBR_OLD $GJ_f/tonne_{biodiesel}$) * (1000 MJ_f/GJ_f) / [(1000 kg/tonne) * (42 MJb/$kg_{biodiesel}$)]

Frank et al. (2012)

Data for EBR is originally stated in terms of BTU/kg-lipid. The LHV was not stated, and when the assumed LHV was used to convert the kg-lipid into MJ_b, the result was an outlier to the other results. The original units were not able to be converted to MJ_f/MJ_b.

Jorquera et al. (2010)

The original data for EBR is stated as GJ/yr. Without knowing the biodiesel production per year, the EBR could not be converted into MJ_f/MJ_b.

O'Connell et al. (2013)

The EBR was originally stated as kWh/t-biodiesel. The LHV was not stated, and when the assumed LHV was used to convert the t-biodiesel into MJ_b, the result was an outlier to the other results. The original units were not able to be converted to MJ_f/MJ_b.

Ventura et al. (2013)

The EBR was originally stated as MWh/yr. The total biodiesel production for the year was not stated, and the original units were not able to be converted into MJ_f/MJ_b.

Missing Data: Campbell P.K. et al. (2010); Hou et al. (2011); Torres et al. (2013)

5.3.2.6 Global Warming Potential Calculations

Brentner et al. (2011)

(GWP_NEW g e-CO_2/MJ) = (GWP_OLD kg e-CO_2/10^4 MJ) * (1000 g/kg) / (10^4)

Frank et al. (2012)

(GWP_NEW g e-CO_2/MJ) = (GWP_OLD g e-CO_2/MMBTU-BD) / (1056 MJ/MMBTU)

Hou et al. (2011); Stephenson et al. (2010)

(GWP_NEW g e-CO_2/MJ) = (GWP_OLD kg e-CO_2/MJ) * (1000 g/kg)

Sander et al. (2010)

(GWP_NEW g e-CO_2/MJ) = (GWP_OLD kg e-CO_2/10000MJ) * (1000 g/kg) / (100000MJ/MJ)

O'Connell et al. (2013)

The GWP data was originally stated as kg e-CO_2/t-biodiesel. When converting to g e-CO_2/MJ_b, the LHV was not stated, and when the assumed LHV was used to convert the t-biodiesel into MJ_b, the result was an outlier to the other results. The original units were not able to be converted to g e-CO_2/MJ_b.

Sevigne Itoiz et al. (2012)

The GWP data was originally stated as kg e-CO_2/t-biodiesel. The LHV was not stated, and when the assumed LHV was used to convert the t-biodiesel into MJ_b, the result was an outlier to the other results. The original units were not able to be converted to g e-CO_2/MJ_b.

Ventura et al. (2013)

The original GWP data was stated in terms of t e-CO_2/yr. The total biodiesel production for the year and LHV of the fuel was not stated, and the conversion was not able to be completed.

Missing Data: Jorquera et al. (2010); Khoo et al. (2011); Lardon et al. (2009); Razon et al. (2011); Torres et al. (2013)

5.3.3 Issues Encountered Converting Units

There were issues encountered converting units from the original units in each individual LCA to the common units. The most common issue surrounded missing information about either land area or quantity.

The land area values are used for comparing production on a certain land area to other configurations and also other biofuel feedstocks. When a production level is showcased as quantity/timeframe without the land area, it does not indicate the true production rate.

For instances when the EBR and GWP are indicated /yr without the total biodiesel production /yr, the values cannot be converted into /MJ_b units. It is useful to know the energy required per production of each MJ biodiesel.

Also, there were data gaps within the LCAs with respect to the chosen metrics. Each LCA study chose its own metrics and scope. There were certain LCAs which were not able to be converted into the metrics defined for the LCA framework. Therefore, more data gaps were identified after the conversion process. The twenty initial LCAs chosen for analysis were then only producing 12-17 data points, except for lipid content.

5.3.4 Data Quality Discussion

Table 9 on the following page presents a qualitative assessment of the data quality characteristics of the utilized literature LCAs. As initially introduced, the characteristics were evaluated with respect to data completeness, data availability, and model flexibility. Studies that were deemed poor in these characteristics were identified after compiling and converting the LCA data for the defined metrics, and subsequently, poor studies were dropped from the upcoming benchmarking effort. Therefore, if the benchmarks were established through incorporating questionable study results, the proposed benchmarks would be suspect. For example, study Ventura, et al. (2013) in Table 9 is identified as having limited data, and therefore is dropped from algae production, biodiesel production, energy balance ratio, and global warming potential categories of the analysis.

Table 9: Assessment of Characteristics of Utilized Literature LCAs			
LCA	**Data Completeness**	**Data Availability**	**Model Flexibility**
Azadi, et al. (2013)	**	**	**
Batan, et al. (2010)	***	***	*
Borkowski, et al. (2013)	*	*	**
Brentner, et al. (2011)	***	***	**
Campbell, et al. (2010)	**	*	**
Frank, et al. (2012)	**	**	*
Holma, et al. (2013)	**	**	**
Hou, et al. (2011)	**	**	***
Jorquera, et al. (2010)	*	*	*
Khoo, et al. (2011)	**	**	**
Lardon, et al. (2009)	**	**	**
O'Connell, et al. (2013)	*	*	*
Razon, et al. (2011)	**	***	**
Sander, et al. (2010)	*	**	**
Sevigne Itoiz, et al. (2012)	*	**	**
Shirvani, et al. (2011)	***	***	**
Stephenson, et al. (2010)	***	***	**
Torres, et al. (2013)	*	*	**
Ventura, et al. (2013)	*	*	*
Zaimes, et al. (2013)	**	**	**
* - Poor ** - Moderate *** - Good			

5.3.5 Literature LCA Data Gap Analysis

The following section will discuss and analyze the data gaps discovered in the LCA literature data after converting to common units. The data gaps analysis can give insights into the quality of LCAs currently available, and further illustrate why an LCA framework would be beneficial to the microalgae biodiesel industry.

Figure 17-21 show the converted data, data gaps, and average values for each metric. A detailed discussion proceeds each graph.

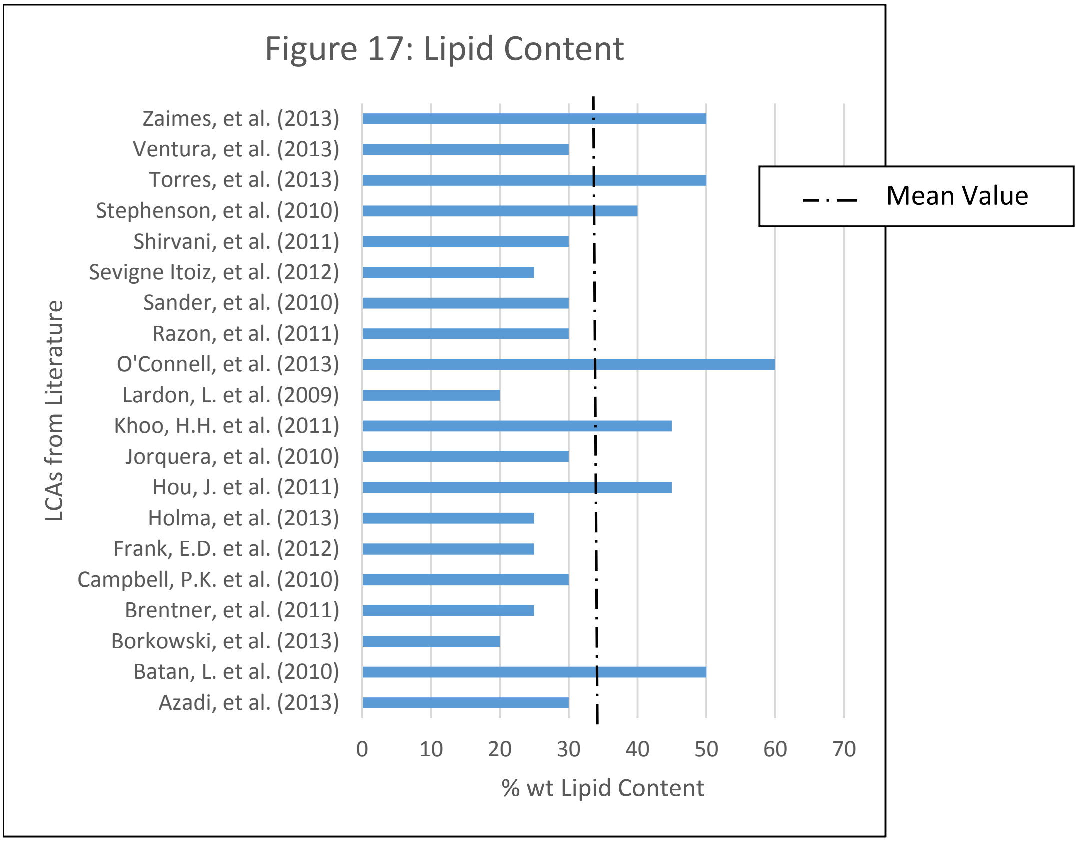


Figure 17: Lipid Content

Figure 17 above depicts the lipid content determined from 20 LCA studies. The average is 35% wt lipid content for dry algae. The values are within +/-15% wt lipid content relative to the average value, with the exception of O'Connell, et al. (2013). The lipid content variable is consistent across all 20 LCAs from literature, and there were no data gaps.

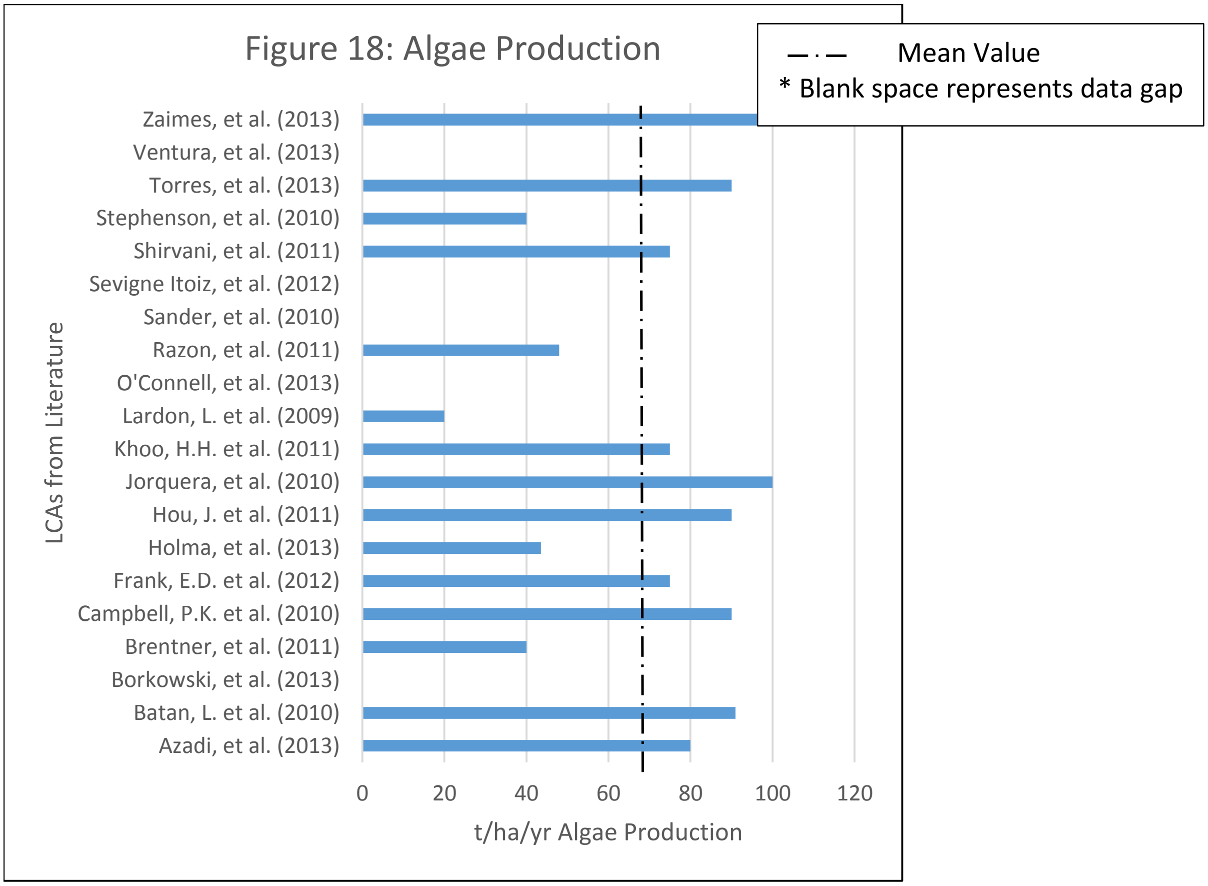


Figure 18: Algae Production

Figure 18 above depicts the algae production in terms of tonnes/hectare/year across 20 LCA studies. The average value for algae production is 70.8 t/ha/yr. The algae production values are not consistent from one LCA to another, and there is a wide deviation in algae production. Also, there are 5 studies which do not state the algae production value.

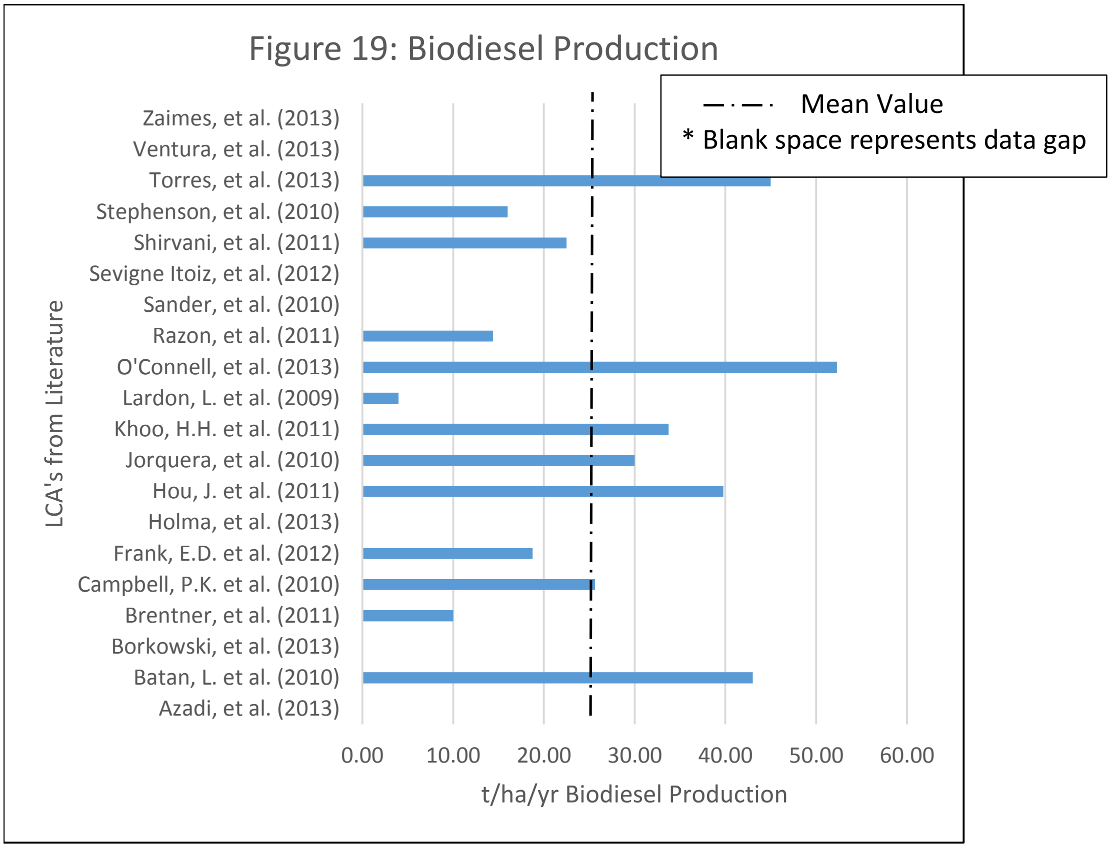


Figure 19: Biodiesel Production

Figure 19 above depicts the biodiesel production in terms of tonnes/hectare/year across 20 LCA studies. The average value for biodiesel production is 25.4 t/ha/yr. There is a wide deviation between values from one LCA to another, which is not unexpected when considering the wide deviation in algae production as well. Also, there are 7 LCAs without values for biodiesel production.

