Master's Thesis:

Evaluation of the Biogas Utilization for Electricity Generation at Multi-Feedstock Bio-Refineries in Thailand

by

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Certification Page

I, Tantiwatthanaphanich Thanapan (Student ID 51215005) hereby declare that the contents of this Master's Thesis are original and true, and have not been submitted at any other university or educational institution for the award of degree or diploma.

All the information derived from other published or unpublished sources has been cited and acknowledged appropriately.

TANTIWATTHANAPHANICH Thanapan

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Summary

A model of multi-feed stock bio-refinery (MFSB) is introduced in this study as a response to Thai Alternative Energy Development Plan (AEDP2015-2036) and to fully utilize these crops by producing bio-ethanol and biodiesel, as well as poly-lactic acid (PLA). MFSB, has high resistance against volatile price risk of products as a producer does not have to rely on single product and has. However, to operate three productions together, producing will have high operating costs; therefore, as of current time, none of MFSB has been established yet in Thailand. This study aims to suggest a model with low operating cost and low greenhouse gas (GHG) emission by utilizing biogas for electricity generation. Life cycle inventory data were analyzed, and a simulation that adopts LCA methodology was applied to calculate profits and GHG emission for comparing no biogas case and biogas utilization case in order to see the improvement. Also, this study is the first to perform optimization analysis and regional analysis for bio-refinery study based in Thailand. As MFSB, the utilization of biogas for electricity generation successfully improved the profit and minimized GHG emissions, with the ratio being [cassava for PLA: sugarcane: oil palm], the best ratio is at 60:30:10. This ratio shows potential to achieved government's target for biofuel production, which consider to be eco-efficient at 14.32. Based on regional analysis, it is found that Northern, North-Eastern and Central region have equal potential for establishment of MFSB. However, the productional yield of energy crops in the three regions still need to regulated for biofuels and bioplastic production with higher eco-efficiency. As a contribution toward policymakers, this study provides the recommendation over the crops production yield which is at the ratio 60:30:10; by doing so, it will be possible for the producers to expand the bio-refineries in Thailand. Also, farmers will gain more income for producing the crops based on this ratio as it will be on demand and job related with plantation will also be generated as well.

Chapter 1: Introduction

Fuel is a major factor in the economic development of Thailand. Due to continuous increase in demand for energy, renewable energy becomes an attractive alternative to increase the energy supply. At present, the government of Thailand aims to increase the use of renewable energy and promotes several types of them based on Alternative Energy Development Plan (AEDP 2015-2036). Biomass energy is the important one due to Thailand status as the agricultural country that can produce large amount agricultural production such as rice, sugarcane, cassava and oil palm (Achawangkul Y., 2015). These products can be transformed into energy which has less impact to the environment in term of greenhouse gas emission comparing with energy from fossil fuel (Nguyen, T. L. T., Gheewala, S. H., & Garivait S., 2007a; Sutabutr, T., 2013). Therefore, the government would like to increase the biofuel utilization to be 20-25 % of total domestic fuel demand by including bio-ethanol and biodiesel as a major fuel (Achawangkul Y., 2015; Japan International Cooperation Agency (JICA)), 2015).The rest of fuel demand include benzene (12%), diesel (31%), LPG (12%), natural gas (9%), plane fuel (9%), and kerosene (2%) (Ministry of Energy, 2015).

Thai government has issued policies that support the plantation of energy crops, including cassava, sugarcane, and oil palm. In 2011, Thailand needed 2.4 million L of bio-ethanol and 3.0 million L of biodiesel per day; however, the sugarcane is always below the demand (SAF, 2011). To increase the sugarcane, it can be grown on the edge of a growing field. Cassava and oil palm also have been pressured to meet the country’s demand; however, both of them became restricted in the amount of land.

Thai farmers apply poly-culture plantation method to increase crops yield for the limited plantation area to meet the demands for agricultural products. By growing several crops in the same field or combining different agricultural activities together, the biodiversity of crops increases and the problem of crop production and animal products can be overcome. In some region of Thailand, Thai farmers efficiently utilize their area by planting sugarcane together with growing cassava in between a row of oil palm in order to increase their production yield of crops and to generate income throughout the year (Palangkaset, 2015; Suratthani Oil Palm Research Center, n.d.). As these three feedstocks have an ability to grow together and also to tolerate a harsh environment condition during dry season in Thailand (Jakrawatana, N., Pingmuangleka, P., & Gheewala, S.H., 2016).

In order to respond to the need of renewable energy and to take full advantage of polyculture plantation, this thesis focuses on a multi-feedstock bio-refinery model, which is a model that apply from a single feedstock facility. The focused feedstocks are cassava, sugarcane, and oil palm, which can utilize to produce bio-ethanol and biodiesel, a major concerned renewable energy. Additionally, cassava and sugarcane contain high contents of carbohydrate and sugar respectively, so these feedstocks have a potential to produce bio-polymer, poly-lactic acid (PLA) which is a biodegradable plastic (Chiarakorn, S., Permpoonwiwat, K. C., & Nanthachatchavanakul, P., 2014). Producing various types of bio-products will create higher value to biomass feedstock than producing only a single because it has a variety of applications. Therefore, it has potential in increasing profitability.

From the previous studies in Thailand, most studies focused on life cycle assessment (LCA) of biofuels and bioplastic production by concerning only one type of feedstock individually to improve energy efficiency and environmental impacts (Nguyen, T. L. T., Gheewala, S. H., & Garivait, S., 2008; Papong, S. & Malakul, P. 2010; Pleanjai & Gheewala, S. H. 2009; Silalertruksa, T., Gheewala, S. H., & Pongpat, P., 2015; Silalertruksa T. & Gheewala, S. H., 2009; Silalertruksa, T, Pongpat, P., & Gheewala, S. H., 2017). Based on the LCA study of (Papong et al., 2014), the overall GHG emission can be lowered by improvement of utilizing wastewater to produce biogas for stream and electricity production in the facility. (Groot, W. J. & Boren, T., 2010) assessed the environmental aspect in the production of bio-plastic, PLA, from sugarcane using LCA method and concluded that producing PLA results in significantly lower emissions of GHG, and use less material resources and fossil fuels when compared to fossil-based polymer. (Papong, S. & Malakul, P. 2010) studied the energy efficiency of biodiesel production from palm oil and found out that palm oil is a very efficient feedstock for biodiesel production as it can produce energy three times of the energy it consumed during production.

Additionally, Italian researchers found that the grouping several related-processes together will improve environmental impact. (Daddi, T., Nucci, B., & Iraldo, F., 2017) used LCA to assess the environmental benefits from the grouping various production together and found that waste from production can be reduced, and the production cost can be lowered. Therefore, a multi-feedstock bio-refinery would be a good configuration on environmental aspects.

Even though a multi-feedstock bio-refinery has such a positive benefit, it is not widely in-practice due to the economical limitations which are high cost of establishment and high cost of energy in order to operate the whole process. Many researchers are seeking the way to improve the energy efficiency and economic performance of the process (Nguyen et al., 2007a; Papong S. & Malakul P., 2010; Chinnawornrungsee R., Malaku; P., & Mungcharoen, T., 2013; Silalertruksa, T. & Gheewala, S. H., 2009). One of the important processes in bio-refinery model is the combustion of non-fossil fuel for generating electricity. Since a normal plant usually requires large amount of electricity, coal is use as a fuel for electricity generation because it has high heating value and can be acquired at low cost. However, coal burning produces substantial amount of CO_2 which are emitted into environment via stacks (Nguyen, T. L. T., Gheewala S. H., & Garivait S., 2008). The idea of using biogas and by-products to generate electricity has attracted more attention in recent years. Even though the energy efficiency from biogas and by-products might not be as good as coal combustion, the environmental impact would be greatly improved (Papong S. & Malakul P., 2010).

