Energy and Sensitivity Analysis of Biodiesel Production from Microalgae Biomass

by

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17409

Dissertation submitted in partial fulfilment of
the requirements for the
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CERTIFICATION OF APPROVAL

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Chemical Engineering Programme
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BACHELOR OF ENGINEERING (Hons)
(CHEMICAL ENGINEERING)

Approved by,

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(Dr. Lam Man Kee)

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September 2015

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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NORHAFIZAH BINTI AHAMAD FAUZI

ABSTRACT

Microalgae have been proposed as a potential feedstock for the production of biodiesel due to its high photosynthetic efficiency, which leads to high oil content available. Lots of studies have provide scientifically proven data that shows the oil content in microalgae biomass is significantly high compared to other oil sources for biodiesel production. However, throughout the production process high energy input is required for microalgae cultivation and oil extractions steps. This may out weight the advantages of microalgae biomass stated earlier. Therefore, there is a need to determine whether microalgal biodiesel can deliver more energy than what has been required to produce it. The method that will be used to achieve the aim is by conducting energy and sensitivity analysis. In this project, all analysis will be done on assumptions that the systems to produce biodiesel from *Nannochloropsis* species which have lipid content of around 35% per dry 1 kg biomass is cultivated in a photobioreactor. The system boundaries are defined which are the cultivation, harvesting, extraction and biodiesel production. Thus all analysis will only focus within these boundaries. The functional unit used throughout the analysis 1 MJ per 1 kg biodiesel. Through energy analysis, net energy ratio (NER) is calculated to determine the ratio of input energy to output energy during biodiesel production. It was found at the end of this analysis that the NER value is 0.06 which shows that it is not feasible to produce biodiesel from *Nannochloropsis* biomass. Sensitivity analysis is done to predict the outcome of energy analysis when several parameters are varied. Data will be extracted from multiple scientific publications and comparative literature. Data representation and graphical illustration will then be plotted to visualize the findings from the analysis.

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LIST OF ABBREVIATIONS

ASACF	Air sparging assisted coagulation flocculation	26
CHP	Combined heat and power	25
DAF	Dissolved air floatation	26
EHE	Ethanol-hexane extraction	35
FAME	Fatty acid methyl esters	13
FYP	Final Year Project	v
GHG	Greenhouse gas	4
LCA	Life cycle assessment	3
MJ	Mega joules	24
NER	Net energy ratio	3
PBR	Photobioreactor	9

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CHAPTER 1
INTRODUCTION

1.1 Background of study

Energy is defined as the ability to do work. The primary source of energy are usually derived from fossil fuels, such as petroleum, coal and natural gas which represents over 80% of total energy supplies today (Demirbas, 2007). This energy is used for various purposes ranging from electricity generation, transportation and industrial power needs (Oncel, 2013). However, excessive energy production from fossil fuels has leaded to a few serious challenges. Depletion of fossil fuels supplies versus increasing demand of energy production, environment pollution, climate change and the emission of greenhouse gases have been some concerns that triggered the need to explore other sources of renewable energy (Lam & Lee, 2012). Renewable energy sources are readily available in nature (Demirbas, 2007). Sources from solar, wind, hydro, geothermal and energy from biomass have succeeded in gaining interest for extensive research and have been explored to be used as alternatives clean energy sources (B. Singh, Guldhe, Rawat, & Bux, 2014).

Biomass is referred to the plant matter that was created during photosynthesis process where energy from the Sun converts water and CO_2 into organic components, such as cellulose, hemicelluloses, lignin, extractives, lipid, starches and other compounds (Demirbas, 2007). By this definition, oil from first (edible) and second (nonedible) generation crop such as rapeseed, soybean, palm and sunflower oil, jatropha, mahua, jojob oil, tobacco seed and salmon oil can be used to produce biodiesel (Rawat, Ranjith Kumar, Mutanda, & Bux, 2013). Biodiesel is a processed fuel which is derived from biological sources. It seems that these oil crops are promising for sustainable energy production, however, when the idea is projected into large scale, the demand for energy production from these oilcrops can create food

supply tension. Due to this conflict, recent researches have revealed the potential of using microalgae as the source of biodiesel production (Rawat et al., 2013).

Microalgae are photosynthetic microorganisms that are able to live under extreme ecological conditions. They can sustain their growth by converting sunlight as an energy source, inorganics nutrients, water and CO_2 to produce carbohydrate, lipids and protein within their cells (Oncel, 2013). Lipids that are contained from the microalgae biomass are useful for biodiesel production. Studies have shown that the lipids contains from microalgae biomass are ten times higher compared to any oil crop harvested from their oil seeds (Taher, Al-Zuhair, Al-Marzouqi, Haik, & Farid, 2014).

Currently, life cycle energy analysis on converting oil crops and biomass to biodiesel has been extensively carried out to justify its sustainability for long term usage. Meanwhile, only a few studies were being conducted to determine whether the energy output from microalgae biodiesel are higher than the energy used to produce it (Razon & Tan, 2011). Lack in extensive analysis on the challenges of microalgal biodiesel production through thermodynamics aspect especially in energy balance were recorded in scientific publications (Lam & Lee, 2012).

1.2 Problem statement

Issues of depleting fossil fuels reserves have been gaining attentions from around the world and therefore studies on the alternatives fuels sources have been intensively done by experts. Biodiesel which is oils from monoalkyl esters of vegetable oils seems like a promising alternative. However, the production of biodiesel from edible oil has created food versus fuels feud which affects the food supplies for the society (Gendy & El-Temtamy, 2013).

Hence, biodiesel produced from microalgae biomass has been the alternatives energy source to overcome the food supplies problems. Microalgae biomass appears as an appealing source for biodiesel production as the lipids contained from their biomass are significantly higher than other crop oil (Chisti, 2007). Microalgae do not require vast area of land for growth and therefore reduce the competition of agricultural land for cultivation. Other than that, biodiesel from microalgae biomass

can reduce the dependency of fossil fuels which has shown severe negative impacts on environmental (Chisti, 2007).

Nevertheless, this alternative needs to be carefully studied in order to realize its potential as one of the renewable energies. According to a study done by Lam & Lee (2012), it was observed that during the production of biodiesel from microalgae and jathropha, 64% and 44% of energy from input resources were destroyed respectively for the production of 1 tonne biodiesel. This will later spare less than half percentage of useful energy left to do work and affect their sustainability to be the new source for biofuels. The situation is worsen with the lack of mature technologies being applied to minimize the energy loss problem. In order to investigate the concern raised, this study thus aims to provide an insight of energy and sensitivity analysis for the production of biodiesel from microalgae biomass. Apart from that, this study aims to utilize visualize the findings from the various upstream experimental procedure such as cultivation, harvesting and extraction processes specifically in energy demand of microalgal biodiesel production.

1.3 Objectives

The research objectives for this study are as shown below:

- To perform energy analysis of biodiesel production from microalgae biomass by using life cycle analysis (LCA) and net energy ratio (NER) approach
- To perform sensitivity analysis of biodiesel production from microalgae biomass

1.4 Scope of study

This project is important in the sense that it provides further research on the possibility of using microalgae biomass to produce biodiesel. This biodiesel can then be used for the means of transportation and energy source to do work, and can then replace the use of fossil fuels. The scope of energy analysis is wide. However, in order to complete this research project within the time frame of 28 weeks, the scope of research will be narrowed down and the selection of parameters in the energy analysis

will only be given to two or three analysis. For example, the energy analysis that uses life cycle assessment (LCA) will only be focusing on the net energy ratio (NER) without studying the environmental impacts such as greenhouse gas (GHG) emission, acid gas emission, nutrient-rich emission and photochemical ozone formation from the production of microalgal biodiesel.

The scope of study that have been identified in this analysis are focusing on microalgae species of *Nannochloropsis*, cultivation method using photobioreactor, systems boundaries set of cultivation, harvesting, extraction and biodiesel production. Lastly, the production rate of dry weight algae biodiesel of 15 g/m2/day is set in order to be the focal point of this analysis. *Nannochloropsis* has high oil content and also high biomass productivity. Due to this reason, it has been proposed as a feedstock for biodiesel production (Jorquera, Kiperstok, Sales, Embiruçu, & Ghirardi, 2010). *Nannochloropsis* is salt water, photosynthetic microalgae that requires essential nutrients in order for them to grow. These essential nutrients named as culture medium is needed to ensure the growth of microalgae (Khoo et al., 2011).

CHAPTER 2
LITERATURE REVIEW

2.1 Microalgae

In liquid biofuels production, microalgae are important to be used as the feedstock. The liquid biofuels can be biodiesel, bioethanol and bio-oil. Biodiesel and bioethanol can be produced from lipids and carbohydrates of microalgae biomass respectively. Whereas bio-oil can be produced from microalgae biomass or residual biomass using thermochemical treatment after lipid extraction and/or saccharification of cellular carbohydrates (Lee, Seong, Lee, & Lee, 2015).

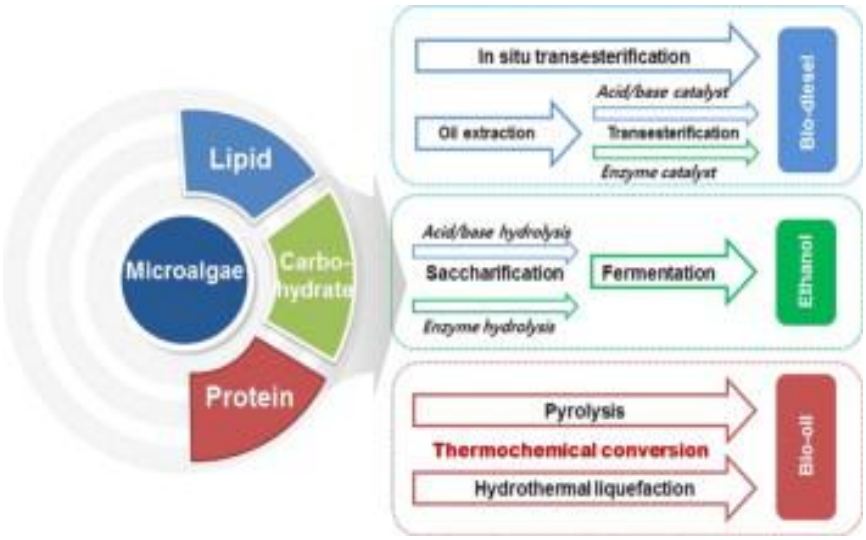

Figure 2.1 The use of microalgae contains for the production of biofuels

Microalgae are active photosynthetic microorganism cells that use sunlight to concert carbon dioxide into bioufuels, foods, feeds and high value bioactives. These microorganisms can produce feeds for several types of renewable biofuels, such as biodiesel, bioethanol and bio-oil. Microalgae can grow very rapid and most of the microalgae species are rich in oil content. Usually they can double their biomass

content within 24 hours (Chisti, 2007). Oil productivity, which is the mass of oil produced per unit volume of the microalgae broth per day is depending on the rate of algal growth and the oil content of the biomass. Microalgae species that have high oil productivity are the top choice in producing biodiesel. Table 2.1 below list several microalgae species with respect to their lipid content and lipid productivity.