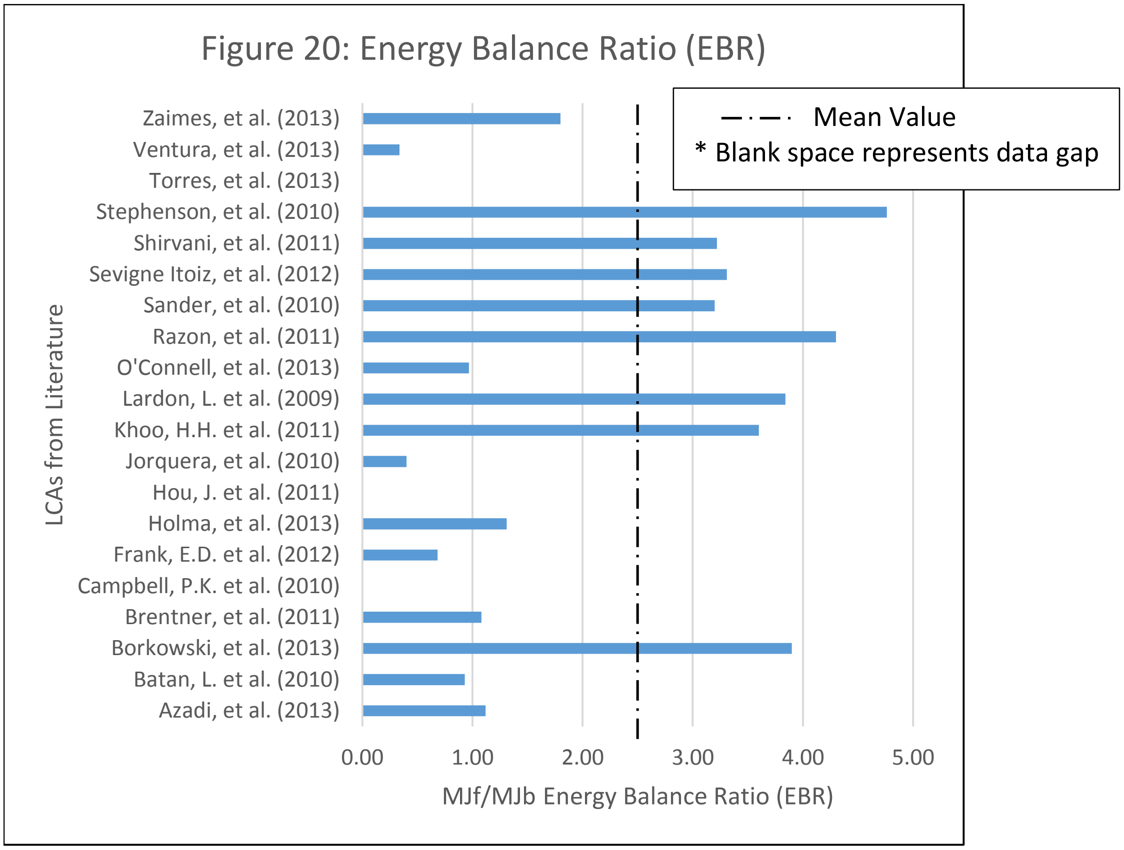


Figure 20: Energy Balance Ratio

Figure 20 above depicts the energy expenditure in terms of MJ fuel compared to MJ biodiesel, or MJ_f/MJ_b. The MJ fuel value would represent the energy required to create the biodiesel from cultivation to synthesis. The MJ biodiesel value is the energy inherent in the biodiesel for future use. The average value is 2.5 MJ_f/MJ_b and also has a wide deviation between LCAs. There are 3 LCAs without data for determining the energy balance ratio.

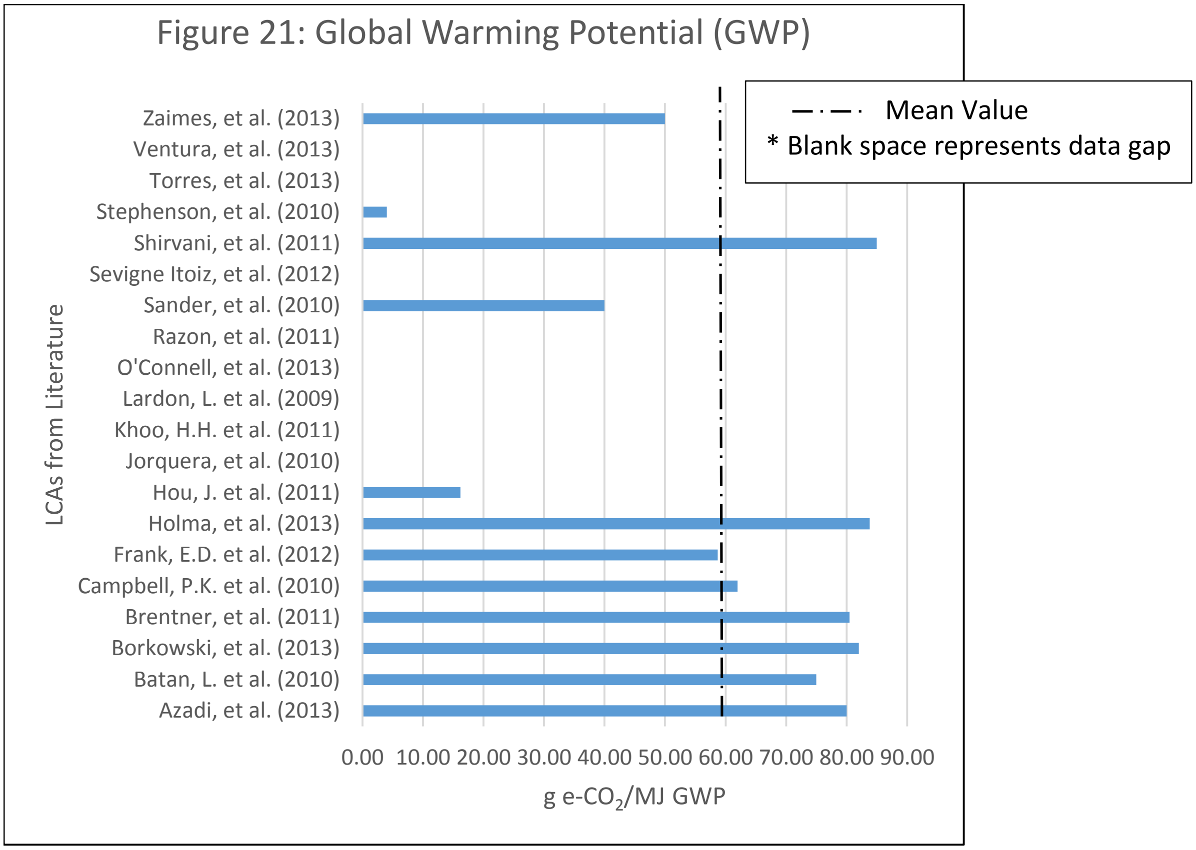


Figure 21: Global Warming Potential (GWP)

Figure 21 above depicts the Global Warming Potential in terms of g equivalent-CO_2/MJ across 20 LCA studies. The GWP has the most data gaps of all metrics because 8 LCAs lack sufficient data. The average GWP is 59.8 g e-CO_2/MJ, but has a deviation similar to previous metrics.

Table 10: Average and Standard Deviation of LCA Metrics from LCA Literature Data				
	Mean/Average		**Standard Deviation**	**Units**
Lipid Content	35	+/-	11.57	% wt
Algae Production	68.75	+/-	25.58	t/ha/yr
Biodiesel Production	22.74	+/-	15.04	t/ha/yr
Energy Balance Ratio (EBR)	2.80	+/-	1.36	MJ_f/MJ_b
Global Warming Potential (GWP)	59.77	+/-	27.44	g e-CO_2/MJ

Table 10 above summarizes the average and standard deviations for *Lipid Content, Algae Production, Biodiesel Production, Energy Balance Ratio, and Global Warming Potential*. The standard deviations are large relative to the average quantities. The lipid content standard deviation is one third the average value, while the standard deviation for energy balance ratio is three-fifths the average value. In relation to the other metrics, the lipid content is the most reliable. The biodiesel production value has the greatest range of published values compared to the other metrics. However, not all studies reported biodiesel production values, and the reasons for the widely varying values from studies that did report it could not be reconciled. Therefore, the values for biodiesel production and any analysis stemming from it carry the greatest uncertainty.

5.4 LCA Framework: Prioritized Focus

The LCA framework should focus on the most relevant, varying, and high impact areas in microalgae biodiesel design for it to be meaningful. Also, the parameters measured need to provide enough information and be realistically obtainable.

From the previous sections, the cultivation phase is the most transitory, and would need to maintain flexibility in LCA design. Pathways are to be designed to accommodate multiple technologies and newer technologies not invented yet for this life stage. The harvesting phase can be streamlined using fixed parameters. The extraction and synthesis phases can also be streamlined using fixed and common parameters.

The metrics to be measured with the LCA framework are:

- Dry algae production per hectare per year
- Biodiesel production per hectare per year
- Energy expenditure in relation to the energy inherent in the biodiesel produced
- Global Warming Potential for biodiesel production in relation to the energy inherent in the biodiesel produced

The LCA framework only considers the LCA phase of production, as it would focus primarily on the production of biodiesel and not its end use in vehicles. The end use has other challenges, and will be scoped out of this report.

5.5 LCA Framework: Definition of Functional Units

A meaningful LCA defines and uses a credible and realistic functional unit. Ideally, the most useful functional units are also implicitly understood by people who are familiar with the technology under investigation. Consequently, the LCA framework being developed in this research should also therefore establish an effective functional unit(s).

The functional units common and relevant to the microalgae biodiesel industry relates to: 1) the production per hectare per year; and 2) per MJ energy in the final biodiesel product. Two functional units were chosen as opposed to only one functional unit because it was deemed beneficial to analyze the industry from two different perspectives. The first perspective is in relation to a growth rate over a particular land area. The second perspective is in relation to the imbedded energy within the fuel. Together, the two functional units give a more complete picture of the microalgae biodiesel industry compared with only one functional unit. Each functional unit will be further described below.

Functional Unit: /ha/yr

The functional unit /ha/yr would be best for comparing the microalgae biodiesel production against other biofuel feedstocks. The land use is an important factor in determining the large scale agri-feedstocks' feasibility for the energy market.

Functional Unit: /$MJ_{biodiesel}$

The functional unit /$MJ_{biodiesel}$ would be best for comparing one configuration design with another for biodiesel production from microalgae. The Lower Heating Values would be within a reasonable range for meaningful comparison in terms of emissions, energy requirements, land use, water use, nutrient use, etc.

5.6 LCA Framework: Benchmarks

An LCA benchmark is a standardized metric base to compare and contrast similar designs. The benchmark acts like an anchor tying together independent assessments, and it allows for transparent and explicit comparisons.

Also, standardized benchmarks can prevent poor designs from receiving favourable ratings if such designs are compared to worst-case scenarios. At times, the worst case scenario are not explicitly stated as such, and the design can therefore appear to perform very effectively. With a standardized benchmark, or set of benchmarks, poor designs can be more easily identified.

The benchmarks were established by looking at the data gap analysis, data range, and data quality. It is marked where a benchmark value should be used with caution due to certain limiting factors. The decision matrix is shown in table 11 below.

Table 11: Decision Matrix for Benchmark Creation							
	AVG	Mode	25th Percentile	50th Percentile	75th Percentile	Benchmark	Units
Lipid Content	35	30	25	30	45	30	% wt
Algae Production	68.75	90	45	75	90	90	t/ha/yr
Biodiesel Production	22.74	#N/A	15.2	22.5	36.77	30	t/ha/yr
Energy Balance Ratio (EBR)	2.80	#N/A	1.31	3.22	3.84	3	MJ_f/MJ_b
Global Warming Potential (GWP)	59.77	#N/A	47.5	68.5	80.875	65	g e-CO_2 /MJ

The following calculations and reasoning were used to derive the LCA benchmark values:

Lipid Content = Mode_LC = 50th Percentile_LC

The Lipid Content is determined to be the mode value which is equal to the 50th percentile due to the narrow data range.

Algae Production = Mode_AP = 75thPercentile_AP

The mode value of 90 t/ha/yr for algae production repeats itself three times amongst fourteen LCAs. One other LCA has an algae production value of 91 t/ha/yr. The average value is significantly lower due to two outlier LCAs at 40 t/ha/yr.

Biodiesel Production = (50thPercentile_BP + 75thPercentile_BP)/2

The average value between the 50th percentile and the 75th percentile was chosen due to the wide range and low number of LCAs with viable data. The average value is significantly lower due to 5 LCAs below 20 t/ha/yr. Biodiesel production should be maximized, and so a higher benchmark based on the data would be appropriate. The benchmark for biodiesel production should therefore be used with caution.

Energy Balance Ratio = (Average_Value_EBR + 50thPercentile_GWP)/2

The average value between the overall average and the 50th percentile was chosen as a balance between factors. The 50th percentile value is the same as the median, and balancing the average and median would eliminate influence from outlier values. The sample size of viable data from the LCAs is low at 13, and the benchmark value should be used with caution.

Global Warming Potential = (Average_Value_GWP + 50thPercentile_GWP)/2

The average value between the average and the 50th percentile was chosen to balance between factors. The 50th percentile value is the same as the median, and balancing the average and median would eliminate influence from outlier values. The sample size of viable data from the LCAs is low at 12, and the benchmark value should be used with caution.