Recently, there was a study in Thailand that focuses on a multi-feedstock bio-refinery of cassava and sugarcane feedstocks that produced bio-plastic and bio-ethanol (Chinnawornrungsee R., Malaku; P., & Mungcharoen, T., 2013). The study found that the eco-efficiency of the bio-refinery improves by integrating efficient feedstock utilization, utilizing bagasse for electricity generation, and minimizing waste. Moreover, he stated that there has not been any multi-feedstock bio-refinery established yet in Thailand.

Therefore, this study would like to develop a new multi-feedstock bio-refinery model that apply biogas utilization for electricity generation in order to achieve in both economic and environmental aspects, and meet the biofuels demand by Thai government. The analysis on energy, profitability, and emission should be conducted in order to study the degree of potential improvement made by utilization of biogas in the multi-feedstock bio-refinery. This research performs optimization analysis by using the combination of cassava, sugarcane and oil palm to find the most suitable ratio that gives high profit and low GHG emission (eco-efficient). The regional analysis is performed in this study to find potential region(s) for establishing a multi-feedstock bio-refinery in Thailand.

1.1. Research Questions

This study aims to suggest an eco-efficient model for cassava, sugarcane, and oil palm based multi-feedstock bio-refinery in Thailand that focused on the effective energy management. The utilization of biogas for electricity generation is concerned in this study. The conducted research will focus on answering the following question:

How would the utilization of biogas, a co-product, for electricity generation in the multi-feedstock bio-refinery in Thailand affect the profitability and environment?

The analyses on energy, profitability, and GHG emission are conducted to see the effect of biogas whether it can improve the operating profits and the GHG emissions.

Furthermore, the extent of how much the profits and emission have been improved by biogas is also assessed as well.

In order to answer the research question, the research would conduct by set the boundary of the process in bio-refinery. The process of cassava includes two different process for products: production of bio-ethanol and production of poly-lactic acid (PLA) resin. The second feedstock, sugarcane is also used to produce bio-ethanol and PLA; in addition, the bagasse left from sugarcane milling will be materials for producing methanol, which can be used for producing the biodiesel. For the last feedstock, oil palm is used as a main ingredient to produce biodiesel, with glycerol as a by-product. The wastewater from all these processes will be collected to produce biogas for electricity generation.

This study wants to determine the ratio for feedstocks because the amount of feedstocks will altogether determine the energy consumption and the amount of waste water produced which, the latter, affect the production of biogas for electricity generation, which ultimately affect the operating profit and GHG emissions. Therefore, optimization analysis is conducted on both before and after applying biogas cases and analysed based on eco-efficiency. Moreover, as the crops grow at a different rate when the climate of each region may differ from each other, regional analysis is conducted to see how the regional yield of crops would affect the profits and emission of bio-refinery as well. Altogether, the results of these analyses will tell us how biogas utilization in the proposed model of Thailand’s multi-feedstock bio-refinery for electricity generation would affect the operating profits and the environment.

2.2. Significance of the Study

This study aims to develop a model of bio-refinery by concerning in both economic aspect and environmental aspect of whole process of multi-feedstock bio-refinery, including bio-ethanol production process, bio-polymer process, and the biodiesel production process. Due to multi-feedstock based bio-refinery is not yet exists in Thailand (Chinnawornrungsee R., Malakul P., & Mungchareon T., 2013) and the high energy cost in production (Himmel et al., 2007), this research would be useful to improve the energy performance of bio-refinery model by concerning in the utilization of biogas for generating electricity.

As a contribution, the results from this study can suggest to manufacturers who seek to pursue the establishment of low operating cost, low GHG emissions multi-feedstock bio-refinery in Thailand with the suitable ratio of cassava, sugarcane and oil palm. The ratio can be suggested to policy-makers as policies that regulate the energy crops growing in Thailand. For researchers, this study can be used as a reference and can suggest the processes that need technological improvement further.

Chapter 2: Literature Reviews

2.1. Thai Energy Development Plan

Thailand is one of the countries in South East Asia, and within the Association of South East Asian Nations (ASEAN), Thailand has the 2nd largest economy (International Energy Agency (IEA)), 2016). The population is 67.96 million and GDP growth is 2.8 % in 2015 (World Bank, 2016). Thai economy mostly depends on exportation of agricultural products such as rice, shrimps, sugarcane and rubber. Others that are international trade such as automotive and electronic goods.

Since Thailand's economy is rapidly growing, several industries and manufacturing plants are established. Therefore, the energy consumption in Thailand has continuously increased over the years. In 2015, the total energy consumption was at 2,595 thousand barrels of oil equivalent per day, and it forecast to increase by 1.8% in 2016. Every types of energy are expected to increase since the economy is expanding by the acceleration of public spending and investment, and slow recover of global economy. The remaining low of world market crude oil prices and the restructure of LPG price affect in increasing petroleum products demand such as diesel, gasoline and gasohol. In term of Electrical demand, it is expected to increase 3.5 % from the previous year and the expected import dependency will reach 31.7 %. Moreover, Thai government has implemented policy to promote Asian tourists come to Thailand, caused the use of jet fuel to grow (EPPO, 2016).

Hence, Thai Ministry of Energy has implanted Thailand Integrated Energy Blueprint (TIEB 2015-2036), which will focus based on 3 categories; (1) Energy

Security, (2) Economy and (3) Ecology. In order to create stability for national energy demand, to create reasonable energy cost and to reduce impacts on the environment. TIEB consists of 5 energy master plans, one of them is Alternative energy development plan (AEDP2015-2036) (Ministry of Energy, 2015; Wiwattanadate, D., 2015). This plan has strategies to promote energy production from the domestic renewable energy resources, as well as considering the environmental benefits in social level. The target of this plan is to increase the renewable energy portion in total energy consumption from 11.9% in 2015 to 30% by 2036; for biofuel alone, the government would like to increase the biofuel utilization from 1,782.16 ktoe to be 8,712.43 ktoe (or from 7 % to be 20-25 % of total domestic fuel demand). This biofuel includes as the following (Achawangkul, Y., 2015; JICA, 2015);

- Bio-ethanol from 3.21 million litre/day to be 11.3 million litre/day
- Biodiesel from 2.89 million litre/day to be 14 million litre/day
- Others are pyrolysis oil, compressed biogas, hydrogen and etc.

Thai Government take several actions to increase an investment, production and workforce on renewable energy market. Several measures and strategies are adopted such as feed in tariff system (FITs), minimum energy performance standards (International Energy Agency (IEA)), 2016), smart grid project implementation, regional energy learning center establishment and high biofuel content on automotive development plan (Ministry of Energy, 2015). By following the renewable energy policy, the expected achievement is to reduce the use of fossil fuels around 39,388 ktoe and to reduce greenhouse gas from burning around 140 million ton CO_2eq.

2.2. Agricultural Production of Thailand

Thailand is the country that abundant in agricultural products, these products generate a lot of residues or biomass. Large amount of biomass is utilized as an energy sources in residential and manufacturing sectors such as biofuel for vehicle transportation, biogas for household cooking and heating, as well as generating electricity (Papong, S., Yuvaniyama, C., Lohsomboon, P., & Malakul P., 2015).

The major source of biomass in Thailand come from important economic crops, which are rice, oil palm, sugarcane and cassava. These crops are considered as a lot of residue availability. The residues from rice is rice straw, which can be utilized as a feedstock for dimethyl ether production, a biofuel for substituting diesel; however, rice is not a commonly used for ether production as it is more important as crop for food consumption (Lecksiwilai, N., Gheewala, S. H., Masayuki, S., & Yamaguchi, K., 2016). For oil palm, it can be directly utilized to produce biodiesel and the residue can be utilized as a compost. Moreover, based on the policy in recent years, Thai government has been promoted in increasing bio-ethanol production. Since sugarcane and cassava have a potential to produce bio-ethanol due to its lignocellulosic content, the cultivation areas have been increasing rapidly (Himmel et al., 2007).