Table 2.1 Lipid content and lipid productivity of several microalgae species

Microalgae species	Lipid content/ Oil content (% dry weight biomass)	Lipid productivity (mg/L/day)	References
Botryococcus braunii	25.0 – 75.0	-	Chisti, 2007
Chaetoceros muelleri	33.6	21.8	Ahmad, Yasin et al., 2011
Chlorella sp.	28.0 – 32.0	-	Chisti, 2007
Chlorella sp.	18.7	42.1	Ahmad, Yasin et al., 2011
Chlorella vulgaris	19.2	32.6	Ahmad, Yasin et al., 2011
Nannochloris sp.	20.0 – 35.0	-	Chisti, 2007
Nannochloropsis sp.	31.0 – 68.0	-	Chisti, 2007
Nannochloropsis sp.	35.7	60.9	Ahmad, Yasin et al., 2011
Neochloris oleoabundans	35.0 – 54.0	-	Chisti, 2007
Pavlova salina	30.9	49.4	Ahmad, Yasin et al., 2011
Phaeodactylum tricornutum	20.0 – 30.0	-	Chisti, 2007
Skeletonema costatum	21.0	17.4	Ahmad, Yasin et al., 2011
Skeletonema sp.	31.8	27.3	Ahmad, Yasin et al., 2011
Spirulina maxima	4.0 – 9.0	-	Mata, Martins, & Caetano, 2010
Spirulina platensis	10.30 ± 0.10	-	Peng, Wu, Tu, & Zhao, 2001
Tetraselmis sueica	15.0 – 23.0	-	Chisti, 2007

2.2 Methods of Microalgae Cultivation

Microalgae can be cultivated by using autotrophic, heterotrophic and mixotrophic method. By going through autotropic cultivation method, microalgae gain energy through a light supply using photosynthesis. In the dark, heterotrophic algae gain energy by consuming dissolved organic matter as opposed to photosynthesis process. Mixotrophic algae use both photosynthesis and the consumption of organic nutrients (Crane & Grover, 2010). Growing microalgae by using autotrophic method has several disadvantages. The reactor for autotrophic cultivated microalgae must have a very large surface area and shallow depth. This is to ensure the microalgae are close enough to the surface of light source to gain sufficient light exposure. Other than that, the maintenance cost for both indoor and outdoor reactor to allow enough light penetration for cultivation is very high. Autotrophic method also needs long cultivation period and the biomass produced is in low quantity (Dhull, Soni, Rahi, & Soni, 2014). Due to the fact that autotrophic cultivation method requires has numerous disadvantages, therefore this method is considered tedious, expensive and not favorable for scale-up cultivation activity (Perez-Garcia, De-Bashan, Hernandez, & Bashan, 2010).

Hence, heterotrophic cultivation method is another option of cultivating microalgae that can overcome the disadvantages autotrophic method has. Heterotrophic method utilizes organic substance such as glucose, acetate and glycerol to be used as energy and carbon (Mata, Martins, & Caetano, 2010). Glucose is a complex carbon substance that produces microalgal biomass and biochemical components of the algae such as lipids. By using glucose as an alternative source of energy, the cost for cultivation is significantly less than providing light. Microalgae cell growth and lipid productivity is also improved resulting in higher yield harvested (Kong et al., 2013). However, there are several problems exist with heterotrophic cultivation that needs to be dealt with:

1. Number of microalgae species that can be cultivated using heterotrophic method is limited. Only *C. protothecoides*, *C. vulgaris*, *Crypthecodinium cohnii* and *Schizochytrium limacinum* species that are able to grow in total darkness yet still producing high lipid quantity (Lam & Lee, 2012).

2. Serious contamination caused by other microorganism happens when microalgae cells mix with organic substance (Chen, Yeh, Aisyah, Lee, & Chang, 2011).
3. Increase of cost and food versus fuel issue exist when adding organic substance. Researches have proven that glucose is most suitable to be used as the organic substance in heterotrophic method because it has high energy content. However, since glucose is derived from sugar-based plant which is also important for human consumption, therefore the use of it in this cultivation method can cause food supply problems.
4. CO_2 is released from microalgae respiration. Thus does not solve the problems of rising CO_2 content in the atmosphere (Y. Li, Horsman, Wang, Wu, & Lan, 2008).

In mixotrophic cultivation method, microalgae grow either phototrophically or heterotrophically depending on the concentration of organic carbon sources and intensity of light (Mata et al., 2010). Due to the combination of organic carbon source and carbon provided to the microalgae through light-driven photosynthesis, it gives the algae an ideal growth condition (Y.-R. Li, Tsai, Hsu, Xie, & Chen, 2014). Since the microalgal cell in mixotrophic cultivation is depending on either photosynthesis or organic carbon substance, thus light energy is not an absolute factor for the cell's growth (Andrade & Costa, 2007).

2.3 Microalgae Cultivation System

Microalgae can be grown in an open system or in different type of closed photobioreactors. The choice for the type of reactor depends on several aspects such as location, available space and water supply, cost allocated and the desired product (Hulst, 2013).

2.3.1 Open Pond Production System

The open pond system is made of a closed loop, oval shaped recirculation ways which 0.2 to 0.5m in depth. This low in depth value is designed in order to allow sufficient sunlight available for microalgae to undergo optimum photosynthesis

process (Brennan & Owende, 2010). The most common open pond culture system is made up of a pond in the shape of a raceway and the liquid (algae broth) is circulated around the pond by a paddle wheel (Gross, 2013). In a continuous production cycle, both algae broth and nutrients are introduced in front of paddlewheel. The paddlewheel is functioning for sedimentation of microalgae biomass and to circulate the culture medium through the loop until the harvest point (Brennan & Owende, 2010). The raceways are commonly made from concrete, or they are molded by being dug into the earth and lined with plastic liner. The open ponds are the most popular cultivation system in commercial scale because it requires low cost of building and easy to scale up (Gross, 2013).

Despite being the most commonly used cultivation systems, open ponds have few disadvantages to it. In open ponds, temperature is difficult to control and it is usually fluctuating. Season change can also affect the temperature. Due to the fact that it is an open pond, the system is exposed to the atmosphere and can cause significant water loss from evaporation (Gross, 2013) and is exposed to high contamination level by undesired microorganisms that influences the growth of microalgae (Lam & Lee, 2012).

2.3.2 Closed Photobioreactor System

Closed photobioreactor (PBR) system is established to overcome several limitations which open pond system has such as low algal cell densities, contamination, loss of water due to evaporation, and large space requirement (Gross, 2013). There is several design of closed PBR such as tubular, flat plate and column. The primary benefit of using closed PBR is it allows single strain culture by regularly maintaining optimum condition for growth to produce high consistency in biomass and lipid productivity (Lam & Lee, 2012). Besides, since PBR allows single-species cultivation of microalgae, the duration can be prolonged and risk of contamination is lowered (Chisti, 2007).

Most commonly used PBR is of tubular design. A tubular PBR has an array of straight tubes which are transparent and are usually made up of plastic or glass (Chisti, 2007). The culture broth circulates through the tubes, collects sufficient sunlight for

photosysnthesis, and returns back to a reservoir. The tubes are ensured to be 10 cm or less in diameter in order to allow light to penetrate deeply into the culture broth. Thus, allowing high biomass productivity of the PBR (Gross, 2013). Typically, these tubes are arranged parallel to each other and flat above the ground. However, they can also be arranged in horizontal, parallel and stack like a fence. Figure 2.2 below illustrates how the tubes are arranged flat above the ground, whereas Figure 2.3 shows how the tubes are stack up like a fence.

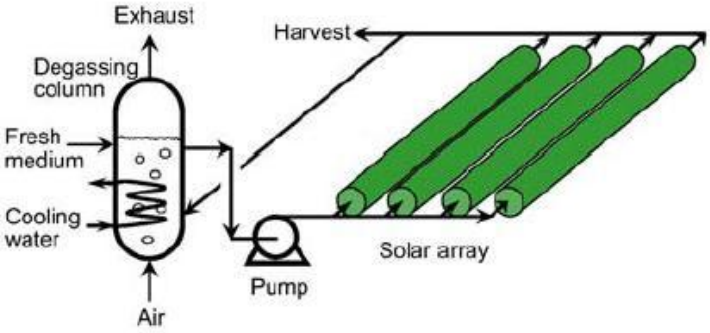

Figure 2.2 A tubular PBR with parallel horizontal tubes

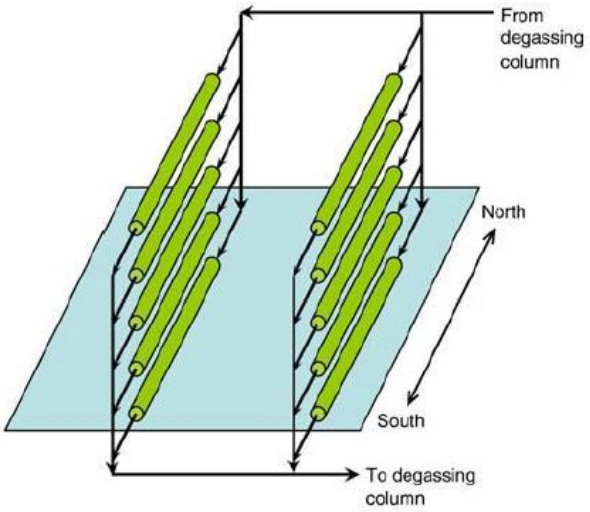

Figure 2.3 PBR consist of horizontal, parallel tubes arranged like a fence

Flat plate PBR is made up of transparent materials shaped into rectangular box where air is bubbled from the bottom of the box to provide enough mixing and gas transfer. This type of PBR can have horizontal baffles run inside it to help the mixing process and gas transfer efficiency. Surface area for light to penetrate the algal cell

increases in this type of PBR, thus resulting in the lipid productivity to be significantly higher compared to open pond system (Gross, 2013). Flat plate PBRs are also reported to used less power supply than tubular PBR for the culture to achieve enough mass transfer, mixing and heat transfer capacity (Sierra et al., 2008). Figure 2.4 below illustrates the general idea of a flat plate PBR arranged vertically with air bubbles aired from the bottom of it.