Table 12 below summarizes the configuration design and LCA metrics for the established benchmark.

Table 12: Benchmark - Based on Industry Trends and LCA Literature Data					
Configuration Design			**Benchmark LCA Metrics***		
Cultivation Phase	**Nutrient Source**	Fertilizer		**QTY**	**Units**
	Water Source	Freshwater	**Lipid Content**	30	% wt
	Carbon Dioxide Source	Factory Emissions	**Algae Production**	90	t/ha/yr
	Algae Strains	Non-GMO	**Biodiesel Production**	30	t/ha/yr
		Photoautotrophic	**Energy Balance Ratio (EBR)**	3	MJ_f/MJ_b
	Cultivation Site	Photobioreactors-Tubes	**Global Warming Potential (GWP)**	65	g e-CO_2/ MJ_b
	Electricity	US Energy Mix			
Harvesting Phase	**Harvesting Technique**	Flocculation			
	Electricity	US Energy Mix			
Extraction Phase	**Extraction Technique**	Hexane Solvent			
	Drying Technique	Mechanical Dryers			
	Electricity	US Energy Mix			
	Waste Product	Biogas			
Synthesis Phase	**Synthesis Technique**	Traditional Refinery			
	Transportation	Tanker Truck			
	Residual Materials	Biogas			
* LCA Metrics determined based on decision matrix					

5.7 LCA Framework: Process Flow Options for Configuration Design

As stated previously, the potential combinations in process configuration design are numerous, and also outputs widely different production levels. However, there are certain process step options which would negate the use of certain choices in other process steps. A configuration can be optimized for its location, facility size, resource availability, social conditions, etc., given the criteria relevant to the particular circumstance. The current LCA framework would then act as a base platform to include other levels of analysis.

Table 13 on the following page summarizes each potential option broken down into life stage and process step. Also, the default process options for the LCA framework are indicated in the chart.

Table 13: Process Flow Options for Configuration Design					
		Option 1 (Default)*	**Option 2***	**Option 3***	**Option 4***
Cultivation Phase	**Nutrient Source**	Fertilizer	Wastewater	Starchy By-products	--
	Water Source	Freshwater	Wastewater	Seawater	Brackish water
	Carbon Dioxide Source	Factory Emissions	Open to Air		
	Algae Strains	Non-GMO	GMO	--	--
		Photoautotrophic	Heterotrophic	Mixotrophic	--
	Cultivation Site	Photobioreactors: Tubes	Photobioreactors: Panels	Photobioreactors: Bags	Raceway Ponds
	Electricity	US Energy Mix	Renewable Energy Mix	Biogas Sourced Onsite	--
Harvesting Phase	**Harvesting Technique**	Flocculation	Centrifugation	Membrane Filtration	Additional Solids Separation
	Electricity	US Energy Mix	Renewable Energy Mix	Biogas Sourced Onsite	--
Extraction Phase	**Extraction Technique**	Hexane Solvent	Dry Extraction	Wet Extraction	--
	Drying Technique	Mechanical Dryers	Solar Dryers	--	--
	Electricity	US Energy Mix	Renewable Energy Mix	Biogas Sourced Onsite	--
	Waste Product	Biogas	Landfilled	Animal Feed	Plastics
Synthesis Phase	**Synthesis Technique**	Traditional Refinery	Transesterification	--	--
	Transportation	Tanker Truck	No Transportation - Onsite	--	--
	Residual Materials	Biogas	Landfilled	--	--

* Options can be combined and interchanged.
The default column represents framework default options.

5.8 LCA Framework: Default Case Configuration and Flowchart

The LCA Framework is developed to rapidly undertake an LCA using established benchmarks, functional units, default settings, and data acquisition rubric. Figure 22 illustrates the default case for the LCA framework. The default settings streamline the LCA analysis by requiring only differing elements to be altered and then incrementally analyzed when comparing one option against another. Also, default settings are provided for the system boundaries within a predefined LCA scope that will be appropriate to most users of the LCA framework.

The default settings were determined from the industry trends analysis, and the LCA literature data analysis. The names for processes and flows are chosen carefully to represent the *overall function the process has instead of a specific process design*. The four process life stages where the algae is transported and processed are:

- Growth Mode
- Harvesting Mode
- Extraction Mode
- Synthesis Mode

The life stages were previously referred to as phases and are now referred to as modes for modelling purposes. In figure 22 on the following page, the default case is shown pictorially. Each box represents a process, and each arrow represents a flow. The algae flows are highlighted by red dashed boxes.

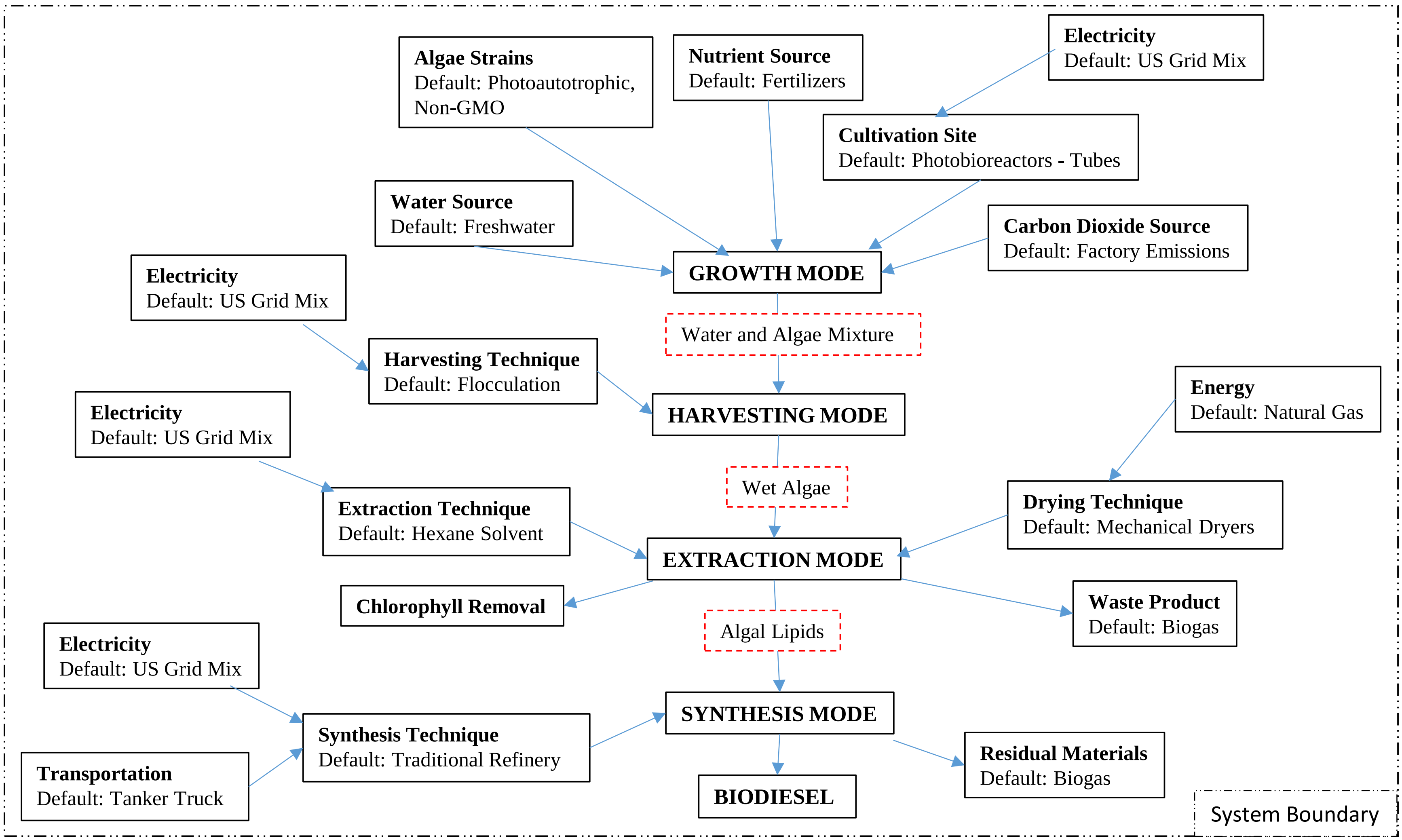


Figure 22: Process Flowchart for Default Case

5.8.1 Default Case: Growth Mode

The Growth Mode represents the cultivation phase of the design configuration. The cultivation phase has the greatest diversity, and yet the general flows are similar. The growth mode requires the following input flows:

- Water Source
- Algae Source
- Nutrient Source
- Cultivation Site
  - Electricity
- Carbon Dioxide Source

The defaults settings are chosen based on industry trends, and are shown in figure 22. The algae source represents the algae strain and whether it is a GMO or not. The nutrient source can be partially contributed by the water source if wastewater is chosen. The quantities within the nutrient source can be altered for different configuration designs. The cultivation site consists of the hardware used for growing the algae, whether it is a raceway pond or photobioreactors. Both raceway ponds and photobioreactors require production materials and electricity. The flow values can be changed for different configuration designs, but the process name can be the same. The carbon dioxide source can be deliberate or not, and the flow value can be changed accordingly. Algae and Water Mixture flows from the Growth Mode to the Harvesting Mode.

5.8.2 Default Case: Harvesting Mode

The Harvesting Mode represents the harvesting phase of the design configuration. The harvesting phase requires the following input flows:

- Harvesting Technique
  - Electricity

The Harvesting Technique represents whatever technique is used to harvest the algae. The two techniques common are flocculation and centrifugation. Both techniques require electricity, while certain flocculation techniques may require salt.

The default setting for the Harvesting Technique is flocculation. Flocculation was shown to be the most common technique used in industry at this time. The Electricity default setting is for a US Energy Mix. Wet Algae flows from the Harvesting Mode to the Extraction Mode.

5.8.3 Default Case: Extraction Mode

The Extraction Mode represents the extraction phase of the design configuration. The extraction phase requires the following input flows, other than the algae:

- Extraction Technique
  - Electricity
- Drying Technique
  - Energy Source

The Extraction Technique represents the method used for extracting the lipids from the algae. The default extraction technique is hexane extraction and requires electricity. The default setting for electricity is a US energy mix.

The extraction phase also has the following output flows:

- Chlorophyll Removal
- Waste Products

The waste products can be landfilled or utilized as a by-product source or biogas source. The default setting for the waste products is biogas. The biogas option would generate electricity and result in energy credits for the overall system. The Algal Lipids flow from the Extraction Mode to the Synthesis Mode.

5.8.4 Default Case: Synthesis Mode

The Synthesis Mode represents the synthesis phase of the design configuration. The synthesis phase requires the following input flows:

- Synthesis Technique
  - Transportation
  - Electricity

From the industry trends analysis, the synthesis technique is balanced 50/50 between transesterification on-site and transporting the lipids to a traditional refinery for synthesis. The default case was chosen to be the traditional refinery route. The traditional refinery route requires the lipids to be transported, while transesterification does not. If the option is different than the default case, the transportation flow value can be set to zero.

The synthesis phase also has the following output flows:

- Residual Materials

The residual materials from the synthesis phase is converted into biogas for electricity generation for the default case.

5.8.5 Default Case: Overcoming Past Obstacles

The default case represents the system boundaries and LCA scope. Processes outside of the system boundaries and LCA scope would not be included in the analysis. This would overcome the past obstacle of LCAs not measuring the same depth of information and the corresponding disparate outcomes.

The default case also represents the most common industry trends. If a configuration is analyzed using the framework, it is likely more than one process and flow will be in common with the LCA framework default case and would not require alterations beyond adjusting the parameters to match the available data. The time and effort to undertake an LCA would be reduced, which would address tight time constraints to perform sustainability analysis in a rapidly evolving industry.

In the GaBi section of the report, another flowchart is shown for the default case using GaBi's plan setup. The LCA framework will further be discussed and developed in the GaBi section of the report.

5.9 LCA Framework: Data Acquisition Rubric

A data acquisition rubric - shown in Table 14 for this research - outlines the parameters for acquiring the data measurements for LCA development. When comparable data is measured similarly, the comparison and outcomes between alternative scenarios become more reliable. Any values which cannot be measured can be substituted with engineering estimates.

The data acquisition rubric also explicitly outlines the LCA scope and boundaries for the LCA practitioner. Not all fields may be applicable to an individual configuration, which the rubric would showcase. Also, new fields may need to be added as the industry is complex and new systems are developed rapidly. The rubric is a base to build upon, and changes as new LCAs are developed using the LCA framework. However, any changes to the rubric must still be in line with the LCA scope and boundaries if the analysis is to remain relevant.

Table 14: Data Acquisition Rubric

Parameter		
Cultivation Phase	Growth Mode	
	GMO/Non-GMO	
	Algae Strain	
	Cultivation Site	
	CO2 source	
	Nutrient source	
	Water source	
Harvesting Phase	Harvesting Technique	
Extraction Phase	Dryer	
	Extraction Technique	
	Solvent	
Synthesis Phase	Transesterification (Y/N)	
	Traditional Refinery (Y/N)	
	Transportation Method	
	Synthesis Technique	
Waste Product	Disposal (Y/N)	
	By-Products (Y/N)	
	Byproduct industry	

Parameter		QTY	Units
Cultivation Phase	Photosynthetic area		ha
	Microalgae biomass yield		t/ha/yr
	CO2 consumption		t/ha/yr
	Water delivery and storage		MJ/ha/yr
	Gas delivery		MJ/ha/yr
	Paddle wheel operation		MJ/ha/yr
	Water pumping to harvesting		MJ/ha/yr
	Construction materials		MJ/ha/yr
	Water use		t/ha/yr
	Nutrients		t/ha/yr
Harvesting Phase	Wet Algae yield		t/ha/yr
	Harvesting processes operation		MJ/ha/yr
	Flocculant production		MJ/ha/yr
Extraction Phase	Extracted oil yield		t/ha/yr
	Electricity		MJ/ha/yr
	Heat production		MJ/ha/yr
	Solvent production		MJ/ha/yr
	Conversion processes		MJ/ha/yr
Synthesis Phase	Biodiesel yield		t/ha/yr
	Esterification		MJ/ha/yr
	Equipment materials		MJ/ha/yr
	Transportation		kg/ha/yr
Waste Products	Waste products yield		t/ha/yr
	Landfilling/spreading		MJ/ha/yr
	anaerobic biodigestion		MJ/ha/yr
	water treatment		MJ/ha/yr
	nutrients credit		MJ/ha/yr
	Energy credit		MJ/ha/yr

5.10 LCA Framework: Development Using GaBi

GaBi is an industry leading LCA software model that is used widely for undertaking LCAs on a variety of products and processes. GaBi uses a *plan, process, and flow* structure. A plan is the frame the system is built upon, the processes are the boxes, and the flows connect the processes together. Within the process database, parameters are used to create formulas for ease of data input. The procedure for testing the case studies in GaBi is presented in the methodology section of the report. Figure 23 below depicts the default case as generated in GaBi.