Thai farmers have been implementing polyculture plantation for a long time. Polyculture farming is a practise that incorporate multiple agricultural activities to meet the consumer demands or to reduce the risk of fluctuating price of agricultural products. The mechanism of polyculture plantation in Thailand was developed through trial and error process, not from an existed knowledge. Sometimes farmers gain the benefits from the activities that coincidentally support each other. By growing several crops in the same field or combining different agricultural activities together, the biodiversity of crops increases and the problem of production of crop and animal product can be overcome. Furthermore, the impact of pests and weeds reduce simultaneously (Ministry of Education, 2008).

Field crop likes sugarcane and cassava is usually planted in the upland farmlands, especially in North east region of Thailand (Ekasingh, B., Gypmantasiri, P., Thong-ngam, K., & Grudloyma, P., 2004). For oil palm, the cultivating area mostly is concentrated in the southern part, however in the past few years; the area has been expanding constantly to the eastern and north eastern region due to the government policy to increase biodiesel production. Expanding the cultivating area of oil palm is a difficult task to perform since the natural environment is hardly suitable for the cultivation. Nevertheless, the expansion of oil palm plantation is still on going until today (Dallinger, J., 2011; Papong et al., 2015; Somnuek, S., Slingerland, M. A. M., & Grünbühel, M. C., 2016).

Thai farmers have been applied polyculture plantation by planting sugarcane, cassava and oil palm together in the same area. By growing cassava in between a row of oil palm, farmer can utilize the area efficiently (Palangkaset, 2015; Suratthani Oil Palm Research Center, n.d.). Moreover, in Nong Khai, which is the province in the northeast region, oil palm is acceptedby some farmers as an alternative crop beyond sugarcane and cassava, which have an ability to tolerate harsh environmental conditions during dry season (Jakrawatana et al., 2016; Nawata, E., Nagata, Y., Sasaki, A., Iwama, K., & Sakuratani, T., 2005), since it has long life cycle and able to generate income throughout the year (Somnuek et al., 2016).

2.2.1. Cassava

Cassava is an agricultural crop which is commercially planted in tropical region country, including Thailand. The major source of cassava is carbohydrates. It can be classified as two types which are sweet and bitter. Both types contain hydrocyanic acid which is a toxic to human; however, the sweet type contains lesser amounts (Jansson, C., Westerbergh, A., Zhang, J., Hu, X., & Sun, C., 2009). Therefore, the sweet type can be eaten directly or through cooking process while the bitter type can be processed into animal feed and used as raw material in the industry (Von Blottnitz, H., & Curran, M. A., 2007). Presently, industry in Thailand mainly use cassava to produce bio-ethanol for gasoline additive and, to produce bio-polymer, poly-lactic acid (PLA) which is a biodegradable plastic (Siriluk, C., Chompoonuh, K. P., & Papondhanai, N., 2014).

2.2.1.1. Cassava Based Bio-ethanol Production

In Thailand, the most suitable biomass materials for ethanol production is cassava because, as one of the largest cassava producer in the world, large amount of cassava feed stocks is on a surplus while sugarcane is always on a shortage (Sorapipatana, C., & Yoosin, S., 2011) and cassava crop has an ability to adapt and grow in harsh conditions. Moreover, the cassava based ethanol production plants can continuously operates compare with sugar based ethanol plants that are operated seasonally, depending on the availability of sugarcane (Nguyen et al., 2007a). Based on the study of (Papong, S. & Malakul P., 2010), the utilization of cassava in Thailand industry can be classified as the following;

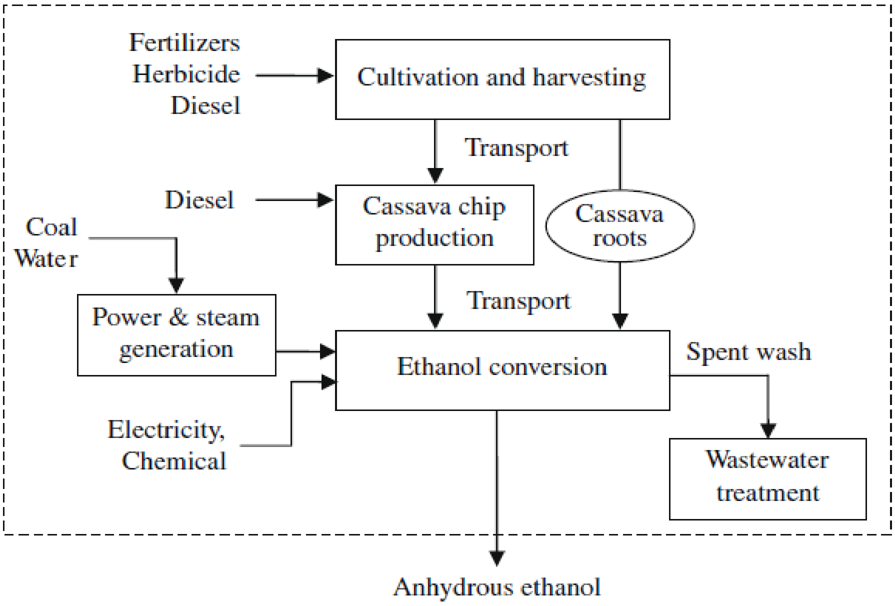

Figure 1: System Boundary of Bio-ethanol Production from Cassava

(Papong, S. & Malakul, 2010)

The production can be classified into 3 main processes which are Cultivation/Harvesting, Chip production and Ethanol conversion as shown Figure 1. The sequences of the processes can be explained as the following; (Papong, S., & Malakul, P., 2010)

1.) Harvest cassava from the farm and transport to the factory as an input material. Fertilizer and herbicides might be used during harvesting.

2.) Input the cassava into chip production process which includes chopping, sun drying and turning to chip.

3.) Transport chip to ethanol conversion process. This process can be briefly explained from the stoichiometry below (KAPI, 2006). Bio-ethanol is produced by, first cassava chip that contains starch requires milling and mixing with water. Then comes in to hydrolysis process with a presence of amylolytic enzymes to produce fermentable sugar which is glucose. After that glucose comes in to yeasts fermentation process and obtained products are bio-ethanol and CO_2. Then, the ethanol product goes to distillate to increase the concentration of bio-ethanol and release fuse oil and thick slop which are considered wastes. This slop contains yeast cell in waste water and residue.

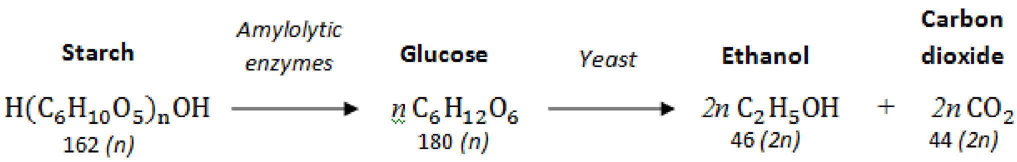

Figure 2: Stoichiometry of ethanol conversion from starch-based feedstock (KAPI, 2006)

From bio-ethanol production, the obtained wastes are CO_2 , fuse oil, waste water which contains yeast cell and residue. For the current time, previous study has shown that manufacturing plants in Thailand use different method for waste disposal. Some of the manufacturers manage waste water by producing biogas through anaerobic digestion process, which can further combust to generate electricity to the factory, but most of manufacturer use coal instead due to low cost. The waste can also be mixed with sludge to make a fertilizer. These utilizations of waste can increase value of the waste product and generate more profits to manufacturer. Besides that, (Papong, S. & Malakul, P., 2010) proposed that the utilization of co-products can reduce the total energy usage in the production by 10-20% instead of coal. However, several plants still do not have CO_2, fuse oil and waste water accumulate system. Their waste management facilities might be impropriated and could have caused environmental impact (KAPI, 2006).