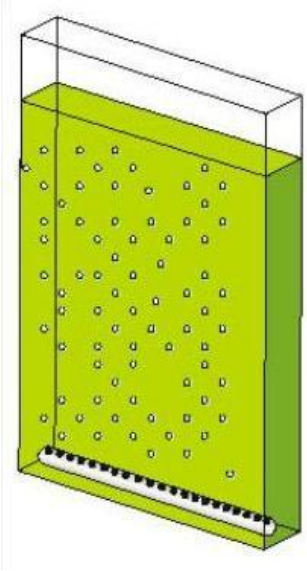

Figure 2.4 A vertical flat plate PBR with bubbles aired from the bottom of the box

On the other hand, column PBR is reported to give the most efficient mixing process, high volumetric mass transfer rates and controllable growth conditions for the microalgae. Column PBR require low cost to be build, compact and easy to operate (Eriksen, 2008). Commonly being arranged vertically, the column includes vertical bubble columns which are usually used for indoor experiments. The diameter is over 20cm, which makes the middle of the column cannot get enough sunlight and is dark. To overcome this problem, an annular column may be formed, consisting of two cylinders of different size to form a wrapped flat plate reactor. Inside this annular column lamps could be fitted to increase productivity (Borowitzka, 1999). Figure 2.5 below shows how vertical column PBRs would look like in outdoor environment.

Figure 2.5 Vertical column PBR

2.4 Biodiesel production from microalgae from its biomass

Microalgae are microscopic organisms that undergo photosynthesis process in order for them to grow. They use sunlight, CO_2, water and other inorganic nutrients to reproduce and generate biomass (Marchetti & Fang, 2011). Due to their simple cellular structure, microalgae are growing at much faster rates compared to other terrestrial crops. In average, the oil content in microalgae was found to be 50% by weight of their dry mass (Chisti, 2007) thus makes it to be the potential source for biodiesel production.

There are three generations of feedstock that can be used to produce biodiesel that have been studied over the years. The first, second, and third generation are food crops, non-food crops, and microalgae respectively. For the production of biodiesel from microalgae, the lipids contained in their biomass needs to be extracted. Based on the study done by Subramanian, Barry, Pieris & Sayre (2013), it was reported that the lipid contained in the microalgae cells can reach up to 75%. From this high numbers of oil contents, it shall provide huge feedstock supplies for biodiesel production.

There are several conversion methods to produce biodiesel, bioethanol and bio-oil such as transesterification, fermentation, pyrolysis, liquefaction and anaerobic digestion (Lee et al., 2015). Lipid is extracted from the microalgal cell by using organic solvent and then transesterified to produce biodiesel with the aid of base or acid catalyst. The lipid content of some microalgae species such as *Botryococcus braunii*

is over 80% of the dry weight (Hu et al., 2008). *Chlorella* and *Dunaliella* are reported to have 50% of dry weight of lipid content (Lee et al., 2015).

Biodiesel is a mono alkyl ester which consists of a long chain of fatty acids derived from vegetable oils and animal fats. In a commercial scale, biodiesel is produced through the transesterification of the vegetable oils with short chain such as methanol and ethanol (Salvi & Panwar, 2012). It can be produced through two-step method of oil extraction-transesterification or one-step transesterification (direct transesterification). Commonly, oil from microalgae is extracted using solvent extraction by hexane, ethanol, methanol and methanol-chloroform mixture (Lam & Lee, 2012). After lipid extraction, alkali, acid catalysts and lipase are used for transesterification. One important thing is microalgae oil generally contains a certain amount of free fatty acid. Thus, an acid-catalyzed conversion can be an efficient method with high conversion, though its reaction rate is approximately 4000 times slower than base-catalyzed processes (Lotero et al., 2005).

In two step transesterification, the extracted lipids are transesterified to fatty acid methyl esters (FAME) using sulphuric acid, hydrochloric acid and lipase. Acid catalyst is used because microalgae biomass generally contains large amounts of free fatty acids. The presence of alkali catalysts would favor the formation of soaps which is unwanted to be happened (Ríos, Castañeda, Torras, Farriol, & Salvadó, 2013).

Other details on the potential conversion of microalgae biomass to biodiesel are discussed as follow:

1. The properties of biodiesel from microalgae biomass is depending on the microalgae strain from which it was produced. Strains that contain high lipid content and were grown with fast growth rate are good feedstock for biodiesel production (Nwokoagbara, Olaleye, & Wang).
2. Biodiesel from microalgal biomass is the only renewable biodiesel which can replace the need to use liquid transport fuels from petroleum (Chisti, 2008).

3. Microalgae biomass have the potential of accumulating oil content in their cell 100 times more oil per acre as compared to terrestrial crop (Mubarak, Shaija, & Suchithra, 2015)
4. Microalgae can offer high biofuel yield by using less water demand than terrestrial crop biomass (Posten & Schaub, 2009).
5. A study done to cultivate microalge using dairy farm wastewater resulted in the production of its microalgae biomass which contain as high as 73% of algal lipid readily available to be converted into biodiesel (Hena, Fatimah, & Tabassum, 2015).
6. Land consumption for cultivation of microalgae in order to produce biodiesel from its biomass is not a huge problem as microalgae only require 0.1 – 0.2 m^2 land/year/kg biodiesel (Ahmad, Yasin, Derek, & Lim, 2011).

However, there are several aspects that need to be considered before scaling up the production of biodiesel from microalgae biomass. One of the issues is the uncertainty of the net energy ratio of energy produced from microalgae biodiesel compared to the energy destructed during its production.

2.5 Energy analysis of the production of biodiesel

In order to determine the sustainability of biodiesel production from microalgae biomass, an energy analysis has to be conducted. Energy analysis could be carried out by using life cycle analysis (LCA) approach, in which this method investigate the productivity, cultivation, lipid extraction and energy conversion of microalgae into biodiesel (Dassey, Hall, & Theegala, 2014). LCA can also be done on investigating the Greenhouse Gas (GHG) emission and the Net Energy Ratio (NER) (Medeiros, Sales, & Kiperstok, 2015).

According to (Grierson, Strezov, & Bengtsson, 2013) LCA was done in order to achieve several aims which are (1) to model impacts of microalgae biomass cultivation towards environment (2) to established a standard life cycle model assessment of microalgae system and (3) to set a performance benchmark towards other microalgae value chain analysis.

Among GHG that has drawn attention in LCA GHG emission analysis are carbon dioxide, methane and nitrous oxide. It can be compared as fossil vs. non-fossil emissions and upstream vs. tailpipe emissions. Fossil emissions are the one resulted from fossil fuels combustion, in which it will add the amount of GHG in the atmosphere. On the other hand, non-fossil emissions are the carbon dioxide emissions resulted from the burning of biomass (algae, canola oil, tress) in which it is just a recycling carbon dioxide that has been fed to the biomass and it do not add extra GHG to the atmosphere. Upstream emissions are those released during the production of biofuel, including harvesting, transporting the fuel to and from refineries and to bowsers in refueling stations, whereas tailpipe emissions are the GHG emissions from the combustion of fuel released from the truck (Campbell, Beer, & Batten, 2011). The energy balance or net energy balance (NER) in this case is the ratio of energy output from the production of biodiesel over energy input that was required to produce the biodiesel (Razon & Tan, 2011). Simply put the formula as:

$$NER = \frac{Energy\ output}{Energy\ Input} \quad (1)$$

The NER of certain microalgae species are shown in the Table 2.2.

Table 2.2 NER value of some microalgae species

Microalgae species	Cultivation method	NER	Reference
Botryococcus sp.	-	1.51	(Lam & Lee, 2012)
Haematococcus pluvialis	Flat-plate photobioreactors	0.45	(Razon & Tan, 2011)
Nannochloropsis	Flat-plate photobioreactors	0.09	(Razon & Tan, 2011)
Tetraselmis suecica	Flat photobioreactors	0.6	(Tredici et al.), 2015
Nannochloris sp.	Open raceways pond	0.64	(Passell et al., 2013)

A study done in 2012 reported that the life cycle boundary covers microalgae cultivation, harvesting, drying, oil extraction, anaerobic digestion, oil transportation, esterification, biodiesel transportation and biodiesel combustion (Yanfen, Zehao, &

Xiaoqian, 2012). The important points highlighted in the study are summarized as follow:

1) During the production of microalgae biodiesel, fossil fuel is still required to run the process. It was found that 41% lower energy needed in the process of microalgae biodiesel production compared to fossil diesel fuels production.
2) Environmental concern on the high amount of CO_2 presents may be overcome with the consumption of microalgae biodiesel. This is due to the fact that during cultivation of microalgae, CO_2 is the main raw materials needed for its growth. As more rapid cultivation process of microalgae is carried out, large amount of CO_2 will be fed. Therefore, greenhouse gases effects on environment through microalgae cultivation shall be reduced.
3) Cultivation of microalgae for the purposes of biofuels production brings advantage to the renewable energy industry as it is a sustainable feedstock for the production of biodiesel.

2.6 Sensitivity analysis of biodiesel production

Sensitivity and economic analysis provides the economics feasibility of a system (Zhang, Dubé, McLean, & Kates, 2003). By conducting this analysis, the economic performances of a biodiesel plant such as fixed capital cost, manufacturing cost, and the breakeven price of biodiesel can be determined. The parameters which affected these performances are the plant location, raw materials price, plant capacity and technologies used in the system. Therefore, sensitivity analysis measures the magnitude of how much the parameters affected the economic performance of the production plant. Other parameters that can be used in sensitivity analysis is capital cost and the maintenance rate price of the plant (Tang, Zhenzhou, Zhiwen, & Ningcong, 2015).

CHAPTER 3
METHODOLOGY

3.1 Flow of the Analysis Project

Prior on conducting this analysis project, the whole flow of the project is determined which basically includes five main stages. The first stage is where the problem statement and objectives of the analysis is outlined which is done in order to identify the purpose of this project. A good way of determining it is by conducting a research on the need for a new analysis project on this particular project title. Hence, any redundancy in research outcomes can be avoided. During this stage, background reading on the current challenges, recommendation or way forward from previous research work is done in order to know the current needs or problems that rise this analysis project. It is also done in order to further improve the objectives of the project. By knowing the current problems and needs in this research field, more objectives can be aimed and achieved to serve or answer the needs.

To equip the analysis project with good source of input, literature review from various research papers, journals, books, articles and technical papers is done. Activities involved in this stage of project flow include reading and collecting information as much as possible from different sources regarding the project. This activity is done in order to fully understand the flow of the project, the current research that have been done by many researchers, the scope of current published works and any gap in between those work that this project can later fill up.

The next stage of the project flow is to define the methodology used in this project. Since analysis project is different from experimental work, the written methodology section will also be different. For example, the experimental steps,

equipment used, the amount of substances used in the experiment will be explained in the methodology section in most research paper. However, in this analysis project this is the stage where the scope of study is further refined and assumption are drawn before collecting data from published analysis. Any equations or scientific constant value to be used would also be determined and stated in this stage. It would later help to direct the analysis project based on a guideline that has been set up.

After all the pre-analysis work are done, data gathering and analysis stage is started. In this research project, no new data will be generated. Rather, published data from journals and research papers will be extracted and tabulated. The data extracted are ensure to follow within the scope and assumptions defined earlier and be given the credits to the respective researcher. This is the challenging stage of research project as not all research published provides data that suit the need of this current research project. Hence, data extracted need to be carefully pick, tabulated and analyzed to ensure optimum result from the research project. It would then be represented in the form of figures, tables or graphs as it would be easier for discussion to be made. Discussion would focus on the findings of this research project and at the same time relating it to current research done in similar topic. This is how analysis works and how it helps to provide insight of any topic. This analysis can later be used to improve research in experimental works.