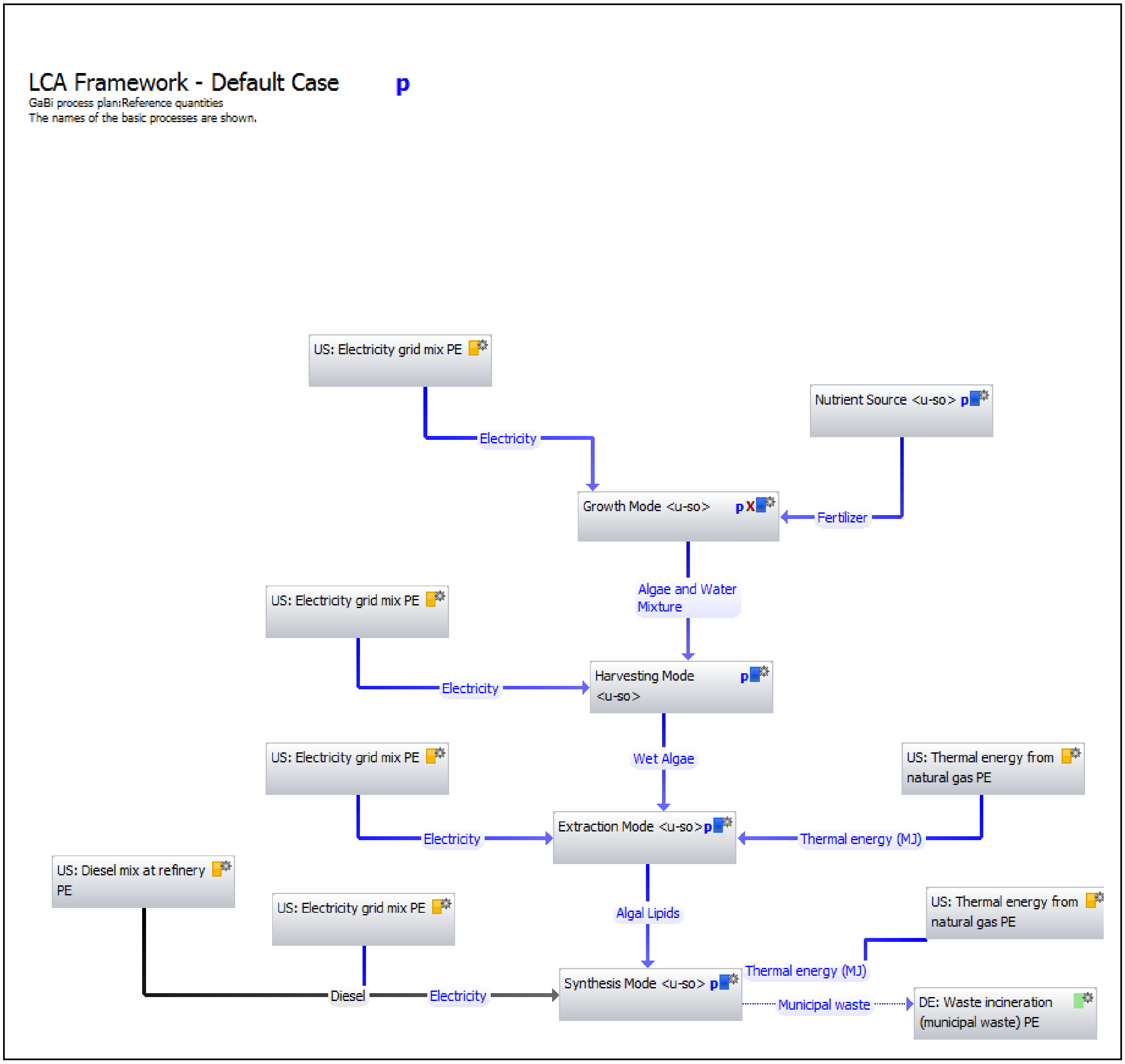


Figure 23: GaBi Default LCA Framework Flowchart

5.11 LCA Framework: Test Framework Using Case Studies

The following section tests the LCA framework using GaBi via two case studies from the LCA literature in order to validate the LCA framework, approach, and default parameters. The case studies are outlined in Appendices A and B. The case studies were chosen based on completeness of datasets, well-described methodology, and convertible metrics and functional units. The case studies also have results for the five metrics measured with the LCA framework. If the framework functions as designed, then the output from the LCA should, in theory, match what the case studies in the literature have already determined. An exact match cannot be expected, nor does a discrepancy necessarily disprove the LCA framework, assuming the published case studies are "correct". However, should results from the developed framework approximate those of the published results, then there is reasonable assurance that the framework is functional.

5.11.1 Case Study #1

Case study #1 presented in Appendix A has two scenarios to test, a base-case scenario and a best-case scenario. The two scenarios are outlined in Appendix A. The base-case scenario as defined by Brentner, L. et al. (2011) consists of a design configuration resulting in low biodiesel production and high energy balance ratio. The best-case scenario as defined by Brentner, L. et al. (2011) consists of a design configuration resulting in highest biodiesel production and lowest energy balance ratio. The base-case and best-case scenarios were chosen based on their contrasting values. Without a benchmark for comparison, the outcomes are not necessarily meaningful for decision making, particularly if comparing the results against the results from other configurations.

The first task for using the LCA framework is to complete the data acquisition rubric. The rubric is not complete for Case #1 base case and best case scenarios because the rubric contains more elements and was developed from a larger dataset. There are data and information gaps in the case study, which the data acquisition rubric also exposes.

Table 15 on the following page is the data acquisition rubric for the Case #1 base case scenario. The rubric is followed by figure 24, the LCA framework flowchart in GaBi for Case #1 base case scenario.

Table 15: Data Acquisition Rubric - Case #1: Base Case Scenario

Parameter			Parameter		QTY	Units
Cultivation Phase	Growth Mode	Photoautotrophic	Cultivation Phase	Photosynthetic area		ha
	GMO/Non-GMO	Non-GMO		Microalgae biomass yield	--	--
	Algae Strain	--		CO2 consumption	--	--
	Cultivation Site	Raceway Ponds		Water delivery and storage	690	MJ
	CO2 source	--		Gas delivery	720	MJ
	Nutrient source	--		Paddle wheel operation	4770	MJ
	Water source	--		Water pumping to harvesting	2810	MJ
Harvesting Phase	Harvesting Technique	Centrifugation		Construction materials	760	MJ
Extraction Phase	Dryer	Mechanical		Water use	1210	m^3
	Extraction Technique	Solvent		Nutrients	--	--
	Solvent	Hexane	Harvesting Phase	Wet Algae yield	--	--
Synthesis Phase	Transesterification (Y/N)	Y		Harvesting processes operation	32000	MJ
	Traditional Refinery (Y/N)	N		Flocculant production	--	--
	Transportation Method	--	Extraction Phase	Extracted oil yield	--	--
	Synthesis Technique	Basic		Electricity	760	MJ
Waste Product	Disposal (Y/N)	Y - Landfill		Heat production	27590	MJ
	By-Products (Y/N)	N		Solvent production	190	MJ
	Byproduct industry	--		Conversion processes	--	--
			Synthesis Phase	Biodiesel yield	--	--
				Esterification	1060	MJ
				Equipment materials	220	MJ
				Transportation	--	--
			Waste Products	Waste products yield	--	--
				Landfilling/spreading	820	MJ
				anaerobic biodigestion	--	--
				water treatment	--	--
				nutrients credit	0	MJ
				Energy credit	0	MJ

Figure 24 below is a screenshot of the flowchart for the base case scenario for Case #1. The flowchart differs from the default case because there is no incineration process for the waste products in Case #1, and no transportation to an offsite refinery. All parameters are updated according to data compiled in the data acquisition rubric.

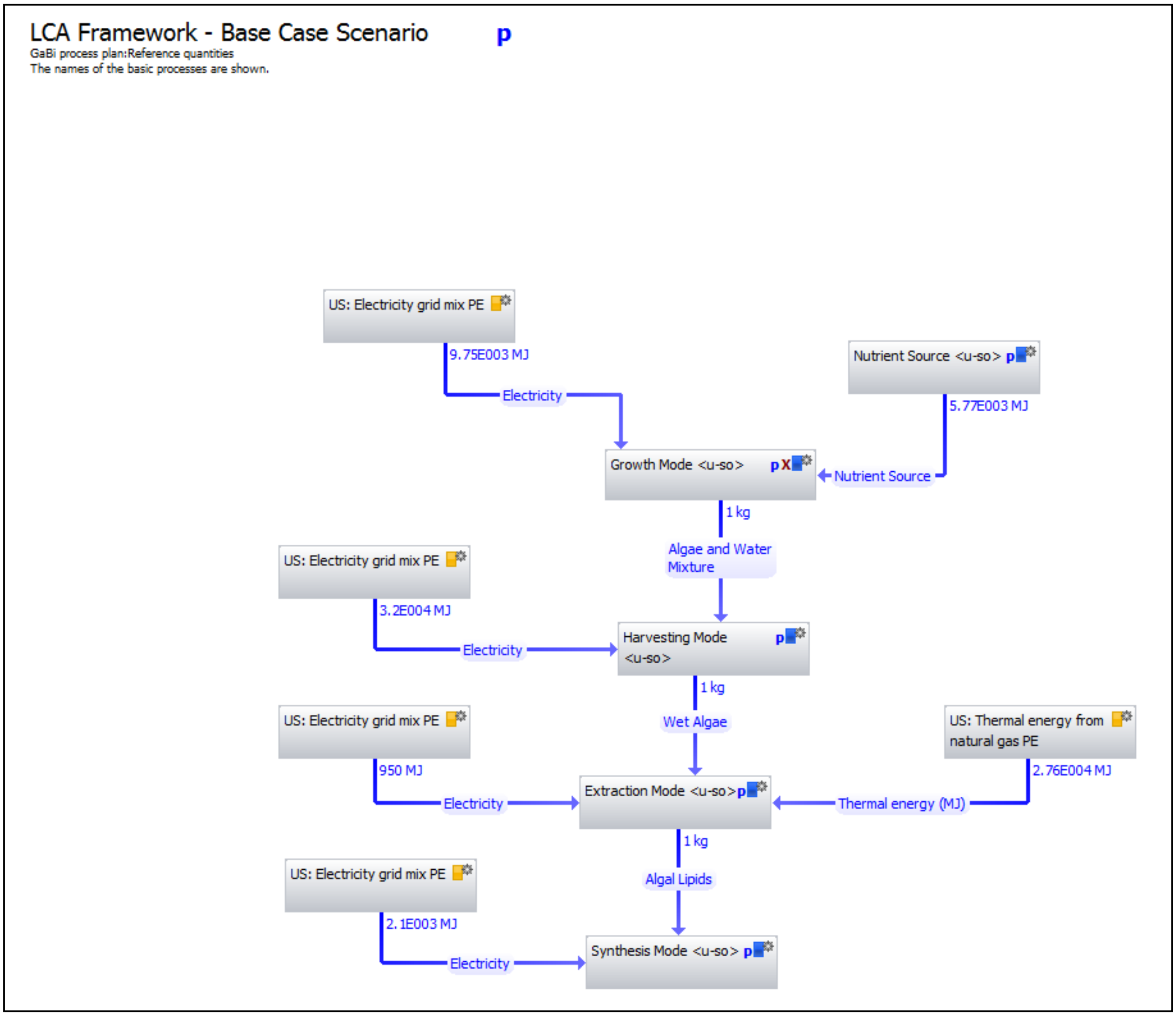


Figure 24 Case #1 Base Case Scenario Framework

Table 16 on the following page is the data acquisition rubric for Case #1 best case scenario.

Table 16: Data Acquisition Rubric - Case #1: Best Case Scenario

Parameter		
Cultivation Phase	Growth Mode	Photoautotrophic
	GMO/Non-GMO	Non-GMO
	Algae Strain	--
	Cultivation Site	Flat Plate PBR
	CO2 source	--
	Nutrient source	--
	Water source	
Harvesting Phase	Harvesting Technique	Flocculation
Extraction Phase	Dryer	--
	Extraction Technique	Wet Algae
	Solvent	--
Synthesis	Transesterification (Y/N)	Y
	Traditional Refinery (Y/N)	N
	Transportation Method	--
	Synthesis Technique	Supercritical
Waste Product	Disposal (Y/N)	Y
	By-Products (Y/N)	Y
	Byproduct industry	Bioincineration

Parameter		QTY	Units
Cultivation Phase	Photosynthetic area		--
	Microalgae biomass yield	--	--
	CO2 consumption	--	--
	Water delivery and storage	350	MJ
	Gas delivery	6620	MJ
	Paddle wheel operation	--	--
	Water pumping to harvesting	350	MJ
	Construction materials	990	MJ
	Water use	625	m^3
	Nutrients	--	--
Harvesting Phase	Wet Algae yield	--	--
	Harvesting processes operation	360	MJ
	Flocculant production	170	MJ
Extraction Phase	Extracted oil yield	--	--
	Electricity	1800	MJ
	Heat production	2070	MJ
	Solvent production	--	--
	Conversion processes	--	--
Synthesis Phase	Biodiesel yield	--	--
	Esterification	1060	MJ
	Equipment materials	--	--
	Transportation	--	--
Waste Products	Waste products yield	--	--
	Landfilling/spreading	190	MJ
	anaerobic biodigestion	2280	MJ
	water treatment	780	MJ
	nutrients credit	-4200	MJ
	Energy credit	-7770	MJ

Figure 25 below is a screenshot of the flowchart for the best case scenario from Case #1. The flowchart for the best case scenario differs from the default case flowchart by no transportation to an offsite refinery. All parameters are updated according to data compiled in the data acquisition rubric