2.2.1.2. Cassava Based Bio-polymer Production

Bio-polymer is a polymer that produces from living organism and can be bio-degradable. Biopolymer is considered as a new industry; many researches and developments on bioplastic around the world has stared by focused on creation of products to replace general plastics. Polylactic acid (PLA) is one type of biodegradable plastics that derived from agricultural crops fermentation to produce lactide monomer and then condense and polymerized into PLA. This bioplastic has high economic value due to its applications for example; implants devices, drug delivery systems, plastic bottle, diapers, electric appliances, and with around 70% of PLA used for packaging applications.(Plastics Institute of Thailand, 2013; Suwanmanee, U., Leejarkpai, T., Rudeekit, Y., & Mungcharoen, T., 2010). PLA properties is considered as good appearance, high mechanical strength and low toxicity, which broaden the applications. It is also considered as no toxicity in production and decompose back into CO_2, water and biomass, which takes around 90-180 days to compost at high temperature in a commercial facility (Auras, R. A., Lim, L. T., Selke, S. E. M., & Tsuji, H., 2011).

Cassava feedstock can be used to produce PLA since mostly of cassava root that produced in Thailand mainly consist of starch or carbohydrate around 25 % (Chiarakorn, S., Permpoonwiwat, K. C., & Nanthachatchavankul, P., 2011). The starch can be transformed to glucose and then to produce lactic acid. Lactic acid is used for synthesis PLA through fermentation, condensation and polymerization process. Figure 3 is shown the process of poly-lactic acid from cassava feed stock based on the study of (Papong et al., 2014) that studied the environmental comparison between PLA and PET bottles.

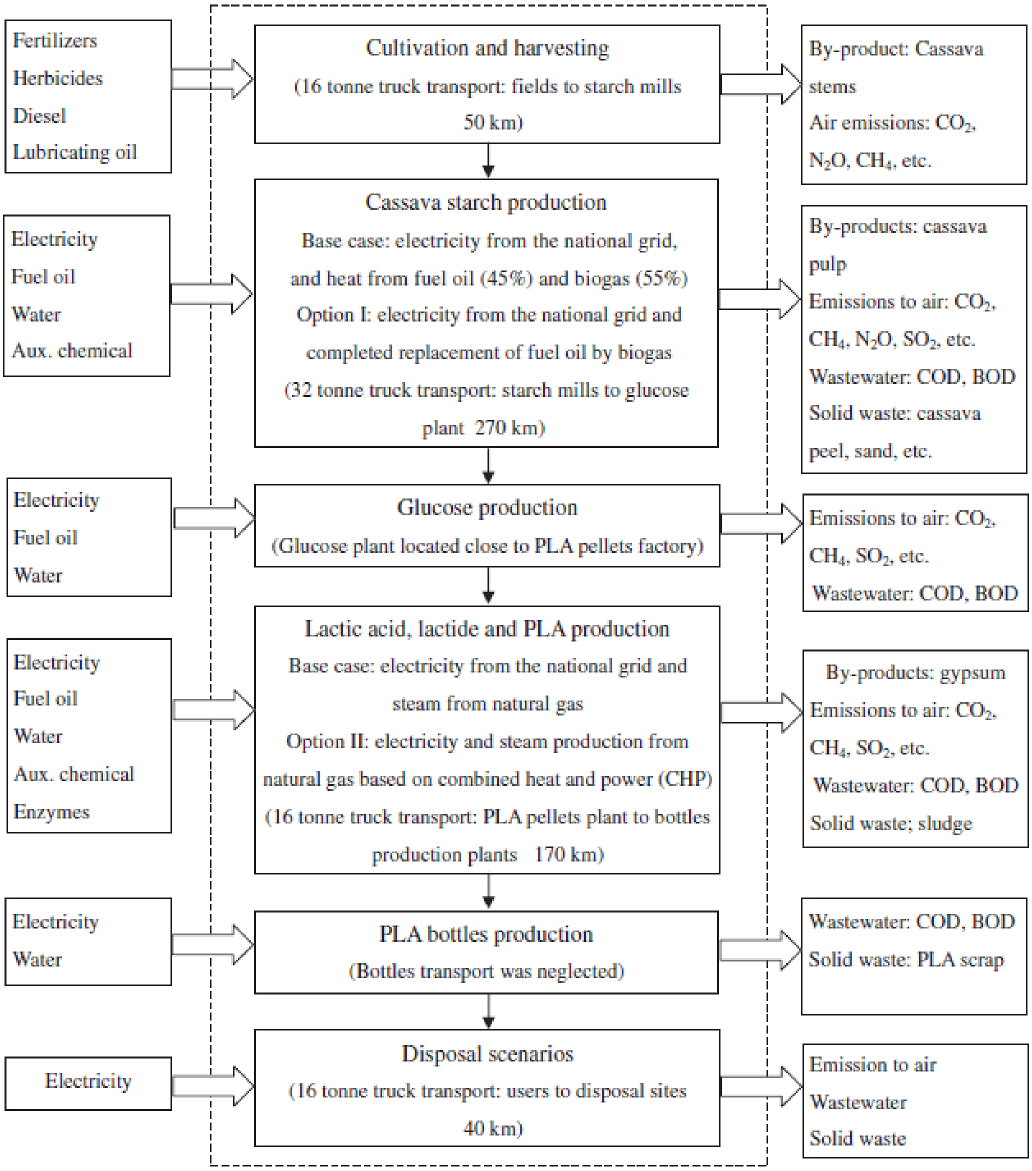

Figure 3: Processes of Cassava based Polylactic acid production

(Papong et al., 2014)

The first 3 processes which are cultivation/harvesting, starch (chip) production and glucose production is the same as in cassava based bio-ethanol production section. After the glucose production process, glucose is fermented into lactic acid in the presence of sulphuric acid, calcium carbonate, and auxiliary chemicals as operating supplies, then purified further. Consequently, lactic acid converts into lactide and undergoes polymerization process. The obtained product is poly-lactide in the presence of a tin catalyst. This poly-lactide can be used to produce bottle containers later on, the electricity and stream are also required during fermentation process. (Papong et al., 2014).

The obtained waste from poly-lactic acid production includes waste water, sludge and others solid waste. Other that there has emission of greenhouse gas such as CO_2, CH_4 and N_2O. The solution of managing waste that come from biodegradable production is to convert into valuable compost through aerobic and anaerobic process which refers to biogas production for generating electricity further (Richard, A. G., & Bhanu, K., 2002). Based on the study of (Papong et al., 2014), the overall global warming potential from cassava based PLA production is less than PET production bottle and can be lowered by improvement of utilizing wastewater to produce biogas for stream and electricity production in the facility.

2.2.2. Sugarcane

Sugarcane is one of the most important crops that grown in tropical region. Many countries around the world grow sugarcane mainly for sugar production. Approximately 80% of the world's sugar comes from sugarcane and the remaining is produced from sugar beet (SUCDEN, N.D.). Brazil is the world largest sugarcane producer while in Asia, India, China and Thailand play an important role by accounting for one third of world's sugarcane production (Center, 2012). Sugarcane is also recognized as a multipurpose crop that can be utilized for food, fuels, electricity, organic chemicals, paper and etc. The main components of sugarcane include juice, bagasse and straw.