After all of the analysis is done, it would then be documented and reported for future reference and use. Conclusion of the analysis is drawn in this stage stating the final decision based on the finding of this analysis project and may be supported with other conclusion from other analysis. This will show the similarities or differences in line with other analysis. For example, in this LCA study, the results and conclusion will be made and later be compared to other analysis. It would contribute on strengthening the findings from other research if it is the same. However, if it is different in will raise another scope of study for future analysis and in fact this is the way research and knowledge in a particular area or topic grows. This project flow is illustrated as in Figure 3.1.

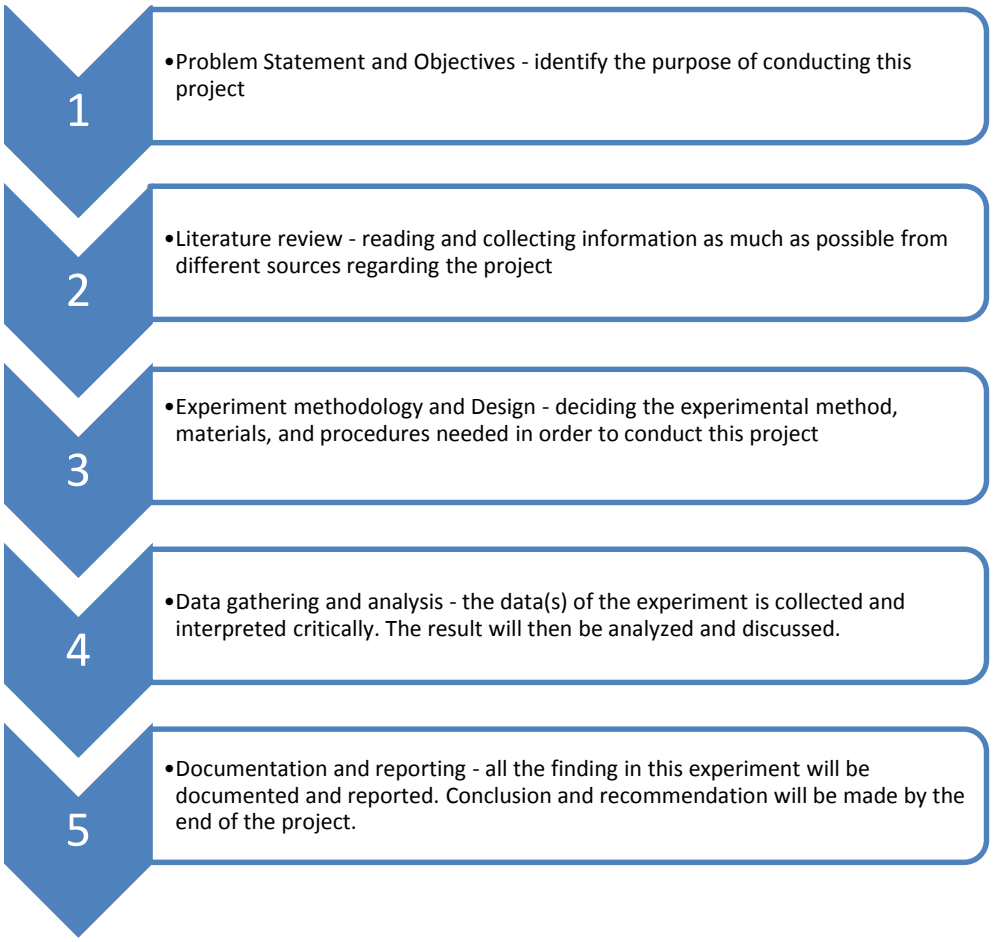

Figure 3.1 Flow of research project

Gantt Chart of FYP I

Table 3.1 Gantt chart of FYP 1

Details \ Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Date		27/5					2/7		13/7			4/8	14/8	
Selection of Final Year Project title		X												
Preliminary research work: Perform literature review related to the research project														
Plan on the methodology of the research project														
Submission of Extended Proposal to supervisor and FYP coordinator							X							
Prepare slides for Project Proposal Defense presentation														
Project Proposal Defense									X					
Defining scope of the energy analysis														
Interim report writing														
Submission of draft Interim Report to supervisor												X		
Submission of Final Interim Report (after revision).													X	

Gantt Chart of FYP II

Table 3.2 Gantt chart of FYP II

Week / Details / Date	1	2	3	4	5	6	7	8	9	10	11	12	13	
								9/11			1/12	7/12	18/12	12/1
Conduct the energy analysis														
Conduct the sensitivity analysis														
Report writing and data analysis														
Submission of progress report								X						
Analysis writing cont.														
Pre-SEDEX poster presentation											X			
Submission of dissertation (soft bound)												X		
Submission of Technical Paper												X		
Viva													X	
Submission of Project Dissertation (hard bound)														X

Key Milestones

Table 3.3 Key milestones of FYP I and II

FYP	Date start	Date End	Period	Milestones
FYP I	27/5/2015	27/5/2015	1 day	Selected the title for the research project.
	1/6/2015	26/6/2015	4 weeks	Literature review and extended proposal report writing
	29/6/2015	3/7/2015	1 week	Make correction and submitted to supervisor for evaluation
	6/7/2015	15/7/2015	2 weeks	Completed and presented proposal defense
	20/7/2015	7/8/2015	2 weeks	Data collection
	10/8/2015	14/8/2015	1 week	Completed interim report writing
FYP II	21/9/2015	9/10/2015	3 weeks	Energy analysis
	12/10/2015	23/10/2015	2 weeks	Sensitivity analysis
	26/10/2015	27/11/2015	5 weeks	Results analysis and technical paper report writing
	30/11/2015	18/12/2015	3 weeks	Completion of project, evaluation and submission of project dissertation.

3.2 System boundaries and assumptions

In this analysis, the net energy ratio calculation for the biodiesel production of microalgal biomass is done based on a specific microalgae species which is the *Nannochloropsis* is was said to be one of the potential microalge species for biodiesel production, alongside with other potentially species such as *Chlorella*, *Ankistrodesmus* and *Scenedesmus* because they have lipids level ranging from 30 – 50% and good productivity rate (Abu-Ghosh, Fixler, Dubinsky, & Iluz, 2015). The system boundaries that is chosen in this life cycle analysis includes the process of cultivation, harvesting, extraction and lastly the biodiesel production as what is illustrated as the proposed process flow diagram of the biodiesel production in Figure 3.2. It is assumed that the processes are working smoothly with no disturbances and give good result due to the reason that some important stages are not included in the consideration. For example, it is assumed that the CO_2 introduced to the cultivation is pure and readily available from external carbon capture system provided by flue gas from the heat and power plant. This allows no greenhouse gas emission as the CO_2 is recycled back into the system from the emission of biomass combustion (Razon & Tan, 2011). In other words, it is assumed that the CO_2 fed into the cultivation process of microalgae for biodiesel production purposes would at the same time brings benefit to the environment by bringing positive carbon cycle where less CO_2 is released to the environment compared to what amount is consumed during the whole process (Lam, Lee, & Mohamed, 2012).

Apart from that, it is assumed that the values of parameter used in this analysis are taken as a range of value extracted from comparative reviews of literature and may not necessarily represent exact amount, as what also has been done previously (Abu-Ghosh et al., 2015). This includes the amount of nutrients used in cultivation process, the amount of solvent used during lipid extraction process and the amount of heat and electricity used to power the whole biodiesel production.

In this energy balance analysis of microalgal biodiesel production which covers four system boundaries, the energy balance is done by comparing the quantity of

output energy of the biodiesel product and the input energy required to produce it. Hence, all of the energy unit values are set to use megajoule (MJ) of biodiesel energy value. The input energy is set as MJ per 1 kg dry biomass output and the output energy is MJ per 1 kg biodiesel (Khoo et al., 2011). The energy content of 1 kg methyl ester (biodiesel) is assumed as 37.8 MJ. Other research work has been using the much similar value of 37 MJ (Razon & Tan, 2011).

The lipid content of *Nannochlropsis* sp. as has been reported to be ranging from 20 – 68 % dry weight biomass (Ahmad et al., 2011; Chisti, 2007). In this analysis, it is assumed that the lipid content of *Nannochloropsis* dry weight biomass is at 35%. Assuming highly efficient extraction productivity of 99.5% (Topf et al., 2014), the amount of dry biomass microalgae that is required to produce 1 kg of lipids is taken as 2.9 kg of dry biomass theoretically. From that 1 kg of lipids, it is assumed that up to 90% of the total fatty acids will be converted to methyl ester (Hempel, Petrick, & Behrendt, 2012). Therefore, the amount of dry microalgal biomass required to produce 1 kg biodiesel is 3.2 kg.

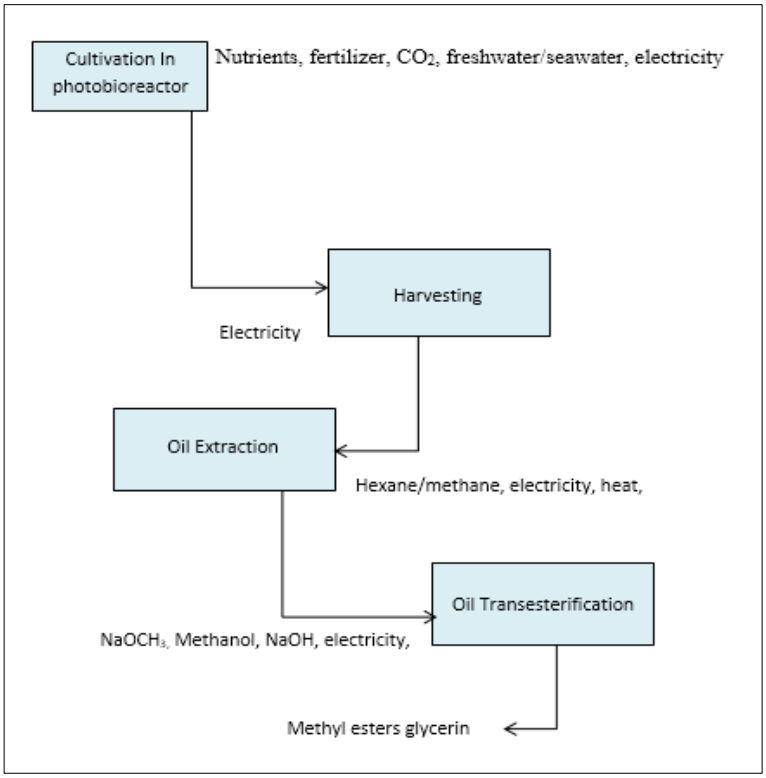

Figure 3.2 Process flow diagram of biodiesel production from Nannochloropsis

3.2.1 Cultivation of microalgae

The energy balance calculated in the energy analysis was based on the technologies that has been used for the cultivation of *Nannochloropsis* to be fed as the biodiesel production. Large scale microalgae cultivation to produce biodiesel are introduced through open pond raceway culture system. However this gives rise to the problem of contamination threatening microalgae growth, evaporation and water loss. Therefore, a closed system in a photobioreactor with the help of artificial lighting is designed and utilized to overcome the problem in the open culturing system (Khoo et al., 2011).