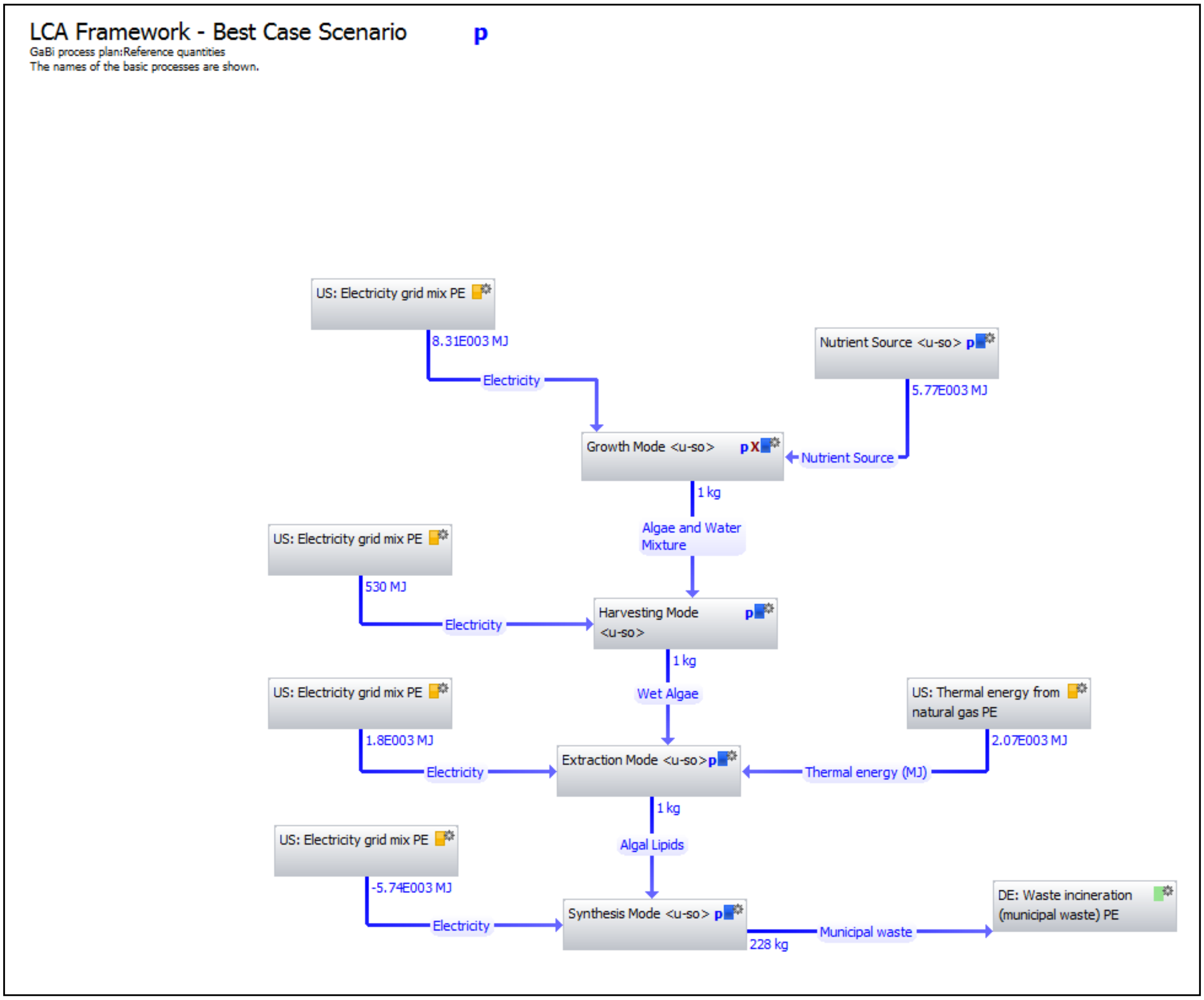


Figure 25 Case #1 Best Case Scenario Flowchart

A summary table for Case #1 base case and best case scenario data as tested in GaBi using the LCA framework as shown in table 17 below. Also, the table compares the original values determined in the literature LCA and the GaBi results. The GaBi raw data results can be found in Appendix C.

Table 17: Comparison Between Original and GaBi Results: Case #1					
Case Study	Scenario	Cumulative Energy Demand (MJ_{eq})	Global Warming Potential (g e-CO_2)/MJ_b	Energy Balance Ratio (MJ_f/MJ_b)	Lipid Content (% wt)
Case #1	Base Case - Original	78200	534	7.82	25
	Base Case - GaBi	78372.60	796.60	7.84	25
	Best Case - Original	10800	80.5	1.08	25
	Best Case - GaBi	10649.91	121.00	1.06	25

For the Global Warming Potential (GWP), the GaBi results are overestimated for both the base case and the best case shown in figure 26. The discrepancy could result from different energy mix data sets, incomplete data sets, or different assumptions. However, given the uncertainties using varied LCA data from the literature, the GaBi global warming potential values are reasonably similar to the original LCA.

The GWP analysis illustrates the need for a benchmark. For any configuration, the lower the GWP, the more preferred it is for its lower contribution to greenhouse gases. In Figure 26, the base case (either original analysis or GaBi analysis) presents significant GWP impacts; in the best case, (either original analysis or GaBi analysis), the configuration presents significantly lower GWP impacts, although it does not meet the proposed benchmark, uncertainties in benchmark development notwithstanding. What this suggests then is that the biodiesel production configuration used in Case Study #1 needs to *operate at or better than the best case scenario* in order to achieve the benchmark environmental performance, and that challenges that prevent this configuration from doing so (i.e., only operate at the base case) should be addressed.

The Cumulative Energy Demand and Energy Balance Ratio results are in line for the original dataset and GaBi as shown in figures 27 and 28, respectively. The LCA framework using GaBi was able to replicate the results with respect to the cumulative energy demand and energy balance ratio. The lipid content is graphed in figure 29 to visually show how the value compares to the benchmark developed in section 5.5.

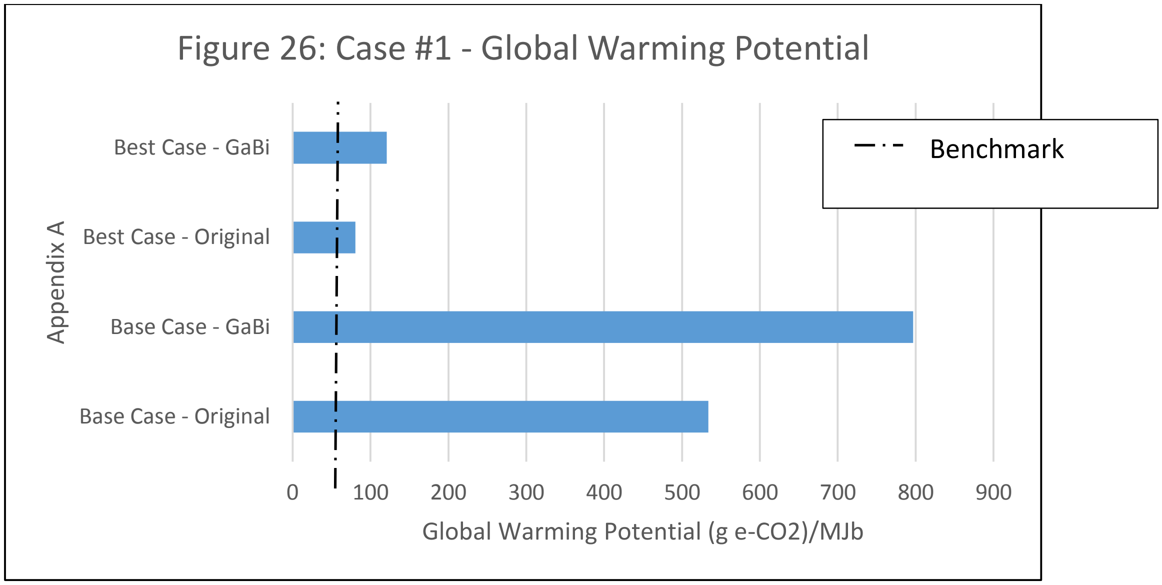


Figure 26 Case #1 Global Warming Potential

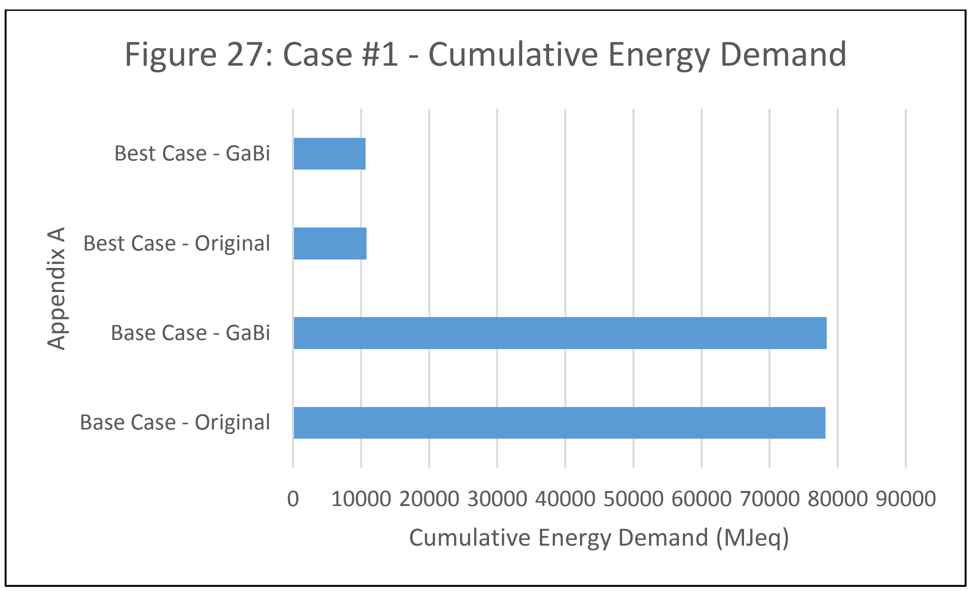


Figure 27 Case #1 Cumulative Energy Demand

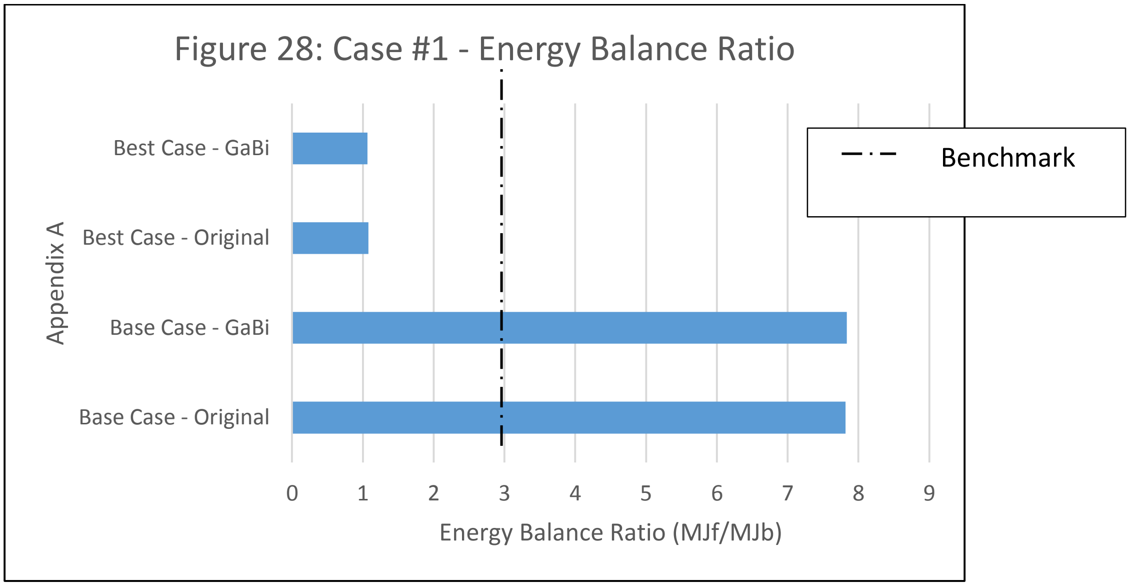


Figure 28 Case #1 Energy Balance Ratio

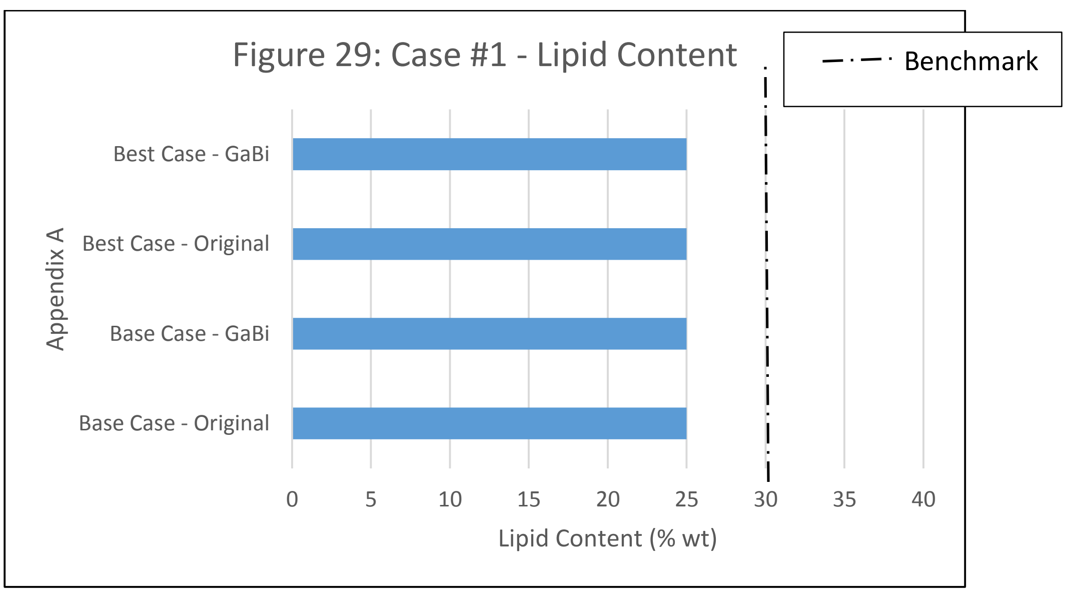


Figure 29 Case #1 Lipid Content

5.11.2 Case Study #2

Case study #2 presented in Appendix B has one scenario to test. The scenario as defined by Batan et al. (2010) consists of photobioreactors, photoautotrophic microalgae, centrifugation, hexane extraction, and offsite refinery. The case study uses the GREET model as described in the literature review.

The first task for using the LCA framework is to fill in the data acquisition rubric. The rubric, shown in Table 18, is not complete for Case # 2 because the rubric was developed from a larger dataset and contains more data elements. There are data and information gaps in the case study, which the data acquisition rubric also exposes. Figure 30 illustrates the LCA framework flowchart in GaBi for Case #2 scenario.