Juice is the sweet liquid part, containing sucrose that use to produce sugar and bio-ethanol. This liquid part is obtained by extracting from sugarcane milling process. Then the sugarcane juice will be clarified and concentrated into syrup. The syrup will be further separated sugar crystal out of the black sticky syrup, called molasses (Silalertruksa et al., 2015). For sugar, it can directly be fermented by yeast to produce bio-ethanol, however, recently, there is an increasing awareness of by-products from processing system for many applications such as molasses can be used for producing bio-ethanol because around 50-55% of molasses concentration are sucrose. Moreover, there is a market demand for sugar as a food, but there is no such market demand for molasses. Therefore, most of bio-ethanol can be produced from this by-product (Inclusive Science and Engineering, 2012). In addition, due to technology development, commercial bioplastics in the market for example; polylactic acid (PLA) and polyhydroxyalkanoates (PHA), can be produced by sugar fermentation from renewable resources. Therefore, sugar from sugarcane has a potential to produce bioplastic as an alternative bioproducts (Chiarakorn et al., 2014).

Bagasse is the dry residue or by-product that left after sugarcane stalks are crushed and extracted their juice in sugar milling process. Since 50% of its content is cellulose, bagasse is considered as lignocellulosic residues which is raw material for cellulosic ethanol. However, producing cellulosic ethanol from bagasse requires large quantity of material, which would affect the supply of fuel for sugar mills (Ferreira, V., Faber, O. M., Mesquita, S. S., & Pereira, Jr. N., 2010). Furthermore, cellulosic ethanol production process involves with hydrolysis and gasification technologies to break down lignocellulosic molecule. The production is more complex and required more processing than traditional sugarcane ethanol because it is manufactured from abundant and various raw materials (Sugarcane.org, 2016). Moreover, during saccharification, the process that hydrolysed sugar molecule into soluble sugar before fermented to ethanol, requires large amount of cellulase enzymes for hydrolysis. As the production of cellulases are expensive and impracticable, further technology improvements for economical production are needed. Therefore, most of the bagasse is used as fuel for boilers in sugar mills instead. This application is considered as more efficient and economical (Pandey, A., Soccol, R. C., Nigam, P., & Soccol, T. V., 2000).

In addition, some producer utilizes bagasse to produce methanol for selling as fuel additives likes gasoline. Methanol (CH_3OH) or methyl alcohol has several applications; it can be used to synthesize into chemicals such as formaldehyde, adhesives, paints, acetic acid and etc. In Brazil, biodiesel is mainly produced from methanol through transesterification process. Normally methanol can be synthesized from not only sugarcane bagasse, but any carbonaceous material such as coal, lignite and wood waste (Benedetto, L. D., & Klemes, J., 2008). The bagasse will undergo through gasification process to form syngas at certain temperature and pressure. Syngas contains sulfur and impurities, which needed to be removed for preventing tar deposition and catalysts poisoning, and then synthesized methanol by the hydrogenation with the presence of catalyst at certain temperature and pressure (Wang, L., Weller, C. L., Jones D. D., & Hannab M. A., 2008).

The last part of sugarcane is straw which is the top and leaves of sugarcane stalks. Normally, sugarcane farmers have burned their field to eliminate the straw and drive away snakes and poisonous animals, this is easier for harvesting cane manually. However, after farmers have applied mechanical harvesting, field burning is no longer required. The straw can be burned for electricity. In addition, straw is considered as lignocellulosic material, it can also be used for producing cellulosic ethanol similar to bagasse (Sugarcane.org, 2016).

Thailand is one of the world's major producers of sugar. Sugar industry strongly contributes to Thai economy. Sugar in Thailand mainly comes from sugarcane which grows well in North-eastern, Central and Northern region respectively, more than 6000,0000 small holders are involved in the rural sectors (Silalertruksa, T. & Gheewala, S.H., 2010; Silalertruksa et al., 2015). During 2015-2016, total sugarcane planted area is 11,012,839 rai (both for industrial and breeding purpose), which increase from the previous year by 4.58 % (Office of The Cane and Sugar Board, 2016). As a result of Thai government try to promotes agricultural zoning project by converting rice planted area that located in inappropriate zone into higher return crops area (ie; sugarcane, cassava, oil palm and maize) or more efficient agricultural activities (ie; animal husbandry and fishery). In order to identify appropriate zone, factors such as land suitability, crop requirement and existing land use, need to be considered. The purpose of this project is to manage agricultural area more efficient, to increase farmer's income and to get the quantity and quality of products that meet the market demand (Ministry of Agriculture and Cooperatives, 2013). The average production yield of sugarcane in Thailand is 9.15 ton/rai, which depends on the water quantity. If sugarcane received enough water throughout growth period, the product yield will increase. Temperature and sunlight are another factor that affect production yield and quality of sugarcane (Office of The Cane and Sugar Board, 2016).

2.2.2.1. Sugarcane Based Bio-ethanol Production

Thai government aims to increase bio-ethanol production to be 11.3 million litres/day based on AEDP plan (2015-2036) in order to reduce the country's dependency of oil import for energy supply and to reduce global warming impact as well as to generate income for farmers and increase the employment in local area (Silalertruksa, T. & Gheewala, S. H., 2009). Currently, rather than cassava, sugar and molasses from sugar cane are a major raw material for bio-ethanol in Thailand. However, since 2013, approximately 60% of total bio-ethanol production in Thailand has produced from molasses. Sugar manufacturers are discouraged to produce bio-ethanol from molasses instead of sugarcane juice directly because of the Cane and Sugar Act required the profit sharing between farmers and millers (Silalertruksa, T. & Gheewala S. H., 2009). The production process of molasses based ethanol is shown as the figure below.