It is assumed to be a flat plate photobioreactor. This is because a tubular reactor would consume more energy as compared to plate and airlift reactor to the ratio of 28:1 (Lehr & Posten, 2009). During the cultivation, *Nannochloropsis* is given medium to grow such as nutrients, light energy and water. The nutrients that mainly given are nitrogen (N), phosphorous (P), and carbon dioxide (CO_2) obtained from external carbon capture system provided from flue gas. Other than that, in order to take an advantage of a clean fuels production process, the CO_2 supplied during the cultivation is assumed to be taken from the CO_2 released and thus created the CO_2 recycling scenario (Monari, Righi, & Olsen, 2015). However, the nutrients were not specified to be coming from any sources such as wastewater, plant compost or agricultural manures.

Nannochloropsis is one of the microalgae species that lives in sea water and this is advantageous since seawater is every high in salinity thus reducing the contamination that could exist during the cultivation (Abu-Ghosh et al., 2015). It was reported that the *Nannochloropsis* growth rate increased by 58% when being supplied by 15% of CO_2 contained in flue gas (Jiang, Luo, Fan, Yang, & Guo, 2011). On the other hand, it is assumed that electricity provided is coming from a natural gas fired combined heat and power (CHP) plant (Razon & Tan, 2011). All of these parameters given to maintain the cultivation will determine the energy requirement and energy balance of the process (Khoo et al., 2011).

In collecting data from previously published work, only direct energy inputs to produce dry biomass are taken. This includes energy input for harvesting, lipid extraction, biodiesel production and cultivation which distributed for air pumping, mixing of microalgae cultivated, and supplying CO_2 for the growth of the microalgae. The energy inputs is quantified as the amount of electricity used to do those work (Abu-Ghosh et al., 2015). Apart from that, the electricity usage in the flat plate photobioreactor during cultivation process has been studied and can be broken down into three which are 1) to pressurize flue gas supplied and to pump it into the cultivation system 2) to pump water for recirculation and 3) to pump water for cooling purposes (Jorquera et al., 2010).

3.2.2 Harvesting

In this analysis project, the harvesting process is taken to include coagulation flocculation/sedimentation, centrifugation and drying of the wet algal slurry into dried algal biomass cake (Medeiros et al., 2015). Other harvesting techniques that have been used but not considered in this analysis project are filtration, dissolved air floatation (DAF), ultrasound, gravity sedimentation and auto-flocculation (DAS, 2010). Algal harvesting process is said to be efficient if it can suit all type of microalgae species, helps in producing high lipid content per dry weight biomass percentage, require small cost, energy and maintenance (Poelman, De Pauw, & Jeurissen, 1997). The goal of harvesting is to separate solid-liquid microalgal biomass and can be done in one or more steps chemically, physically or biologically (Mata et al., 2010).

There are a few assumptions made in this analysis project. Firstly, an addition of chemical to act as a coagulant is needed because of the small size of *Nannochloropsis* cells which is around 2 – 5 µm (Jorquera et al., 2010). Aluminum sulfate ($Al_2(SO_4)_3$) or iron (III) chloride hexahydrate ($Fe_3.6H_2O$) is used and assumed can assist in sufficient flocculation (Khoo et al., 2011; Razon & Tan, 2011). Physically, harvesting is done by settling the microalgal cells by air sparging assisted coagulation flocculation (ASACF) and further concentrated to 15 – 20% of biomass solids by dewatering most of the water content from the wet biomass through centrifugation (Abu-Ghosh et al., 2015; Khoo et al., 2011). Drying the wet slurry is done by using

belt dryer and heat contributed from CHP plant although other method of drying such as zero energy input solar drying has been introduced (Abu-Ghosh et al., 2015).

Next, it is assumed that through all steps of harvesting, high amount of lipids is gained, no huge loss goes into waste and 100% lipids converted into biodiesel theoretically (Abu-Ghosh et al., 2015; Khoo et al., 2011). And lastly, the harvesting efficiency is considered to be around 70 – 90 % efficient in separating the microalgae biomass (Collet et al., 2014; Dassey et al., 2014).

3.2.3 Extraction

Nannochloropsis is one of the species that was discovered to have lipids level between 30% to 50% content which is ready to be extracted (Abu-Ghosh et al., 2015). Factors that affect the amount of extracted yield are the techniques used and the microalgae species involved. The techniques used can be mechanical or non-mechanical, depending on the algae cell wall and the nature of the product wanted (Dassey et al., 2014).

Instead of mechanical lipids extraction, this analysis considered the use of cheap and popular chemical which is hexane for solvent extraction (Khoo et al., 2011). Other attributes of using hexane is because it does not dissolve in water, thus making it easy to be removed or be recycled back into the process (Dassey et al., 2014). Hexane added is assumed to be recycled back into the process although some might be lost into the air and water (Passell et al., 2013).

Hexane (non-polar) and methanol (polar) are mixed to produce solvents that produce good yielding efficiency compared to the used of only non-polar solvent. (Khoo et al., 2011). Hexane will destruct the algae cells wall and extract the lipids while with the help of methanol, they will be separated into two phases when water is added. This will ease the process of separating the lipids in downstream processes (Dassey et al., 2014; Passell et al., 2013).

3.2.4 Biodiesel production

The final step in biodiesel production is the transesterification of triglyceride and alcohol with the help of alkaline or acid catalyst to produce fatty-acid methyl ester (FAME) and glycerol (by-product) (Passell et al., 2013). In this analysis, methanol is considered as it is the most common alcohol used for transesterification due to inexpensive, easily dissolved and fast reaction with triglycerides and alkaline catalyst (Yusuf, Kamarudin, & Yaakub, 2011). Alkaline catalyst is assumed in this analysis because alkaline catalyst is highly effective than acid catalyst (Ma & Hanna, 1999). There are several characteristics of alkaline catalyst which affect the product yield that needs to be considered before choosing it. Firstly, potassium-based catalyst yields better than sodium-based catalyst. Secondly, methoxide catalyst gives higher yield than hydroxide catalyst. Lastly, potassium-based catalyst produced more soap (unwanted product in biodiesel production) than sodium-based catalyst (A. Singh, He, Thompson, & Van Gerpen, 2006). Hence, sodium-catalyst which is sodium hydroxide (NaOH) and sodium methoxide ($NaOCH_3$) are both considered in this analysis.

This analysis will used the data of energy produced from transesterification of lipid, methanol and catalyst to produce biodiesel and glycerol. The equation representing transesterification process is as Equation 2 below:

$$Lipid + Methanol \xrightarrow[Catalyst]{} Biodiesel\ (90\%) + Glycerol\ (10\%) \qquad (2)$$

There has been two assumptions on the ratio of biomass extracted to biodiesel produced. First assumption stated that 2.2 kg dry algal biomass with 50% lipid per 1 kg dry biomass is required to produce 1 kg of biodiesel (Abu-Ghosh et al., 2015). Another assumption made states that 4 kg of algal biomass is needed to produce 1 kg of biodiesel, but without considering lipid extraction and biodiesel production process (Khoo et al., 2011). In this analysis, the assumption used is 3.2 kg dry algal biomass with lipid content of 35% will produce 1 kg of biodiesel.

3.3 Energy analysis

This analysis will be using Net Energy Ratio (NER) equation to calculate the ratio of input energy to output energy during microalgal biodiesel production. Data used are from various scientific publications and literature review that have been extracted following system boundaries and assumptions set in previous section. The NER equation is as equation (1).

The net energy ratio in this biodiesel production system is calculated by comparing the input energy of each LCA study stage with the output energy of the biofuel product. Lots of factors during this biodiesel production from microalgae biomass can influence the energy ratio (Khoo et al., 2011). The LCA study stages are as what determined as the system boundaries in previous section which is microalgae cultivation, harvesting, lipid extraction and biodiesel production.

3.4 Sensitivity analysis

Sensitivity analysis basically is used to estimate the effects of varying assumptions (Monari et al., 2015). This sensitivity analysis is done by varying certain parameters in this production of biodiesel which is the lipid content, lower energy requirement in harvesting and extraction process and more output energy demanded. The trend will be analyzed and plotted into graph to show either increment or decreasing.

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Net energy ratio

Appendix 1.1 shows the energy demand by each parameter of each system boundary to produce 1 kg of biodiesel. The net energy input per 1 kg dry biomass output is 633.5020677 MJ. This value is then converted to net energy input per 1 kg biodiesel will result in 2027.206617 MJ. The output energy per 1 kg biodiesel is 128.2026 MJ. By using equation (1), this will give the NER value of ≅ 0.06.

This NER value obtained is in line with other energy analysis such as with Razon & Tan (2011) and Passell et al. (2013) which obtained NER value of 0.09 and 0.64 respectively. This value is obtained regards to the good assumptions on the energy demanded along the production process. The energy consumed in the production of biodiesel is far larger the energy being produced (Dassey et al., 2014). Since the NER value is <1, it can be said here that the cultivation of microalgae to be converted into biodiesel is not feasible (Medeiros et al., 2015).

However, the NER value obtained in this study is contradicting with Jorquera et al. (2010) which yields >1. NER value due to the different system boundaries considered (no consideration given to harvesting, extraction and biodiesel production) in their study. If the NER value is 1 it will mean that the whole biodiesel production process is thermodynamically breakeven where all of the energy input provided will be producing the same amount of energy output. However in real life practice, this conclusion will not be feasible despite of really optimistic assumptions were made. Some energy will eventually loss to surrounding which will then decrease the efficiency of the whole process (Razon & Tan, 2011). Therefore, in order to achieve

the target of using 100% biofuels with zero environmental impacts and achieve high NER value, advancement and more researches need to be done in cultivating microalgae using renewable energy such as wind or hydropower and study the microalgae species that have high lipid content and high biomass production rate to utilize it (Passell et al., 2013).