Table 18: Data Acquisition Rubric - Case #2

Parameter		
Cultivation Phase	Growth Mode	Photoautotrophic
	GMO/Non-GMO	Non-GMO
	Algae Strain	*Nannochloropsis salina*
	Cultivation Site	Open Pond
	CO2 source	--
	Nutrient source	Fertilizer
	Water source	freshwater
Harvesting Phase	Harvesting Technique	Centrifugation
Extraction Phase	Dryer	mechanical
	Extraction Technique	solvent
	Solvent	hexane
Synthesis	Transesterification (Y/N)	Y
	Traditional Refinery (Y/N)	N
	Transportation Method	Truck
	Synthesis Technique	--
Waste Product	Disposal (Y/N)	Y
	By-Products (Y/N)	N
	Byproduct industry	--

Parameter		QTY	Units
Cultivation Phase	Photosynthetic area	--	ha
	Microalgae biomass yield	91000	kg/ha/yr
	CO2 consumption	--	--
	Water delivery and storage	--	--
	Gas delivery	--	--
	Paddle wheel operation	41404	kWh/ha/yr
	Water pumping to harvesting	--	--
	Construction materials	--	--
	Water use	--	--
	Nutrients	167	g/kg dryalgae
Harvesting Phase	Wet Algae yield	--	--
	Harvesting processes operation	30788	kWh/ha/yr
	Flocculant production	--	--
Extraction Phase	Extracted oil yield	43009	L/ha/yr
	Electricity	12706	kWh/ha/yr
	Heat production (natural gas)	141994	MJ/ha/yr
	Solvent production	--	--
	Conversion processes	--	--
Synthesis Phase	Biodiesel yield	43009	L/ha/yr
	Natural Gas	2.1	MJ/kg biodiesel
	Methanol	0.1	g/kg biodiesel
	Esterification	0.03	kWh/kg biodiesel
	Equipment materials		
	Transportation	0.0094	L/kg biodiesel
Waste Products	Waste products yield	--	--
	Landfilling/spreading	--	--
	anaerobic biodigestion	--	--
	water treatment	--	--
	nutrients credit	--	--
	Energy credit	--	--

Figure 30 below is a screenshot of the flowchart for Case #2. The flowchart for Case #2 differs from the default case by the exclusion of 'incineration of waste products' as it is not applicable to Case #2. All parameters are updated according to data compiled in the data acquisition rubric.

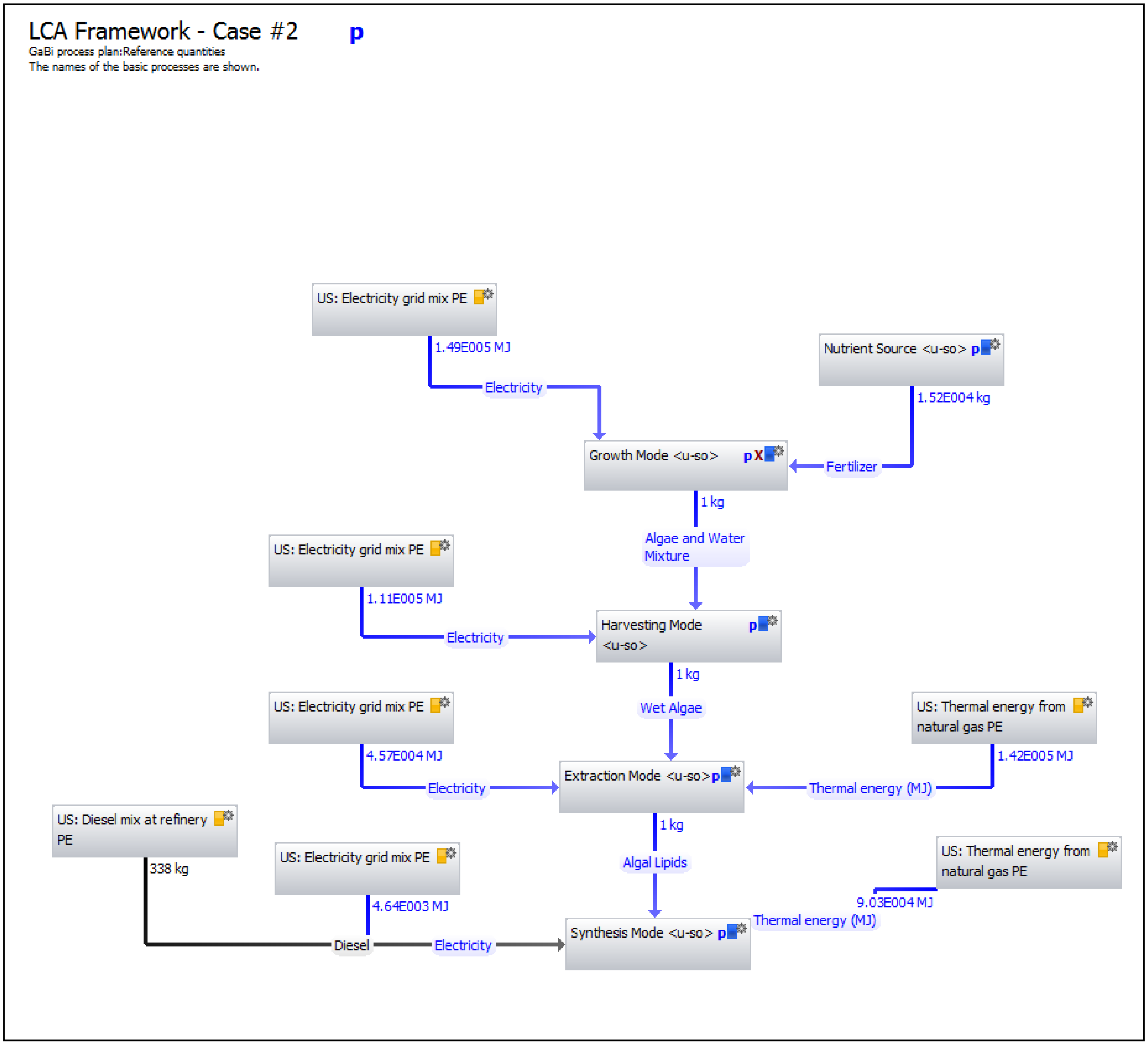


Figure 30 Case #2 Flowchart

A summary table for Case #2 case study data as tested in GaBi is shown in table 19 below. Also, the table compares the original values determined in the literature LCA and the results from GaBi. The GaBi raw data results can be found in Appendix D.

Table 19: Comparison Between Original and GaBi Results - Case #2						
Case Study	**Scenario**	**Cumulative Energy Demand (MJ_{eq}/ha/yr)**	**Global Warming Potential (g e-CO_2/MJ_b)**	**Energy Balance Ratio (MJ_f/MJ_b)**	**Lipid Content (% wt)**
Case #2	Base Case - Original	1679580	75	0.93	50
	Base Case - GaBi	1239254	39.08	0.69	50

For the case study presented in Case #2, the LCA framework using GaBi underestimated the global warming potential, cumulative energy demand, and energy balance ratio as shown in figures 31, 32, and 33 below, respectively.

GaBi underestimated the cumulative energy demand by 26%. The cumulative energy demand value is used to derive the energy balance ratio; therefore the EBR is also underestimated. The global warming potential value for Gabi is underestimated by 48%.

The underestimation could indicate insufficient data, different energy mix data sets in GaBi versus the original case study analysis, or that different assumptions were used. There is not enough information to reproduce the LCA for Case #2 using GaBi. Finally, the underestimation may not represent a flaw in the proposed LCA framework, but may be due to the limitations of GREET as previously described in the literature review.

In practically all instances, the configuration for biodiesel production in Case Study #2 betters the benchmark for all proposed parameters. Interestingly, the underestimation does "improve" the configuration's performance, but the original study already showed the configuration was already superior to the benchmark in most instances. The output from the LCA framework is consistent in terms of its trends compared to what was concluded in the original study; the LCA framework is not outputting contrary results. Assuming the original study was not flawed significantly, this suggests that the LCA framework is functioning as intended.

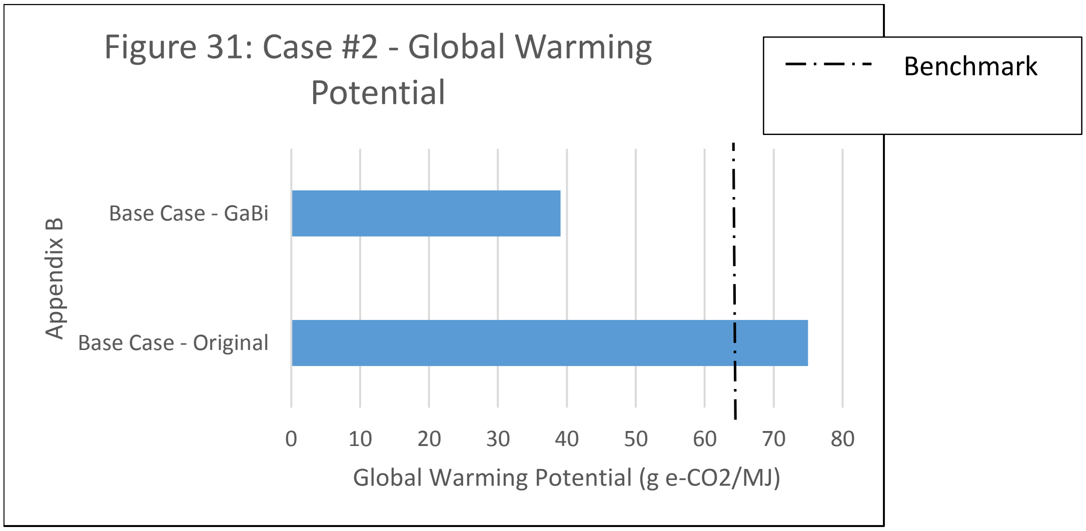


Figure 31 Case #2 Global Warming Potential

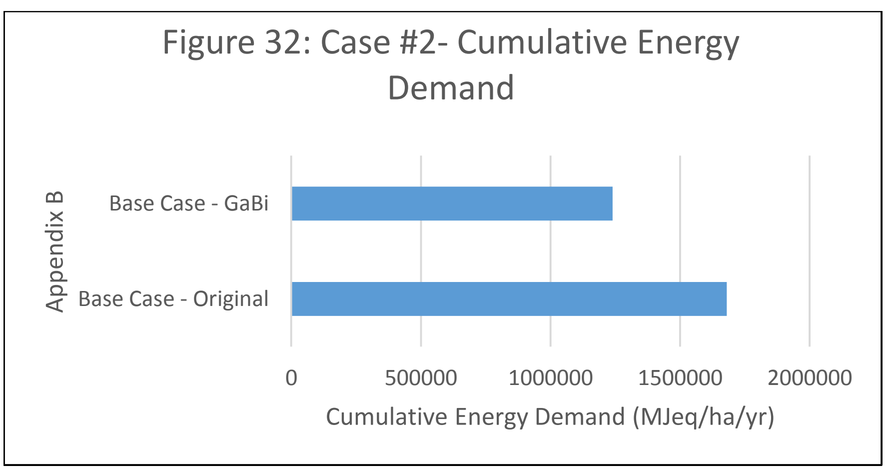


Figure 32 Case #2 Cumulative Energy Demand

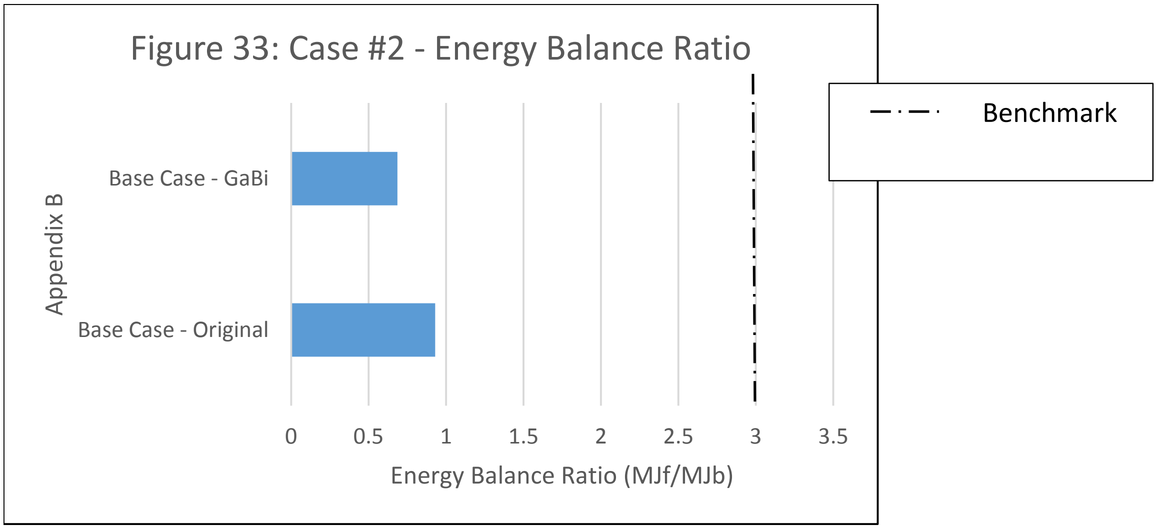


Figure 33 Case #2 Energy Balance Ratio

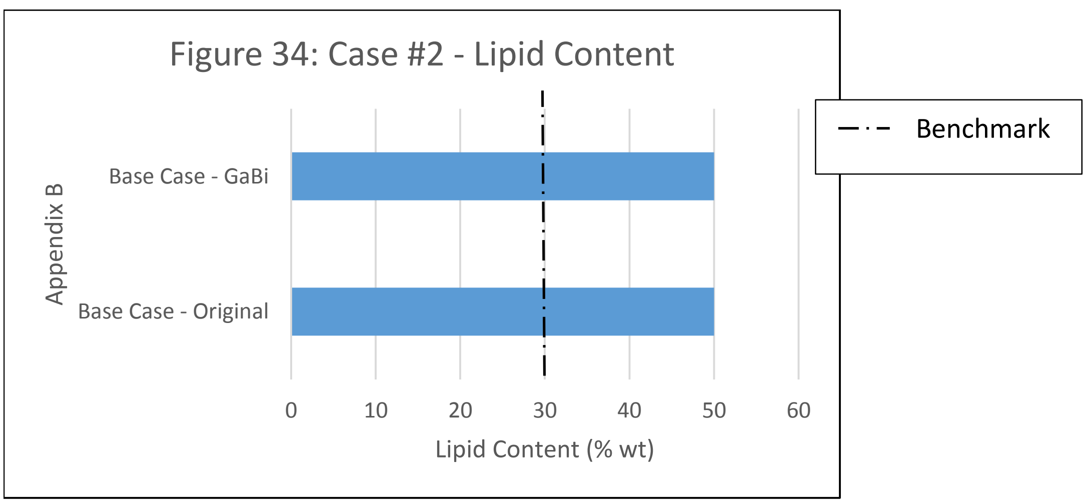


Figure 34 Case #2 Lipid Content

6.0 CONCLUSIONS

An LCA framework was developed for the microalgae biodiesel industry based on industry and literature data and configuration designs. This framework would establish a template for conducting LCAs within this industry by establishing common, default guidelines and parameters to conduct an LCA. The industry trends in configuration design were coupled with LCA data sets from literature to create a default case and benchmark for the industry. GaBi was used to test the LCA framework against two case studies.

The LCA framework focused on the *well-to-wheels* flow of energy and materials, and not the microalgae biodiesel end use. The metrics measured were dry algae production, biodiesel production, energy balance ratio, and global warming potential. Future metrics measured by the LCA framework would include economics, biosecurity risks, and human toxicity potential.