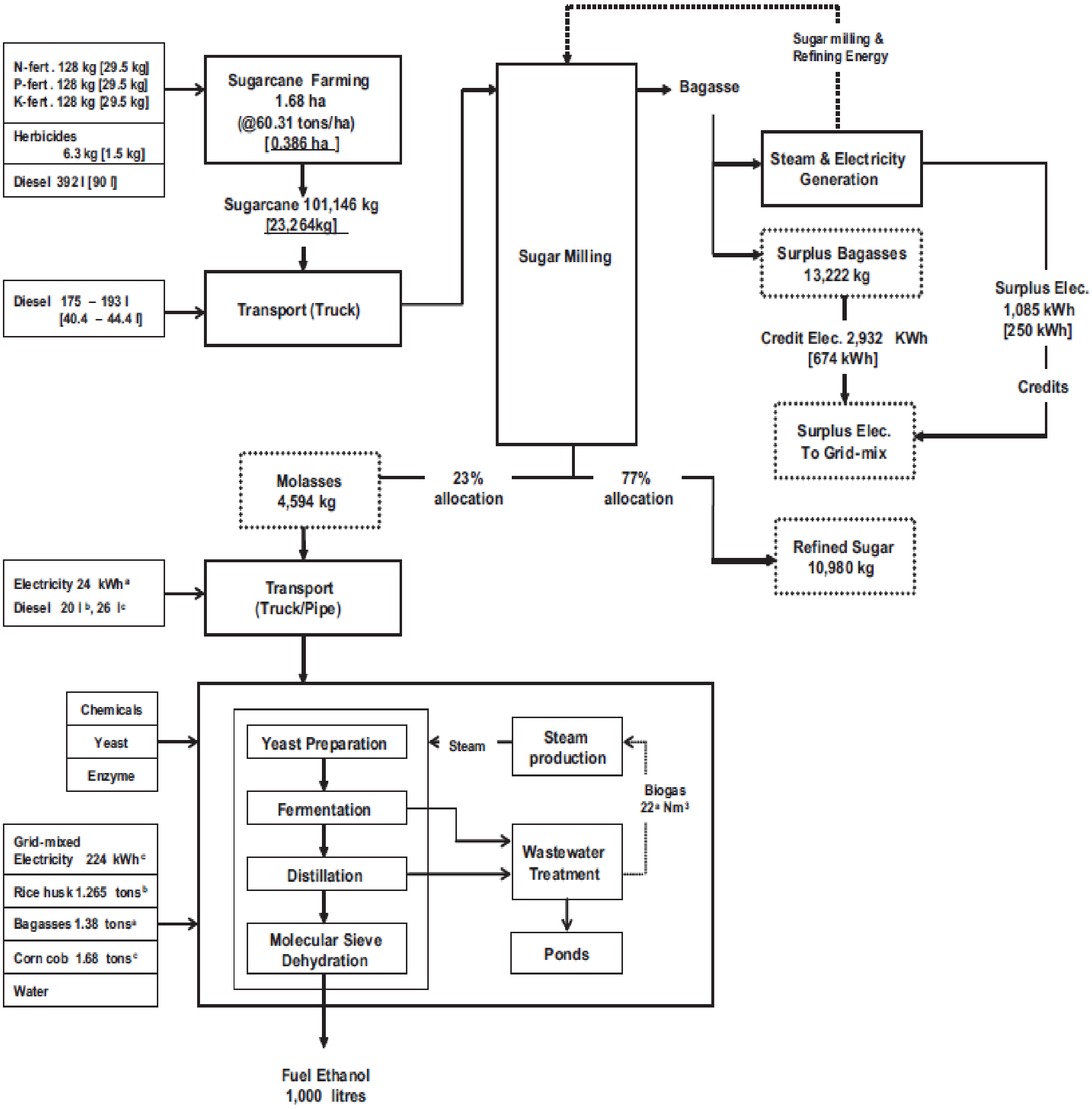

Figure 4: Sugarcane's bio-ethanol production processes

(Silalertruksa, T., & Gheewala, S. H., 2009)

Based on (Silalertruksa, T. & Gheewala S. H., 2009), the system can be divided into 3 main stages which are sugarcane farming and harvesting, sugar milling and bio-ethanol conversion. Each step connects by transportation as shown in the Figure 4, generally, trucks will be used for transporting molasses to bio-ethanol plants, however, some plants are received molasses through the pipeline. The sequences of each stages can be explained as the following;

1.) **Sugarcane farming and harvesting –S**ugarcane planting and harvesting have a cycle around 12 months. There are 2 period for sugar cane planting. First is rainy season which is mostly done in Central region, land clearing will start during April to June and harvesting will start during February to March. Second period is the end of rainy season which land clearing is done during October to November and harvesting is around November to February. The second period plantation is mostly applied in Northeast region since there is less water for land preparation. Pesticides, herbicides and fertilizers are required in this stage. The amount of fertilizers is around 156-625 kg/ha. Water from rain or irrigation is required after planting. Harvesting can be done by both mechanical and manual. After harvesting, most of the farmers will use tractors to eliminate weeds and cane trash, so diesel will be required as an input material. However, in some areas, farmer still burn their cane trash since it is easier and cheaper than using tractor (Pongpat, P., Gheewala, S. H., & Silalertruksa, T., 2017).

2.) **Sugarcane milling –** Sugarcane will be first feed into washing and crushing unit to extract sugarcane juice which bagasse is by-product. The juice will be removed impurities and then concentrated into syrup. The syrup needs to seeded with raw sugar crystals in a vacuum pan, after boiling sugar crystals will be formed and grown. When it passes centrifugal process, molasses will be separated out from the crystals. Therefore, the products and by products from milling process are raw sugar, refined sugar molasses and bagasse. Sugar will be sold to food industries. Bagasse is commonly used for burning to produce steam and electricity for operation and excess electricity can be exported to grid-mixed (Silalertruksa et al., 2015; Silalertruksa et al., 2017). However, based on the study of (Renó et al., 2011), bagasse has a potential to produce methanol, a raw material for biodiesel production. Bagasse methanol is counted as an alternative energy for the substitution of methanol obtained from fossil fuel.

3.) **Bio-ethanol Conversion –** This process includes yeast preparation, fermentation, distillation and dehydration. Most of sugar content in molasses is disaccharide, called sucrose. After yeast preparation process, sucrose will be converted into glucose or fructose which is monosaccharide, through hydrolysis reaction as shown in the stoichiometry below. Then, these glucose and fructose will be fermented to produce bio-ethanol and carbon dioxide. The bio-ethanol is produced in to 995 % anhydrous alcohol by passing through distillation and dehydration system (Nguyen, T. L. T., Gheewala S. H., & Garivait S., 2008; Silalertruksa et al., 2015).

Sucrose **Glucose** **Fructose** **Ethanol** **Carbon dioxide**

$$C_{12}H_{22}O_{11} + H_2O \longrightarrow C_6H_{12}O_6 + C_6H_{12}O_6 \xrightarrow{Yeast} 4C_2H_5OH + 4CO_2$$

Figure 5: Stoichiometry of ethanol conversion from sucrose

(KAPI, 2006)

The amount of waste water generated from sugar milling process is around 260 L/tonne of sugarcane, which contains high organic matter (Yuttitham, M., Gheewala, S. H.,& Chidthaisong, A., 2011). Moreover, based on (Silalertruksa et al., 2017) that study the life cycle assessment of sugarcane bio-refinery, found that there is an emission of aqueous effluent called vinasse, which contains high content of chemical oxygen demand (COD) around 100,000-130,000 mg/L. Most of Thai sugar mill and molasses ethanol manufacturers mainly treat waste water by oxidation and stabilizing pond system. This type of treatment emits a lot of methane (CH_4) from anaerobic digestion process. Furthermore, during the wet season, the wastewater that is kept in open lagoon system can leaked to natural water bodies. The estimated methane emissions from the open lagoon system is around 2 kg CH_4/litre of ethanol based on 10 L of vinasse/litre of ethanol. However, some of manufacturers treat this wastewater by utilizing as organic fertilizer or collect methane to produce biogas, which is more effective in reducing environmental impacts (Silalertruksa, T., & Gheewala, S. H., 2009).

2.2.2.2. Sugarcane Bio-polymer Production

As Thailand is one of the leaders' agricultural countries in Southeast Asia, plentiful of agricultural resources that contains high carbohydrate, glucose and cellulose such as rice, cassava and sugarcane are available. These multiple raw materials can be utilized for bioplastic production. Sugar from sugarcane is currently use for lactic acid production in Thailand, since PURAC, the world largest lactic acid company from Netherlands opened lactide monomers plant at Rayong province in 2012. The factory can produce lactic acid around 120 tons/year with most of the product is for export. In the future, the company aims to establish PLA polymerisation unit and adding more extension for lactic acid in order to grow PLA market in Thailand as fast as possible. Several development projects have been done with the cooperation between two countries (Barot S., 2016; der Linden, S. V., 2016; Groot, W. J. & Boren, T., 2010)

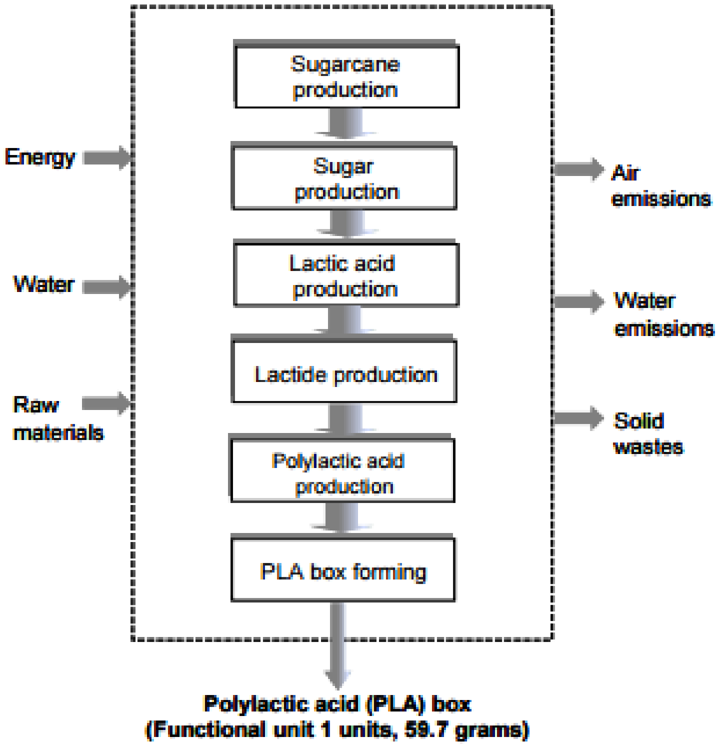

Figure 6: Sugarcane's PLA production processes

(Suwanmanee, 2012)