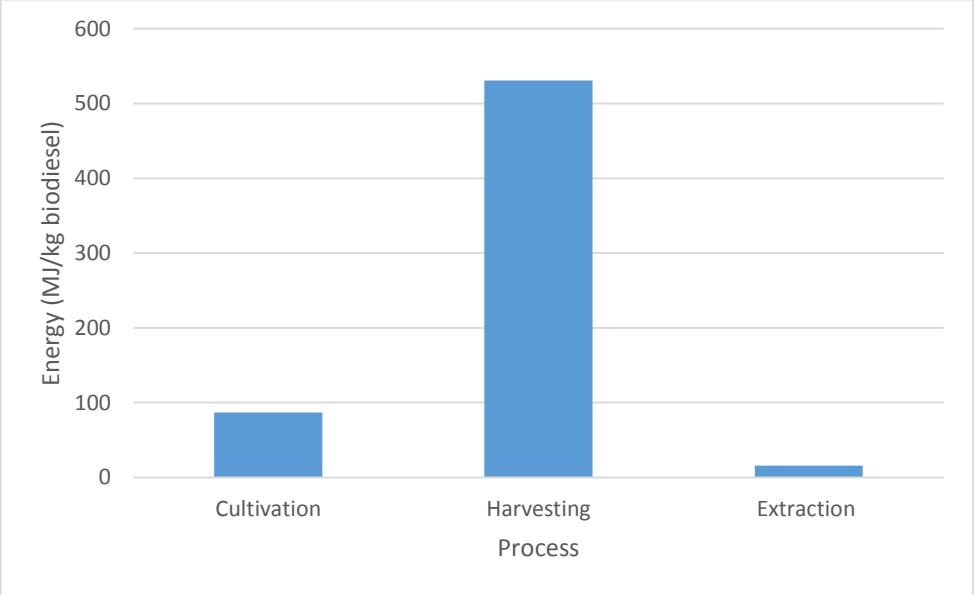

Figure 4.1 Comparison of energy demand to produce 1 kg of microalgal biomass

4.2 Harvesting

It is worth to analyze the energy demand breakdown by each biomass production process. Figure 4.1 shows that the energy demand for harvesting process is the highest compared to other processes. This will commonly happen when the production system deals with microalgae with low biomass concentration and if the systems increases the concentration to much higher consistency. Other than that, it demands high amount of energy due to the reason that it involve large amount of water that involves in this process to produce comparatively small amount of product (Dassey et al., 2014). Monari (2015) states that harvesting process is significant to be studied in energy consumption.

Heat from CHP plant shows a significant value compared to other parameters. This can be explained due to the requirement in centrifugation and drying techniques

which needs the CHP plant to allocate several supplies to electricity and energy allocation. It was assumed that this analysis only consider harvesting efficiency of average 80%. If the efficiency is considered much higher, it will increase the cost and would eventually increase the energy demand. It was suggested that rather than increasing the harvesting efficiency, it would be much preferable to trade it with saving the cost of operation (Dassey et al., 2014). It is also parallel with the findings from (Passell et al., 2013) that states among the largest contributor of energy demand is from the energy used in centrifugation in harvesting process.

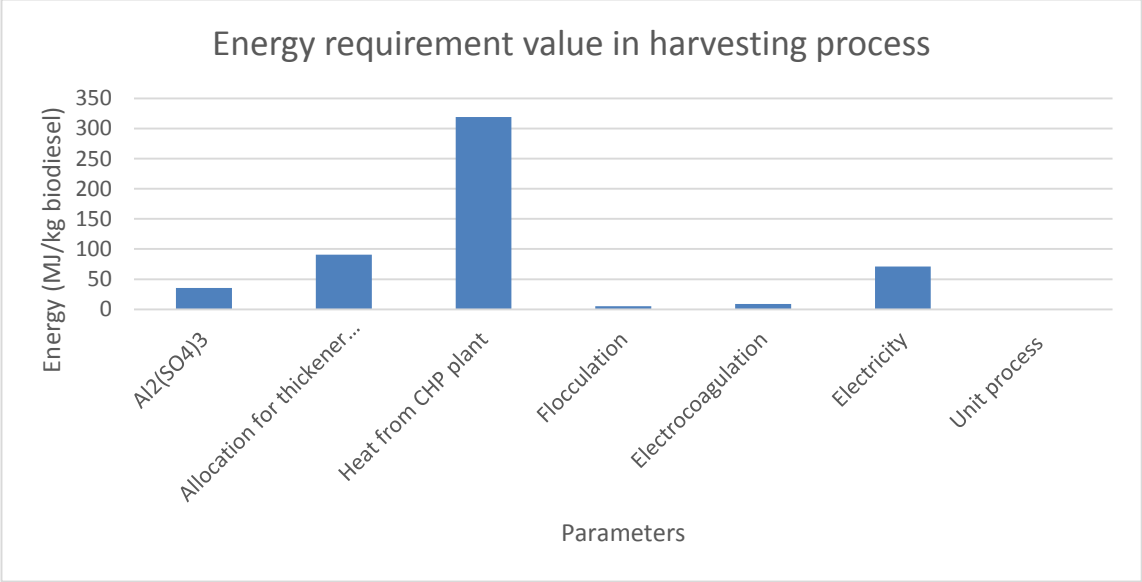

Figure 4.2 Energy demand breakdown on harvesting stage parameters

In Figure 4.2, it can be seen that the energy demand for flocculation is less compared to centrifugation that is represented under electricity as a parameter. Centrifugation requires 50% more energy compared to flocculation and other harvesting techniques such as filtration and separation (Sander & Murthy, 2010). This is due to the fact of small cell size of *Nannochloropsis* which demands the huge energy during centrifugation (Rodolfi et al., 2009). Despite flocculation requires less energy but it also has its downside. The flocculation done with aluminum sulfate produce settlements that are toxic for anaerobic digestion (Monari et al., 2015).

Energy demanded by aluminum sulfate is used during flocculation to separate microalgae cells from the wet slurry. Due to the microalgae cell wall containing negative charge, they prevent themselves from separation. In order to overcome these

negative charges, polyvalent ions (flocculants) are added (M. Singh, Shukla, & Das, 2013). The more microalgae cultivated and needs to be harvested, means they will be more cell walls that needed to be broken. Hence more energy is required during flocculation.

4.3 Cultivation

The second large energy demand contributors is the cultivation process. In this analysis, the cultivation system considered is flat plate photobioreactor (PBR). Based on Figure 4.3, significant energy demand was shown by electricity, nutrients for algae growth (KNO_3, P_2O_5 and NaOCl) and the PBR. In this analysis, even though the nutrients to be fed for microalgal growth which is mainly N and P do not really require much energy, however if this cultivation is to be made into large scale production, considerations have to be given in locating the location of source and cost of potential nutrients such as wastewater, waste nutrients and waste CO_2 that can beneficial to the cultivation of microalgal growth. Eventually, this strategy may help in realizing the aim of meeting energy demand in the future (Passell et al., 2013).

In comparison with open raceway pond and tubular PBR, flat plate PBR is more feasible because it favors high aerial and volumetric productivity, generates higher biomass concentration, consumes low volume of water and needs lower energy for pumping compared to tubular PBR (Jorquera et al., 2010). PBR is also affirmative in contributing to high energy input especially in mixing the microalgae broth (Abu-Ghosh et al., 2015).

Electricity shows the highest energy demanded in the cultivation process. This finding is parallel with other study where it is indicated that the electricity demand is used for flue gases and water pumping in the cultivation system (Medeiros et al., 2015). However, this demand for electricity can be reduced to 50 – 85% if the cultivation process uses electricity for flat plate PBR around values of 0.3 to 0.94 kWh per kg of dry biomass (Medeiros et al., 2015). Although no environmental impact assessment is included in this LCA study, it is worth to mention that high electricity consumed resulted in more than 50% of total value for environmental impacts such as

climate change, thinning of ozone layer, toxicity, radiations and etc. (Collet et al., 2014).

This is proven in the findings by Collet at al. (2014) that stated the nuclear plant operated to generate electricity for European energy supply is blazing out this the ionizing radiation. CO_2 demands no significant energy amount due to the reason that at the beginning of the analysis, it has been assumed that CO_2 is optimistically assumed to be obtained from external carbon capture system and utilizing the flue gas coming from the CHP plant that provides heat for the harvesting process (Abu-Ghosh et al., 2015). This finding is supported with the same discussion made where it was stated that CO_2 is insignificant in the whole energy consumption and does not make any obvious trend when illustrated in a graph due to its low energy estimates (Dassey et al., 2014).

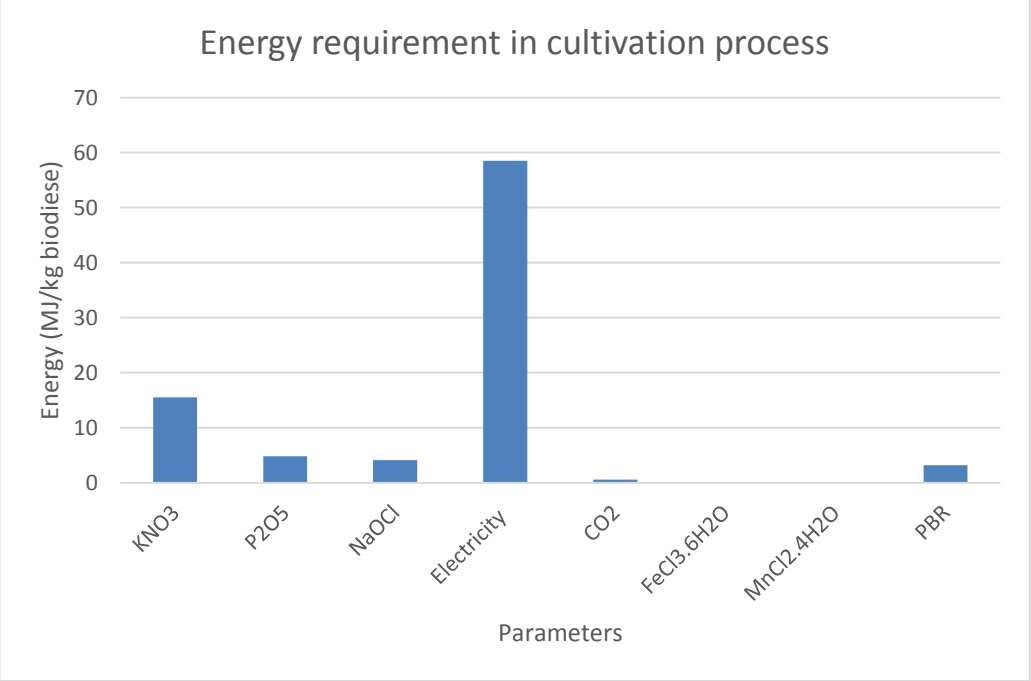

Figure 4.3 Energy demand breakdown for cultivation process parameters

4.4 Extraction

Based on Figure 4.4, lipids extraction shows the least energy demand compared to the other biomass production stages. Parallel with the analysis result from Lam & Lee (2012), this finding is in contrast with other analysis which discovered that lipids

extraction stage is the most energy demanding process (Khoo et al., 2011; Razon & Tan, 2011). This may be due to the technique selected for harvesting stage which was assumed to use non-mechanical lipids extraction technique which is by using chemical solvent and different lipids productivity assumed. Other than that, it may also be due to the technique of chemical solvent extraction that is used. This technique is said to be more efficient compared to mechanical technique of lipids extraction due to the high selectivity of chemical solvent (hexane and methanol in this case) towards microalgae lipid thus making it easier to diffuse and disrupt the algae cells for lipids extraction (Lam et al., 2012). Hence, contributing to less energy needed in overall biomass production stages. Figure 4.4 below shows the breakdown of each parameter involved in harvesting stage in this microalgal biodiesel. The chemicals involve are hexane and methanol whereas electricity and heat are the basic energy requirement to get the process working.