Data quality and reliability were analyzed and data gaps were identified. There are discrepancies within the literature and the disparate results are difficult to compare. Each LCA assumed its own metrics and scope of study, and certain metrics were not able to be converted into the metrics defined by the LCA framework. Data variability with respect to biodiesel production was the highest, while lipid content was the lowest.

A benchmark is useful for comparing the LCA analysis of different biodiesel production configurations. All future LCAs could be compared to the one set of benchmarks instead of each LCA practitioner choosing their own benchmark or baseline case for their investigation. A benchmark would further increase transparency for LCAs' results for the microalgae biodiesel industry. Benchmarks were developed for lipid content (30 wt %), algae production (90 t/ha/yr), biodiesel production (30 t/ha/yr), energy balance ratio (3 MJ_f/MJ_b), and global warming potential (65 g e-CO_2/MJ_b). The data available for determining the benchmark for each metric was considerably limited, compounded by wide variances within the data; therefore the benchmarks should be used with caution until more data points are established and the proposed benchmarks are more robustly defined.

The LCA framework established functional units to compare system designs within the industry. These functional units also allowed for explicit comparisons between biofuels, bio-feedstocks, and traditional fuels. An *energy density comparison* is used as each fuel has a different lower heating value, while an *energy balance ratio* provides more information than other metrics.

A data acquisition rubric is essential for the LCA framework to be used efficiently and appropriately. Future work would involve improving the data acquisition rubric by developing a user guide that would provide recommendations for measurement devices, units, and metrics.

The LCA framework developed was shown to be feasible for assessing the eco-efficiency performance for the microalgae biodiesel industry while still maintaining flexibility for handling the variability and complexity inherent in the industry. The framework was tested using the data of two different case studies to demonstrate that it could reproduce the major outcomes and findings from the original studies. Assuming the original studies were not inherently flawed, the LCA framework was able to achieve reasonably consistent outcomes compared to the original findings, thus validating the general robustness and applicability of the framework. The LCA framework streamlines the LCA process for practitioners, and allows the LCA practitioners to focus on higher level analysis because the basic setup has already been developed within the LCA framework.

Difficulties in developing the LCA framework and benchmark arose from the lack of reliable data from literature. Disparate results were further difficult to compare. The benchmark proposed herein could be used to rectify issues from disparate LCAs. Future LCAs based on this LCA framework proposed would all follow a similar development and analysis, and the results could be readily compared.

7.0 FUTURE WORK

The future work would consist of further testing, creation of an algorithm with user interface, and the creation of an LCA user guide. The guide would be used to facilitate the implementation of the LCA framework. The user guide would also clearly define each step in the process, how to collect data and what instruments to use, how to interpret the data, and how to use the data in the iterative design process. The following list describes the next steps in this research:

1. Generate the steps needed to complete any conversions necessary from the data provided to the functional units.
2. Expand data acquisition rubric to include other parameters.
3. Identify more robust benchmarks.
4. Develop benchmarks for other metrics, including:
    a. Economics
    b. Social conditions
    c. Eutrophication
    d. Resource consumption
5. Create the algorithm with interactive user interface.
6. Develop the user guide:
    a. Define each step in the process.
    b. Research measurement instruments and define within the guide which instruments to use for what function.
    c. Describe how to interpret the data based on established benchmarks.
    d. Present tools on how to use the data in the iterative design process.
    e. Provide additional guidance on how final decisions might be made if there are tradeoffs to be considered.

APPENDIX A: CASE STUDY #1 FOR LCA FRAMEWORK TESTING

Case study #1 is based on the article "Combinatorial Life Cycle Assessment to Inform Process Design of Industrial Production of Algal Biodiesel" by Laura B. Brentner et al. (2011) from the journal *Environmental Science and Technology 2011 vol. 45*. The information in the following table is taken from the journal article, and will be used to compare with the results from the LCA framework.

Table 20: Case #1 data from Journal Article - Brentner et al. 2011

parameter		base case	best case
Cumulative Energy Demand (MJ_{eq})			
cultivation processes	water delivery and storage	690	350
	gas delivery	720	6620
	paddle wheel operation	4770	--
	water pumping to harvesting	2810	350
	construction materials	760	990
	nutrient production	5770	5770
harvesting processes	operation	32000	360
	flocculant production	--	170
lipid extraction processes	electricity	760	1800
	heat production	27590	2070
	solvent production	190	--
conversion processes	esterification	1060	1060
	equipment materials	220	--
waste management processes	landfilling/spreading	820	190
	anaerobic biodigestion	--	2280
	water treatment	--	780
	credit (nutrients)	0	-4200
	credit (energy)	0	-7770
Total CED		78200	10800
GHG emissions (kg CO_2 eq)		5340	805
eutrophication (g Neq)		2820	615
direct water use (m^3)		1210	625
cultivation land use (m^3)		4.1	1.9
functional units (MJ)		10^4	10^4

APPENDIX B: CASE STUDY #2 FOR LCA FRAMEWORK TESTING

Case study #2 is based on the article "Net Energy and Greenhouse Gas Emission of Biodiesel Derived from Microalgae" by Batan, L et al. (2010) from the journal *Environmental Science and Technology 2011 vol. 44*.

The information in the following table is taken from the journal article, and will be used to compare with the results from the LCA framework.

Table 21: Case #2 data from Journal Article Batan et al. 2010

Stage	Parameters	QTY	Unit
Growth Stage	photosynthetic area per facility area	0.9	ha/ha
	salt consumption	134	g/kg-dry algae
	nitrogen fertilizer consumption	147	g/kg-dry algae
	phosphorus fertilizer consumption	20	g/kg-dry algae
	polyethlene consumption	1.17	m^2/ha
	diesel fuel consumption	10	L/ha
	electricity consumption	41404	kWh/ha
	microalgae biomass yield	91000	kg/ha
Dewater Stage	electricity use	30788	kWh/ha
Extraction Stage	natural gas consumption	141994	MJ/ha
	electricity consumption	12706	kWh/ha
	extracted oil yield	43009	L/ha
Conversion Stage	natural gas consumption	2.1	MJ/kg-biodiesel
	electricity consumption	0.03	kWh/kg-biodiesel
	methanol consumption	0.1	g/kg-biodiesel
	sodium hydroxide consumption	0.005	g/kg-biodiesel
	sodium methoxide consumption	0.0125	g/kg-biodiesel
	hydrochloric acid consumption	0.0071	g/kg-biodiesel
Transportation and Distribution	diesel fuel consumption	0.0094	L/kg-biodiesel

APPENDIX C: GABI DATA FOR CASE STUDY #1

Table 22: GaBi Raw Data: Case #1 Base Case Scenario (Energy)				
Energy (gross calorific value) MJ Base Case Scenario				
	LCA Framework	**LCA Framework**	**LCA Framework**	**LCA Framework**
	Extraction Mode <u-so>	**Growth Mode <u-so>**	**Harvesting Mode <u-so>**	**Synthesis Mode <u-so>**
Flows	**28729.90963**	**15520**	**32000**	**2122.691604**
Resources	0	0	0	0
Material resources	0	0	0	0
Renewable resources	0	0	0	0
Water	0	0	0	0
Water (fresh water)	0	0	0	0
Carbon dioxide	0	0	0	0
Valuable substances	**28729.90963**	**15520**	**32000**	**2122.691604**
Energy carrier	**28540**	**9750**	**32000**	**2100**
Electric power	**950**	**9750**	**32000**	**2100**
Electricity	950	9750	32000	2100
Thermal energy	**27590**	0	0	0
Thermal energy (MJ)	27590	0	0	0
Materials	189.909633	0	0	**22.69160392**
Intermediate products	189.909633	0	0	**22.69160392**
Organic intermediate products	189.909633	0	0	**22.69160392**
Hexane (n-hexane)	189.909633	0	0	0
Methanol	0	0	0	22.69160392
Algae and Water Mixture	0	0	0	0
Algal Lipids	0	0	0	0
Nutrient Source	0	5770	0	0

Table 23: GaBi Raw Data: Case #1 Base Case Scenario (GWP)				
CML2001 - Nov. 2010, Global Warming Potential (GWP 100 years) g e-CO2 - Base Case Scenario				
	LCA Framework	LCA Framework	LCA Framework	LCA Framework
	US: Electricity grid mix PE	US: Electricity grid mix PE	US: Electricity grid mix PE	US: Electricity grid mix PE
Flows	1733.662668	168.9209779	373.4042669	5689.969781
Resources	-53.35077584	-5.198280723	-11.49093633	-175.0999822
Energy resources	0	0	0	0
Land use	0	0	0	0
Material resources	-53.35077584	-5.198280723	-11.49093633	-175.0999822
Valuable substances	0	0	0	0
Energy carrier	0	0	0	0
Materials	0	0	0	0
Algae and Water Mixture	0	0	0	0
Algal Lipids	0	0	0	0
Nutrient Source	0	0	0	0
Wet Algae	0	0	0	0
Production residues in life cycle	0	0	0	0
Secondary fuel	0	0	0	0
Secondary fuel renewable	0	0	0	0
Deposited goods	0	0	0	0
Consumer waste	0	0	0	0
Radioactive waste	0	0	0	0
Stockpile goods	0	0	0	0
Emissions to air	1787.013444	174.1192586	384.8952032	5865.069763
Heavy metals to air	0	0	0	0
Inorganic emissions to air	1723.246639	167.9060828	371.1608146	5655.783842
Organic emissions to air (group VOC)	63.76680419	6.213175793	13.73438859	209.2859214

Table 24: GaBi Raw Data: Case #1 Best Case Scenario (Energy)

Energy (gross calorific value) Best Case Scenario				
	LCA Framework	**LCA Framework**	**LCA Framework**	**LCA Framework**
	Extraction Mode <u-so>	**Growth Mode <u-so>**	**Harvesting Mode <u-so>**	**Synthesis Mode <u-so>**
Flows	**4059.909633**	**14080**	**530**	**-8020**
Resources	0	0	0	0
Energy resources	0	0	0	0
Land use	0	0	0	0
Material resources	0	0	0	0
Valuable substances	**4059.909633**	**14080**	**530**	**-5740**
Energy carrier	**3870**	**8310**	**530**	**-5740**
Electric power	**1800**	**8310**	**530**	**-5740**
Electricity	1800	8310	530	-5740
Thermal energy	**2070**	0	0	0
steam	0	0	0	0
Thermal energy (MJ)	2070	0	0	0
Materials	189.909633	0	0	0
Algae and Water Mixture	0	0	0	0
Algal Lipids	0	0	0	0
Nutrient Source	0	5770	0	0
Wet Algae	0	0	0	0
Production residues in life cycle	0	0	0	0
Secondary fuel	0	0	0	0
Secondary fuel renewable	0	0	0	0
Deposited goods	0	0	0	**-2280**
Consumer waste	0	0	0	-2280

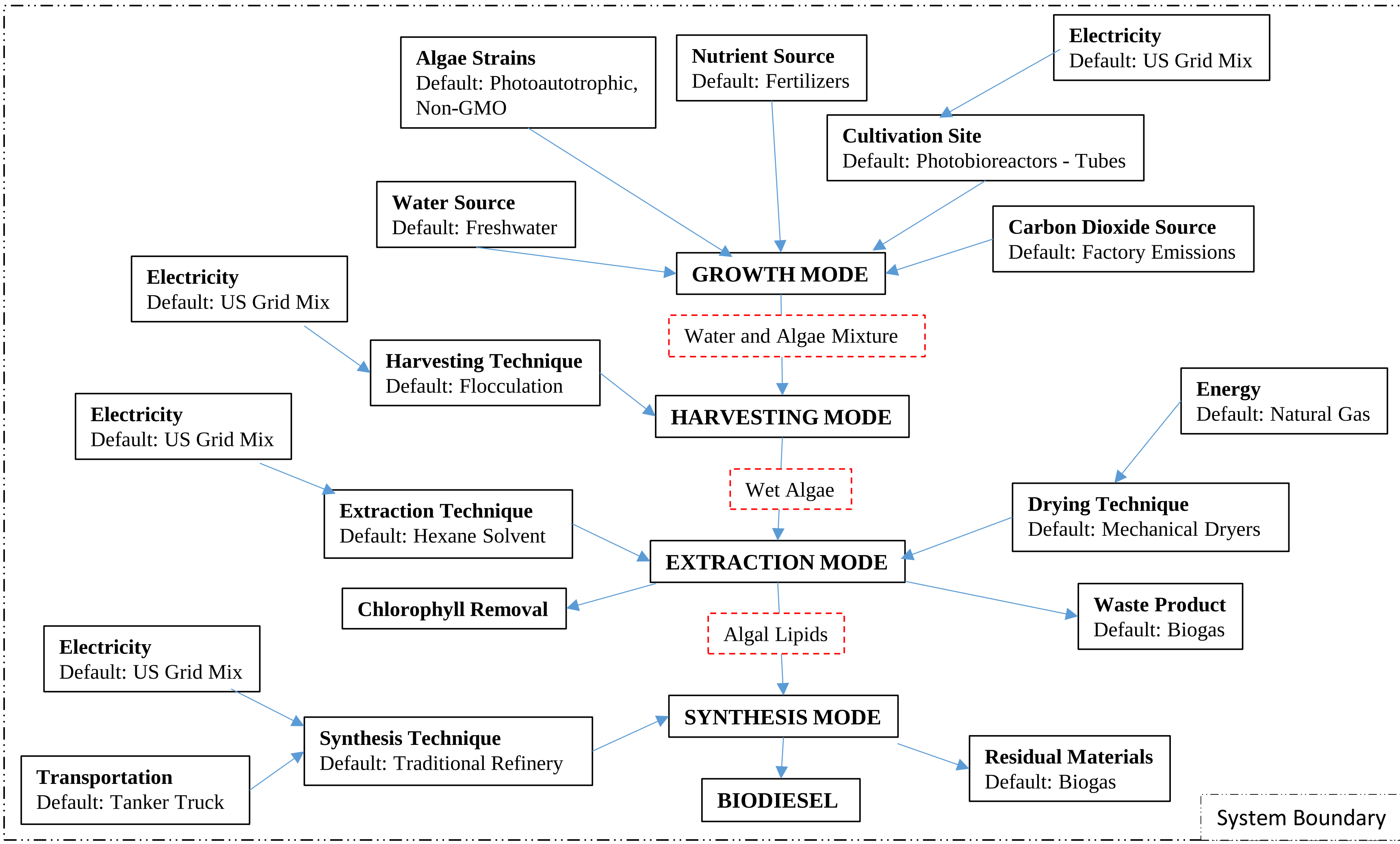
Table 25: GaBi Raw Data: Case #1 Best Case Scenario (GWP)						
CML2001 - Nov. 2010, Global Warming Potential (GWP 100 years) Best Case Scenario						
	LCA Framework	**LCA Framework**	**LCA Framework**	**LCA Framework**	**LCA Framework**	**LCA Framework**
	DE: Waste incineration (municipal waste) PE <p-agg>	**US: Electricity grid mix PE**	**US: Electricity grid mix PE**	**US: Electricity grid mix PE**	**US: Electricity grid mix PE**	**US: Thermal energy from natural gas PE**
Flows	196.1242406	1477.61403	320.0608	-1020.6383	94.2401245	142.630422
Resources	-0.757347725	-45.471277	-9.849374	31.4085593	-2.9000935	-0.1314618
Energy resources	0	0	0	0	0	0
Land use	0	0	0	0	0	0
Material resources	-0.757347725	-45.471277	-9.849374	31.4085593	-2.9000935	-0.1314618
Non renewable elements	0	0	0	0	0	0
Non renewable resources	0	0	0	0	0	0
Renewable resources	-0.757347725	-45.471277	-9.849374	31.4085593	-2.9000935	-0.1314618
Air	0	0	0	0	0	0
Carbon dioxide	-0.757347725	-45.471277	-9.849374	31.4085593	-2.9000935	-0.1314618
Nitrogen	0	0	0	0	0	0
Oxygen	0	0	0	0	0	0
Emissions to air	196.8815884	1523.0853	329.910174	-1052.0469	97.140218	142.761884
Heavy metals to air	0	0	0	0	0	0
Inorganic emissions to air	195.1656728	1468.73637	318.137841	-1014.5062	93.6739199	137.093519
Organic emissions to air (group VOC)	1.715915546	54.3489377	11.7723331	-37.540662	3.46629807	5.66836483