The detail information of sugarcane based PLA production processes are shown as figure above. The processes of sugarcane plantation and sugar production are the same as explained in the sugarcane based bio-ethanol section. After obtaining sugar from milling process, these sugars or glucose will be fermented into lactic acid with the presence of chemicals and then lactic acid can be polymerized into polylactic acid (PLA) further (Suwanmanee et al., 2012). Most of the processes are the same as in cassava based PLA production, since it derived from glucose. Therefore, after their glucose production, it can be processed in the same facility.

2.2.3. Oil Palm

Palm oil production has been getting attention globally because it can utilize for food, chemical industry and biofuel (Saswattecha, K., Kroeze, C., Jawjit, W., & Hein, L., 2016).In 2009, 45.3 million tons of palm oil were produced worldwide (Dallinger, J., 2011). Then the production reached 54.3 million tons in 2013 and has been increasing continuously (FAOSTAT, 2015). The United States Department of Agriculture (USDA) estimates that the production will be 64.5 million tons in 2016(Global Palmoil Production.Com, 2016). Oil palm which is a feedstock, is mostly grown in tropical region. The top most producing country is Indonesia, the 2nd is Malaysia and followed by Thailand.

In Thailand, 87 % of the oil palm planting area is located in southern region, the remaining are central, north and north eastern (Rewtarkulpaiboon L., 2015). The utilization can be divided into two types; domestic consumption and export. For domestic consumption, palm oil can be used to produce food products (such as cooking oil, margarine and sweetened condensed milk), industrial commodity (such as cosmetic, soap and candle). Additionally, Oil palm has been the Thai important commercial crop since Thai government promote biodiesel production based on AEDP. For export, only small amount is export to neighbour countries such as Singapore and Malaysia (Termmahawong W., 2011)

2.2.3.1. Biodiesel Production

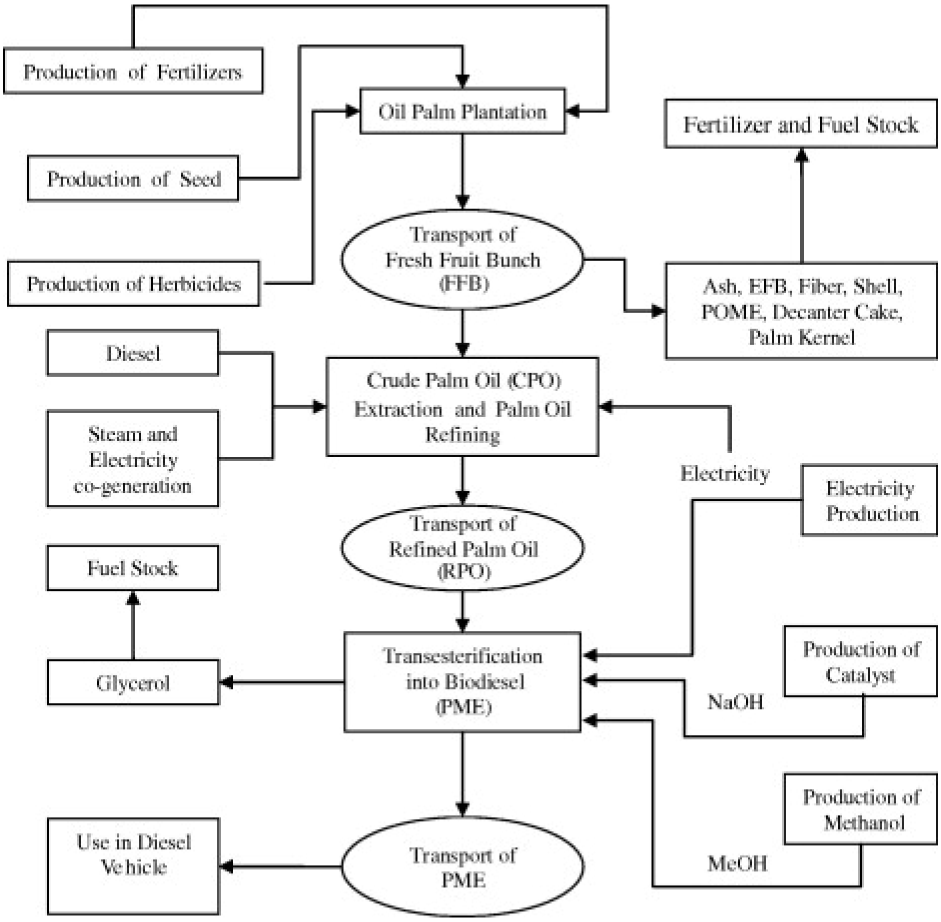

Figure 7: Oil palm's biodiesel production processes

(Pleanjai, S. & Gheewala S. H., 2009)

Biodiesel production process can be divided into 3 main steps which are oil palm plantation, crude palm oil (CPO) production (; including extraction and refining), biodiesel production (or transesterification). Each step connects by transportation as shown in the Figure 7. The sequences of the processes can be explained as the following;

1.) **Harvesting and cultivating process** – In the beginning, land need to be well prepared by levelling, ploughing and digging. After planting oil palm seeds, several input materials will be required such as fertilizers, herbicides (glyphosate and paraquat are used for weed control) Fresh fruit bunches (FFB) from oil palm can be used as raw materials for palm oil industry (Papong et al., 2015). Normally, FFB harvesting can be done manually every 15-20 days by using chisel with young palm and using sickle with tall palms (Saswattecha et al., 2016). There is no fossil fuel energy need during harvesting. However, some fossil fuel is used during transportation to the crude palm oil mill (Pleanjai, S. & Gheewala S. H., 2009).

2.) **Crude palm oil (CPO) extraction and refining process** –this process includes sterilization, threshing, fruit digestion, pressing, purification and CPO storage. First FFB will be heated with stream for about 1 hour through the sterilization process (The Palm Oil Mill, 2011). This process stops enzyme that generate free fatty acid in the fruits which softens and makes it easier to separate. Next the fruits are conveyed to the threshing machine to separate the fruits from the bunches. The fruits will be pressed in a digester to extract CPO, which is mixed with water and particles (sand and dirt). This extracted CPO will be separated from the sludge using heat and gravitational force, also remove moisture through vacuum chamber (IPST, 2012b). Then, the clean oil will be stored in storage tanks for transporting to the biodiesel manufacturer. Electricity and diesel are required in this step for stream heating and running the machine. The empty fruit bunches (EFB), fiber, shell, kernel and palm oil mill effluent (POME) can be further utilized for bio-compost (Saswattecha et al., 2016).

3.) **Biodiesel production (transesterification)** – This process requires refined palm oil and methanol (MeOH) as raw materials, together with sodium hydroxide (NaOH) or potassium hydroxide (KOH) as a catalyst (Pleanjai, S. & Gheewala S. H., 2009). Transesterification occurs as shown in the stoichiometry below.