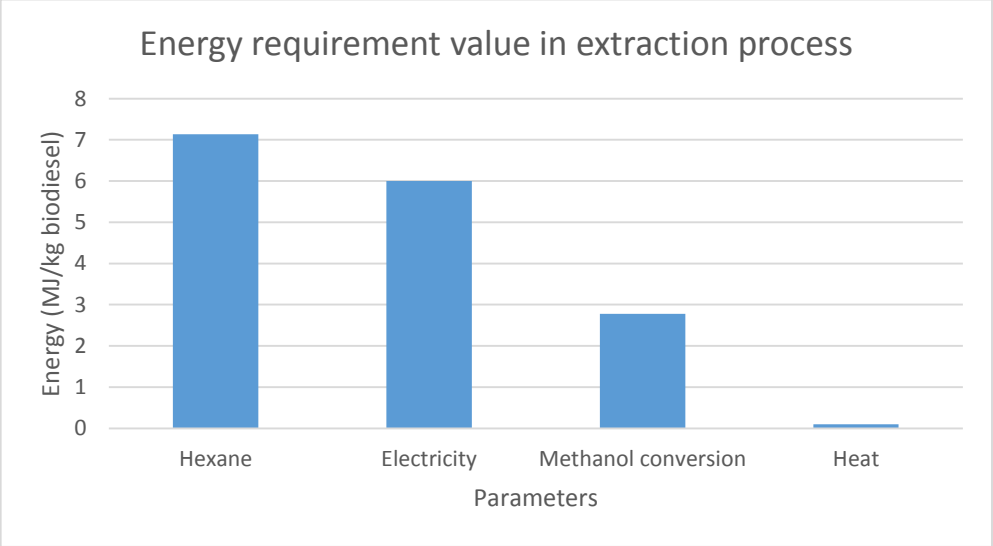

Figure 4.4 Energy demand breakdown for lipids extraction process parameters

Hexane uses the most energy compared to the other parameters yet still in the proportional ratio with methanol since the use of them were in ratio of 3:1 when lipids extraction takes place (Khoo et al., 2011). On the point of view where lipid extraction is done on a lab scale basis, the energy demanded by hexane and methanol for solvent extraction in this analysis is high and around the same value of energy required by ethanol-hexane extraction (EHE) method which is 7 MJ. This may be due to extra energy demand to condense the solvent from lipids that have been extracted to be recycled back in solvent recovery (González-Delgado & Kafarov, 2013).

The finding from one of the life cycle assessments notes that the parasitic energy demand in extraction is the one of the major hurdles that needs to be countered to ensure feasible microalgae to biodiesel production (Khoo et al., 2011).

4.5 Sensitivity analysis

Sensitivity analysis is done in order to study the effect and trends towards several parameters estimation to the energy demanded in this biodiesel production. Figure 4.5 below shows the overall sensitivity plotted in this analysis. Trend is observed for energy demanded in each system boundary except in this analysis the harvesting and extraction stage is combined to give better result representation. In general, it can be observed that the trend shows with respect to each parameter changes, the energy demanded is proportionally change as well. Changes are made referring to the base case of biodiesel production, which is taken from the energy analysis in the previous section. Three parameters change were considered in this analysis which is 1) increase in the lipids content from 20 - 70% 2) decrease in the energy requirement in harvesting and extraction stage and 3) increase in output energy produced.

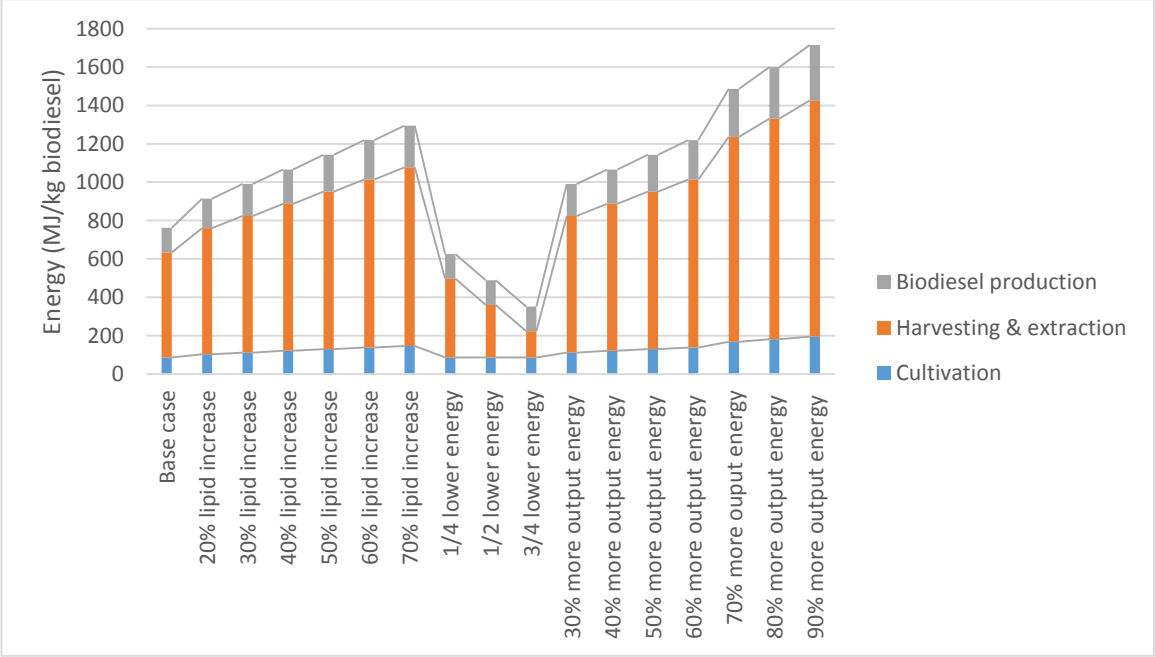

Figure 4.5 Overall sensitivity analysis of parameters in all system boundaries

4.5.1 Increment of lipids percentage (%)

Figure 4.6 below shows the sensitivity analysis result in estimating the increase in lipid content of the microalgae biomass extracted. Increasing lipid content in the microalgae cells is possible regardless of how much content they naturally have. In the base case, *Nannochloropsis* content around 35% lipid per dry 1 kg biomass. Increasing the lipid content from 20 – 70% manipulates the lipids to be ranging from 42 – 59.5% lipid content. It can be done by varying the lipid metabolism through providing less nutrients during microalgae growth or choosing species with high lipid content (Greenwell, Laurens, Shields, Lovitt, & Flynn, 2009).

Figure 4.6 shows that with the increase in lipid content, the energy demand in every system boundary would also increase. This is a logical and foreseen estimation as the more lipid content that needs to be gained, the more energy is needed to do the work. Normally, high lipid content per dry 1 kg biomass is ranging from 25 – 50% dry weight (Montero, Aristizábal, & Reina, 2011).

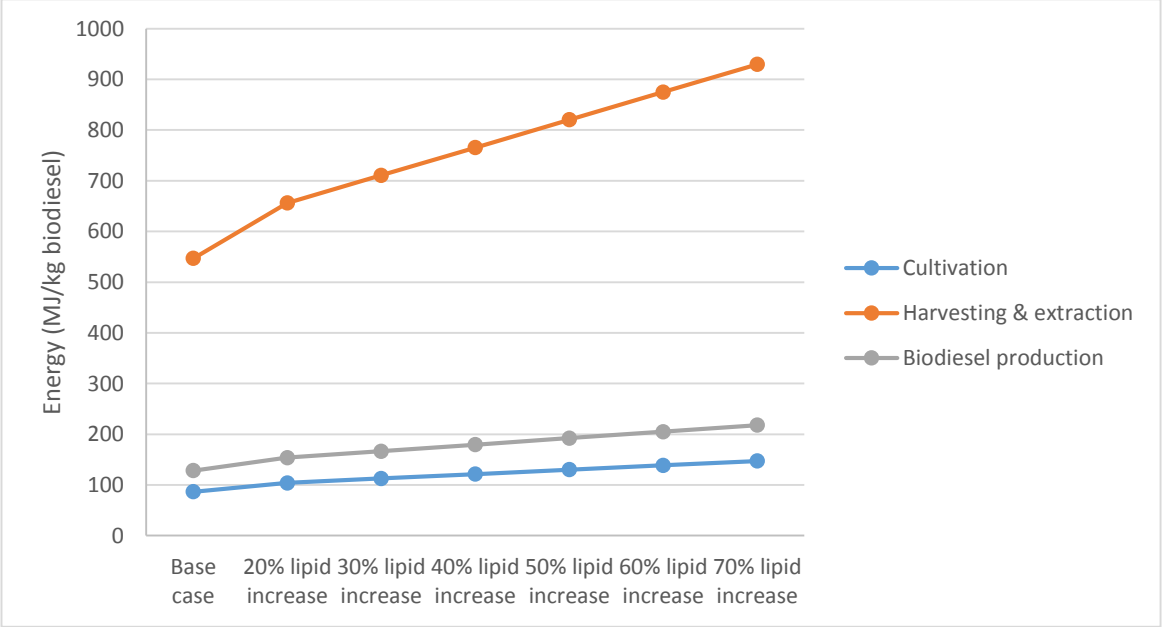

Figure 4.6 Sensitivity result for increase in lipid content

4.5.2 Lower energy in harvesting and extraction process

Figure 4.7 below shows the sensitivity analysis result in estimating the decreased in energy demand in harvesting and extraction stage and its effect towards the NER value. The energy analysis in the previous section found that harvesting and extraction were the two most energy demanding stage in biodiesel production process. This sensitivity analysis shows that if the energy demand could be minimize to the most possible rate, the NER value would shows a satisfying increment in its ratio. Increasing the NER means the biodiesel production from microalgal biomass is becoming more feasible and realizable.