APPENDIX D: GABI DATA FOR CASE STUDY #2

Table 26: GaBi Raw Data: Case #2 (Energy)						
Energy (gross calorific value) MJ/ha/yr						
	US: Electricity grid mix PE	**US: Electricity grid mix PE**	**US: Electricity grid mix PE**	**US: Electricity grid mix PE**	**US: Thermal energy from natural gas PE**	**US: Thermal energy from natural gas PE**
Flows	568222.37	174375.26	4917.75	422529.96	42305.33	26903.75
Resources	445239.36	136634.42	3853.38	331079.84	181129.40	115187.86
Valuable substances	-149053.21	-45741.23	-1290.00	-110835.91	-141994.00	-90300.00
Energy carrier	-149053.21	-45741.23	-1290.00	-110835.91	-141994.00	-90300.00
Electric power	-149053.21	-45741.23	-1290.00	-110835.91	0.00	0.00
Electricity	-149053.21	-45741.23	-1290.00	-110835.91	0.00	0.00
Thermal energy	0.00	0.00	0.00	0.00	-141994.00	-90300.00
Thermal energy (MJ)	0.00	0.00	0.00	0.00	-141994.00	-90300.00
Emissions to air	249831.88	76668.05	2162.20	185774.90	3093.26	1967.14
Other emissions to air	249831.88	76668.05	2162.20	185774.90	3093.26	1967.14
Unused primary energy from solar energy	543.51	166.79	4.70	404.16	4.03	2.56
Unused primary energy from wind power	4293.20	1317.49	37.16	3192.42	12.79	8.14
Waste heat	244995.17	75183.76	2120.34	182178.32	3076.44	1956.44
Particles to air	0.00	0.00	0.00	0.00	0.00	0.00
Emissions to fresh water	22190.05	6809.65	192.05	16500.51	52.10	33.14
Other emissions to fresh water	22190.05	6809.65	192.05	16500.51	52.10	33.14
Unused primary energy from hydro power	2258.12	692.97	19.54	1679.14	9.49	6.04
Waste heat	19931.93	6116.68	172.50	14821.37	42.61	27.10
Emissions to sea water	14.28	4.38	0.12	10.62	24.55	15.61
Other emissions to sea water	14.28	4.38	0.12	10.62	24.55	15.61
Waste heat	14.28	4.38	0.12	10.62	24.55	15.61

Table 27: GaBi Raw Data: Case #2 (GWP)						
CML2001 - Nov. 2010, Global Warming Potential (GWP 100 years) kg CO2-Equiv./ha/yr						
	US: Electricity grid mix PE	**US: Electricity grid mix PE**	**US: Electricity grid mix PE**	**US: Electricity grid mix PE**	**US: Thermal energy from natural gas PE**	**US: Thermal energy from natural gas PE**
Flows	26503.38	8133.32	229.38	19707.91	9783.90	6221.99
Resources	-815.60	-250.29	-7.06	-606.48	-9.02	-5.73
Material resources	-815.60	-250.29	-7.06	-606.48	-9.02	-5.73
Renewable resources	-815.60	-250.29	-7.06	-606.48	-9.02	-5.73
Carbon dioxide	-815.60	-250.29	-7.06	-606.48	-9.02	-5.73
Emissions to air	27318.98	8383.61	236.44	20314.39	9792.91	6227.73
Inorganic emissions to air	26344.15	8084.45	228.00	19589.50	9404.09	5980.46
Bromine	0.00	0.00	0.00	0.00	0.00	0.00
Carbon dioxide	25429.67	7803.82	220.08	18909.50	9385.23	5968.46
Carbon dioxide (biotic)	777.18	238.50	6.73	577.91	4.26	2.71
Nitrogentriflouride	0.00	0.00	0.00	0.00	0.00	0.00
Nitrous oxide (laughing gas)	137.29	42.13	1.19	102.09	14.60	9.29
Sulphur hexafluoride	0.00	0.00	0.00	0.00	0.00	0.00
Organic emissions to air (group VOC)	974.84	299.16	8.44	724.89	388.83	247.27
Group NMVOC to air	0.38	0.12	0.00	0.28	0.00	0.00
Hydrocarbons (unspecified)	0.83	0.25	0.01	0.62	0.01	0.01
Methane	973.63	298.79	8.43	723.99	388.82	247.26

APPENDIX E – COMPILED LCA FRAMEWORK



Functional Unit: /ha/yr

Functional Unit: /MJbiodiesel

Benchmark LCA Metrics*		
	QTY	**Units**
Lipid Content	30	% wt
Algae Production	90	t/ha/yr
Biodiesel Production	30	t/ha/yr
Energy Balance Ratio (EBR)	3	MJ_f/MJ_b
Global Warming Potential (GWP)	65	g e-CO_2/ MJ_b

Industry Trends: Configuration Design		
Cultivation Phase	**Nutrient Source**	Fertilizer
	Water Source	Freshwater
	Carbon Dioxide Source	Factory Emissions
	Algae Strains	Non-GMO
		Photoautotrophic
	Cultivation Site	Photobioreactors-Tubes
	Electricity	US Energy Mix
Harvesting Phase	**Harvesting Technique**	Flocculation
	Electricity	US Energy Mix
Extraction Phase	**Extraction Technique**	Hexane Solvent
	Drying Technique	Mechanical Dryers
	Electricity	US Energy Mix
	Waste Product	Biogas
Synthesis Phase	**Synthesis Technique**	Traditional Refinery
	Transportation	Tanker Truck
	Residual Materials	Biogas

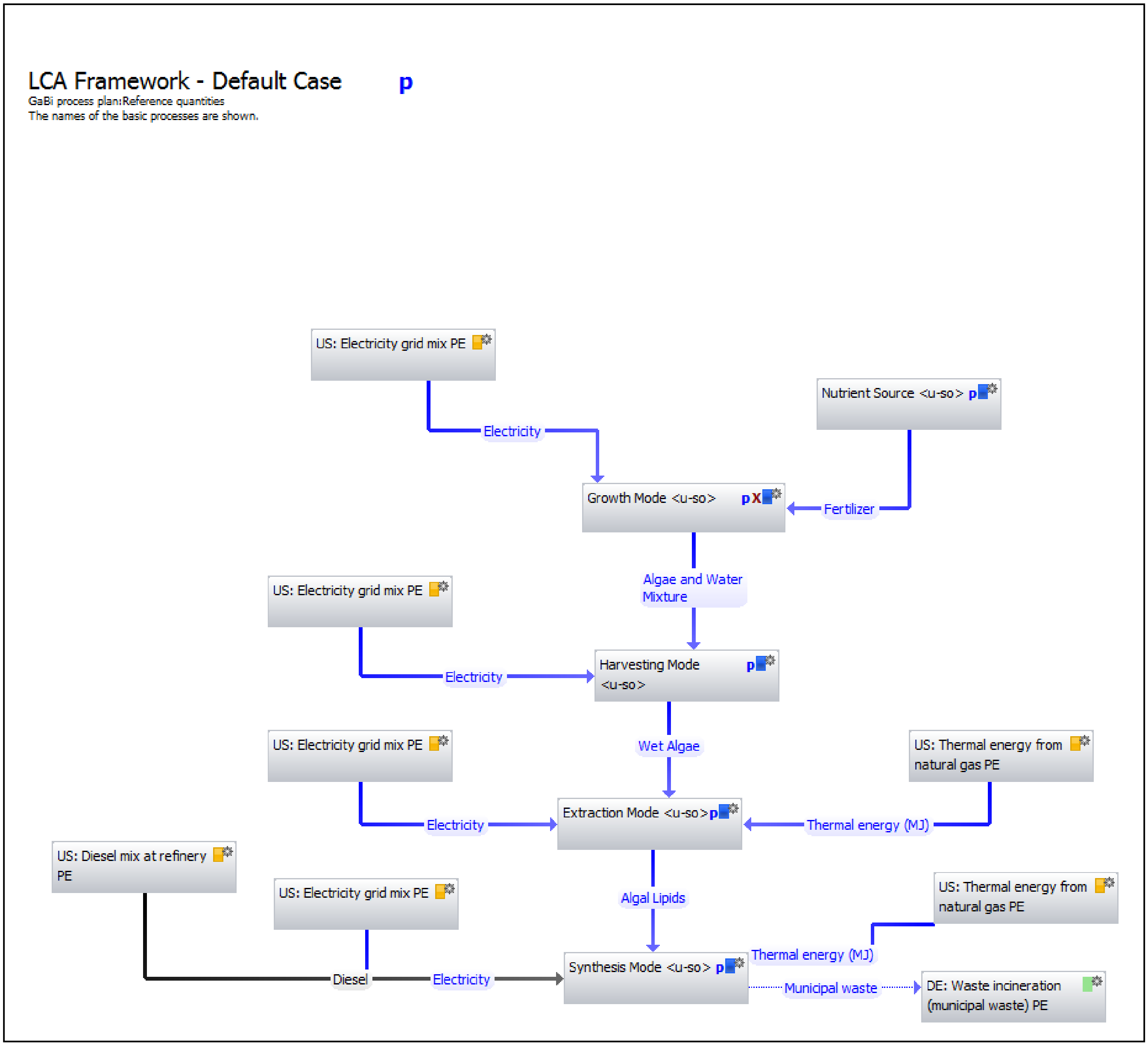
Process Flow Options for Configuration Design					
		Option 1 (Default)*	**Option 2***	**Option 3***	**Option 4***
Cultivation Phase	**Nutrient Source**	Fertilizer	Wastewater	Starchy By-products	--
	Water Source	Freshwater	Wastewater	Seawater	Brackish water
	Carbon Dioxide Source	Factory Emissions	Open to Air		
	Algae Strains	Non-GMO	GMO	--	--
		Photoautotrophic	Heterotrophic	Mixotrophic	--
	Cultivation Site	Photobioreactors: Tubes	Photobioreactors: Panels	Photobioreac tors: Bags	Raceway Ponds
	Electricity	US Energy Mix	Renewable Energy Mix	Biogas Sourced Onsite	--
Harvesting Phase	**Harvesting Technique**	Flocculation	Centrifugation	Membrane Filtration	Additional Solids Separation
	Electricity	US Energy Mix	Renewable Energy Mix	Biogas Sourced Onsite	--
Extraction Phase	**Extraction Technique**	Hexane Solvent	Dry Extraction	Wet Extraction	--
	Drying Technique	Mechanical Dryers	Solar Dryers	--	--
	Electricity	US Energy Mix	Renewable Energy Mix	Biogas Sourced Onsite	--
	Waste Product	Biogas	Landfilled	Animal Feed	Plastics
Synthesis Phase	**Synthesis Technique**	Traditional Refinery	Transesterification	--	--
	Transportation	Tanker Truck	No Transportation - Onsite	--	--
	Residual Materials	Biogas	Landfilled	--	--

* Options can be combined and interchanged.
The default column represents framework default options.

Data Acquisition Rubric

Parameter		
Cultivation Phase	Growth Mode	
	GMO/Non-GMO	
	Algae Strain	
	Cultivation Site	
	CO2 source	
	Nutrient source	
	Water source	
Harvesting Phase	Harvesting Technique	
Extraction Phase	Dryer	
	Extraction Technique	
	Solvent	
Synthesis Phase	Transesterification (Y/N)	
	Traditional Refinery (Y/N)	
	Transportation Method	
	Synthesis Technique	
Waste Product	Disposal (Y/N)	
	By-Products (Y/N)	
	Byproduct industry	

Parameter		QTY	Units
Cultivation Phase	Photosynthetic area		ha
	Microalgae biomass yield		t/ha/yr
	CO2 consumption		t/ha/yr
	Water delivery and storage		MJ/ha/yr
	Gas delivery		MJ/ha/yr
	Paddle wheel operation		MJ/ha/yr
	Water pumping to harvesting		MJ/ha/yr
	Construction materials		MJ/ha/yr
	Water use		t/ha/yr
	Nutrients		t/ha/yr
Harvesting Phase	Wet Algae yield		t/ha/yr
	Harvesting processes operation		MJ/ha/yr
	Flocculant production		MJ/ha/yr
Extraction Phase	Extracted oil yield		t/ha/yr
	Electricity		MJ/ha/yr
	Heat production		MJ/ha/yr
	Solvent production		MJ/ha/yr
	Conversion processes		MJ/ha/yr
Synthesis Phase	Biodiesel yield		t/ha/yr
	Esterification		MJ/ha/yr
	Equipment materials		MJ/ha/yr
	Transportation		kg/ha/yr
Waste Products	Waste products yield		t/ha/yr
	Landfilling/spreading		MJ/ha/yr
	anaerobic biodigestion		MJ/ha/yr
	water treatment		MJ/ha/yr
	nutrients credit		MJ/ha/yr
	Energy credit		MJ/ha/yr


LCA Framework - Default Case
p
GaBi process plan:Reference quantities
The names of the basic processes are shown.
US: Electricity grid mix PE
Electricity
Nutrient Source <u-so> p
Growth Mode <u-so> p X
Fertilizer
Algae and Water Mixture
US: Electricity grid mix PE
Electricity
Harvesting Mode <u-so> p
Wet Algae
US: Electricity grid mix PE
US: Thermal energy from natural gas PE
Electricity
Extraction Mode <u-so> p
Thermal energy (MJ)
US: Diesel mix at refinery PE
US: Electricity grid mix PE
Algal Lipids
US: Thermal energy from natural gas PE
Thermal energy (MJ)
Diesel
Electricity
Synthesis Mode <u-so> p
Municipal waste
DE: Waste incineration (municipal waste) PE

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