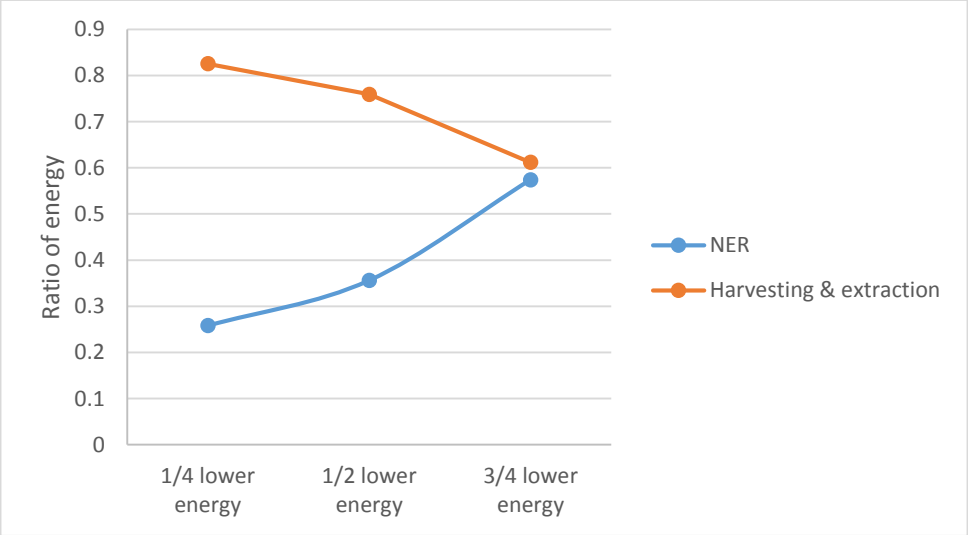

Figure 4.7 Sensitivity result of lowering energy demand in harvesting & extraction

Note that the graph plotted is between the lowered energy demand in harvesting and extraction stage combined and the ratio of energy. This means that y-plot does not represent the energy demand for the combined stages but the ratio of the new lowered energy forecasted and to the new total energy in biomass production (cultivation, harvesting and extraction).

4.5.3 Increment in output energy

Figure 4.8 shows the sensitivity analysis of predicted increment in output energy and its effect to the energy demand in each system boundary of microalgal biodiesel production. It shows here that in line with the increment in output energy

wanted, more energy demanded in the cultivation, harvesting and extraction stages. About 40% more energy needed to be supplied in these stages in order to produce more output.

However, in order to achieve more output energy, more consideration and study focusing on the upstream microalgal growth and cultivation process needs to be given. Research area that is potentially to be explored in order achieve that aim is search on improving productivity rate of lipid by manipulating the nutrients sources provided or the microalgae species that have thin cell walls thus requiring less energy for extraction steps (Medeiros et al., 2015; Razon & Tan, 2011).

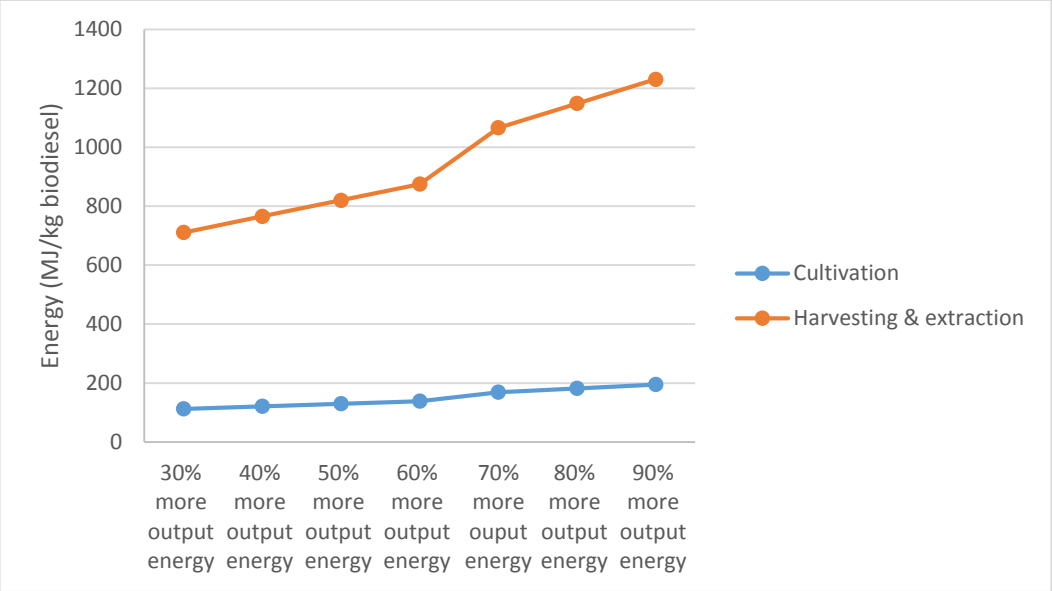

Figure 4.8 Sensitivity result from expecting more output energy

CHAPTER 5
CONCLUSION AND RECOMMENDATION

It is crucial for every aspect of LCA for biodiesel production from microalgae species to be done in order to provide further research on the possibility of utilizing it as the renewable energy in the future. This biodiesel source can then be used for the means of transportation and energy source to do work, and can then replace the use of fossil fuels. The result from this analysis project proves the potential of producing biodiesel from microalgae biomass. However, it is not feasible and not a viable choice to produce commercial biodiesel from microalgae biomass at this point as the NER value shows it is less than 1 despite optimistic assumptions and scope were determined. Primary target of generating biodiesel from microalgae biomass is to achieve pure energy generation of taking full advantage of photosynthesis to produce energy for human usage (Razon & Tan, 2011). This aim however is proven not possible in this analysis.

High energy input was consumed in several loopholes such as in providing the electricity, nutrients for growth as well as allocation of energy for the solvent based lipid extraction. This finding suggests the needs to explore and invent new techniques of favoring low energy demand for upstream microalgae biomass production. It is recommended to use natural sources of where nutrients are available for the cultivation of microalgae such as wastewater and natural compost. Apart from providing organic nutrients for the algae growth, environmental issues can also be contained and reduced.

As a recommendation, it is a good choice to consider *Nannochloropsis* for biodiesel production as it has high salinity of the seawater and therefore can minimize the contamination during cultivation process (Abu-Ghosh et al., 2015). However, in future research it is hoped that more research can done on *Nannochloropsis* species to

ensure the thoroughness of the LCA study. Apart from that, it is suggested for other species that might have the potential to be the focal point of research as well such as *Tetraselmis sueica*, *Haematococcus pluvialis* and *Tetraselmis chui* as they contain comparatively high lipid content (Chisti, 2007).

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APPENDICES

Appendix 1.1 Master data table of input and output energy for microalgal biodiesel production

Process	Parameters	Amount (kg)	Input Energy (MJ)	Output Energy (MJ)	References
Cultivation	KNO_3	0.17	15.5	0	(Razon & Tan, 2011)
	K	0.0000708	0.000201	0	(Ferreira et al., 2013)
	N	0.0000285	0.000272	0	
	P_2O_5	0.1	4.8	0	(Razon & Tan, 2011)
	P	0.00000507	0.0000446	0	(Ferreira et al., 2013)
	NaOCl	0.23	4.1	0	(Razon & Tan, 2011)
	Na	0.0000195	0.0000381	0	(Ferreira et al., 2013)
	Electricity	nil	58.512	0	(Razon & Tan, 2011), (Medeiros et al., 2015), (Passehl et al., 2013, (Monari et al., 2015)
	CO_2	nil	0.584	0	(Khoo et. al., 2011)
	$NaNO_3$	0.00015	0.002577	0	
	NaH_2PO_4	0.00001	0.0001718	0	
	$FeCl3.6H_2O$	0.0000063	0.000108234	0	
	$ZnSO_4.7H_2O$	0.000004	0.00006872	0	
	CuSO4.5H2O	0.000002	0.00003436	0	
	CoCl.6H2O	0.000002	0.00003436	0	

	$MnCl_2.4H_2O$	0.0000036	0.000061848	0	
	$NaMoO_4.2H_2O$	0.0000013	0.000022334	0	
	PBR	nil	3.21	0	(Khoo et. al., 2011), (Jorquera et. al., 2010)
Total energy (input) for cultivation (MJ)			86.70963436		
Harvesting	$Al_2(SO_4)_3$	3.9	35.6	0	(Razon & Tan, 2011)
	Allocation for thickener underflow	nil	90.9	0	
	Heat from CHP plant	nil	319	0	
	Flocculation	nil	5.09	0	(Dassey et. al., 2014)
	Electrocoagulation	nil	8.9	0	
	Electricity	nil	71.28	0	(Passehl et al., 2013), (Monari et al., 2015)
	Unit process	nil	0.0167	0	
Total energy (input) for harvesting (MJ)			530.7867		
Extraction	Hexane	0.003	7.133333333	0	(Razon & Tan, 2011), (Dassey et. al., 2014)
	Electricity	nil	5.9968	0	(Razon & Tan, 2011), (Passehl et al., 2013)
	Methanol conversion	nil	2.7756		
	Heat	nil	0.1	0	(Monari et al., 2015)
Total energy (input) for extraction (MJ)			16.00573333		
Total energy (input) per dry 1 kg biomass ouput (MJ)			633.5020677		
Total energy (input) per dry 1 kg biodiesel (MJ)			2027.206617		
Biodiesel Production	Methanol	0.605	22.689		(Razon & Tan, 2011), (Khoo et. al., 2011)
	Allocation for oil	nil	0	122.8	(Razon & Tan, 2011)

	NaOH	0.502	0.0756		(Razon & Tan, 2011), (Chee Loong & Idris, 2014)
	$NaOCH_3$	0.01	0.378		(Razon & Tan, 2011)
	Electricity	nil	0.36		(Razon & Tan, 2011), (Khoo et. al., 2011), (Monari et al., 2015)
	Heat	nil	0	2.8	(Razon & Tan, 2011), (Monari et al., 2015)
	Glycerol	nil	0	20.9	(Razon & Tan, 2011)
Total energy (output) per 1 kg biodiesel				146.5	

Appendix 1.2 Sensitivity analysis data calculation

Process	Cultivation	Harvesting & extraction	Ratio of energy lower to total energy input	Total energy input	Biodiesel production	NER
Base case	86.7096344	546.792433		633.5020674	128.2026	
20% lipid increase	104.0515613	656.1509196		760.2024809	153.84312	
30% lipid increase	112.7225247	710.8301629		823.5526876	166.66338	
40% lipid increase	121.3934882	765.5094062		886.9028944	179.48364	
50% lipid increase	130.0644516	820.1886495		950.2531011	192.3039	
60% lipid increase	138.735415	874.8678928		1013.603308	205.12416	
70% lipid increase	147.4063785	929.5471361		1076.953515	217.94442	
1/4 lower energy	86.7096344	410.0943248	0.82546509	496.8039592	128.2026	0.258054707
1/2 lower energy	86.7096344	273.3962165	0.759210704	360.1058509	128.2026	0.356013655
3/4 lower energy	86.7096344	136.6981083	0.611877219	223.4077427	128.2026	0.573850299
30% more output energy	112.7225247	710.8301629		823.5526876	166.66338	
40% more output energy	121.3934882	765.5094062		886.9028944	179.48364	
50% more output energy	130.0644516	820.1886495		950.2531011	192.3039	
60% more output energy	138.735415	874.8678928		1013.603308	205.12416	
70% more output energy	169.0837871	1066.245244		1235.329031	249.99507	
80% more output energy	182.0902322	1148.264109		1330.354342	269.22546	
90% more output energy	195.0966774	1230.282974		1425.379652	288.45585	