Triglyceride that presents in refined palm oil, react with an alcohol (methanol) under high temperature with the presence of catalyst to accelerate the conversion. The products are a mixture of glycerol and palm methyl esters (Achawangkul Y.), called biodiesel (Borges, M. E., & Díaz, L., 2012; Meher, L. C., Vidya Sagar, D., & Naik, S. N., 2006). The mixture can be separate by gravity and glycerol will sink to the bottom. PME will be washed with water and dried by heating (IPST, 2012a). Electricity is required for operating the machine.

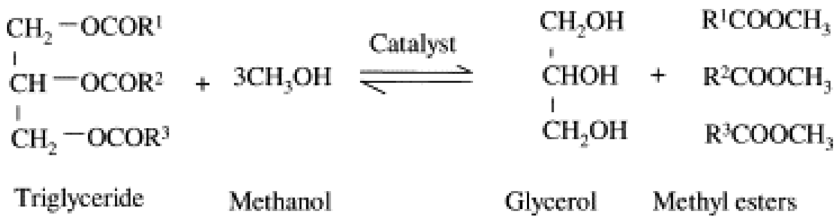

Figure 8: Stoichiometry of triglycerides transesterification with methanol (Meher et al., 2006)

In the CPO extraction process, large amount of water is utilized to generate stream. The waste water or effluent that contains organic compounds is required to be treated properly before discharged to the environment. Based on the study of waste water quality from CPO production in northeast of Thailand, the wastewater has high Biochemical oxygen demand (BOD) as 25,000 mg/litre and has high oil and grease value 4,000-6,000 mg/litre, which are referred as low quality level. The quality of wastewater depends on the wastewater treatment technology, the utilization of wastewater to produce biogas and electricity generation is one of the suggestion which additional benefit is the reduce in environmental impacts (Center of Excellence on Environmental Health, 2012).

The main problem of oil palm production in Thailand is farmers lack of knowledge about soil and fertilizer management and lacking fund for high cost fertilizer investment. Several planting areas are located in provinces with low rainfall level. Moreover, many small holder farmers are affected by the fluctuation price and don’t have bargaining power, compare with the large farmers (Termmahawong W., 2011).

2.3. Previous Studies of LCA in Thailand and Other Countries

2.3.1. Study of Biofuels of Production

LCA is a method that can be used to study environmental impact from a product during its life cycle. The type of study may vary according to the objective of a particular study. Some researchers used LCA to study the life cycle energy and potential of fuel products. (Papong S. & Malakul P., 2010) studied the energy efficiency and potentials of biodiesel production from palm oil; the results showed that palm oil is a very efficient feedstock for biodiesel production as it can produce energy three times of the energy the process consumed, and it can be a substitute for diesel and decrease the need of oil import. Some studies use LCA to assess the environmental and economic aspect of bio-refinery. (Silalertruksa T., Gheewala S. H., & Pongpat P., 2015) assessed the combined environmental and economic sustainability indicator, “Eco-efficiency”, of scenarios in single-feedstock sugarcane bio-refinery in Thailand through LCA method; it was founded that the scenarios utilized the biomass by-product cane trash for electricity increases eco-efficiency by 20-70%.

Eco-efficiency is an indicator for assessing economic values per the unit of environmental impact created; in the study of (Silalertruksa, T., Gheewala, S. H., & Pongpat, P., 2015) on the sustainability of sugarcane bio-refinery and molasses ethanol production in Thailand, they defined eco-efficiency indicator as gross value added per total GHG emission. While on the study of (Chinnawornrungsee R., Malaku; P., & Mungcharoen, T., 2013), they defined the eco-efficiency indicator as revenue per energy resource impact.

2.3.2. Study of Bioplastic Production

LCA studies can be used to analyze for environmental impact in bio-refinery. (Groot, W. J. & Boren, T., 2010) assessed the environmental aspect in the production of bioplastic, PLA, from sugarcane using LCA method; the results showed that PLA results in significantly lower emissions of GHG, and use less material resources and non-renewable energy when compared to fossil-based polymers. Moreover, similar to the biofuels, biorefineries of bioplastic were studied in similar manner. (Chinnawornrungsee R., Malaku; P., & Mungcharoen, T., 2013) also evaluated the performance of a two-feedstock, cassava and sugarcane, biorefinery model in Thailand that produced bioplastic and bio-ethanol using the Eco-efficiency indicators as well; they found that the eco-efficiency of the bio-refinery improves by integrating efficient feedstock utilization, utilizing bagasse for electricity generation, and minimizing waste (Chinnawornrungsee, 2013).

2.3.3. Study of a Production with Related-Processes Group Together

Sometimes, LCA is also used to study productions that have several processes and complex material flow. (Daddi T., Nucci B., & Iraldo F., 2017) used LCA to assess the environmental benefits from the grouping various production together. They found that by grouping waste from production can be reduced, and the production cost can be lowered. Their study provided suggestions in both policy and managerial levels; for policymakers, they suggested that the development of sharing resource and common services can improve environmental benefits and LCA will help policymakers in justifying decision by identifying and magnifying the advantages of the common resources and services. At managerial level, they suggested that collective actions (co-operating and coordination between different functional units) can improve environmental footprint of their products.

2.3.4. Study of Bio-refinery

Bio-refinery is a model that aims to utilize all of products, including wastes, called “zero emission” concept (Gravitis J. & Motoyuki S., 1999; Kuehr, 2007). Bio-refinery can be classified in to two categories. One category of bio-refinery is biomass producing which is popular in agricultural countries such as Brazil, China and country in Southeast Asia, including Thailand. Second is waste-material-utilization type which appropriates with lack space of landfills country such as Japan (Cherubini, F., 2010; Ohara H., 2003). In this thesis focused on cassava, sugarcane, and oil palm feedstocks which are the important economic crop of Thailand. Therefore biomass-producing type would be studied.

There are several studies about bio-refinery in Thailand such as the study of (Silalertruksa, T., Gheewala, S. H., & Pongpat, P., 2015) about using the combination of environmental and economic indicators (Eco efficiency) to evaluate the sugarcane based bio-refinery which include ethanol production. The results show that bio-refinery concept can induce greenhouse gas emission reduction from ethanol production process. Around 20-70% of eco-efficiency improvement is proposed for the new systems. Another study is (Gheewala et al., 2011) study about the sustainability assessment by applying environmental, social and economic indicators through the same feedstock of sugarcane based bio-refinery model. They found that maximizing biomass utilization performance in the bio-refinery model can benefit greenhouse gas emission reduction as well as enhancing living condition of farmers and employees which further influenced profits and incomes.

2.4. The Utilization of Biogas in Thailand

In the early 1960, a small scale of biogas plants was introduced to Thailand for solving sanitation problems in the community. However, the number of livestock was increased continuously as the amount of wastewater and manure (Suwanasri et al., 2015). Livestock wastes were managed by traditional way which was dumping into a pond. This management caused natural stream to be contaminated by the leakage, which lead to increase in amounts of nitrogen and phosphorus and depleting of oxygen in water surface.

Moreover, a severe odor was produced and caused social problems. In 1988, the project of biogas to produce renewable energy was launched out under the collaboration between Thai and German government to establish fixed dome digestion biogas plants in livestock farms. The further benefits of this project were reduction of odors, GHG emissions and organic wastes, and fertilizer production from byproduct for enriching soil (Aggarangsi, P., Tippayawong, N., Moran, J. C., & Rerkkriangkrai, P., 2013). The result from this project was more than 150 biogas plants were built and the project was also requested to extend in order to include more sectors (Suwanasri et al., 2015).

The organic waste can be converted into biogas by anaerobic digestion technology. The principle of anaerobic digestion is a process in free oxygen environment that promote the growth of micro-organism to generate methane (CH_4) or biogas. Normally, the organic wastes are the major input. The process are divided into 4 main phases based on the figure below, which are as the following; (de Mes, T. Z. D., Stam, A. J. M., Reith, J. H.,& Zeeman, G., 2003)

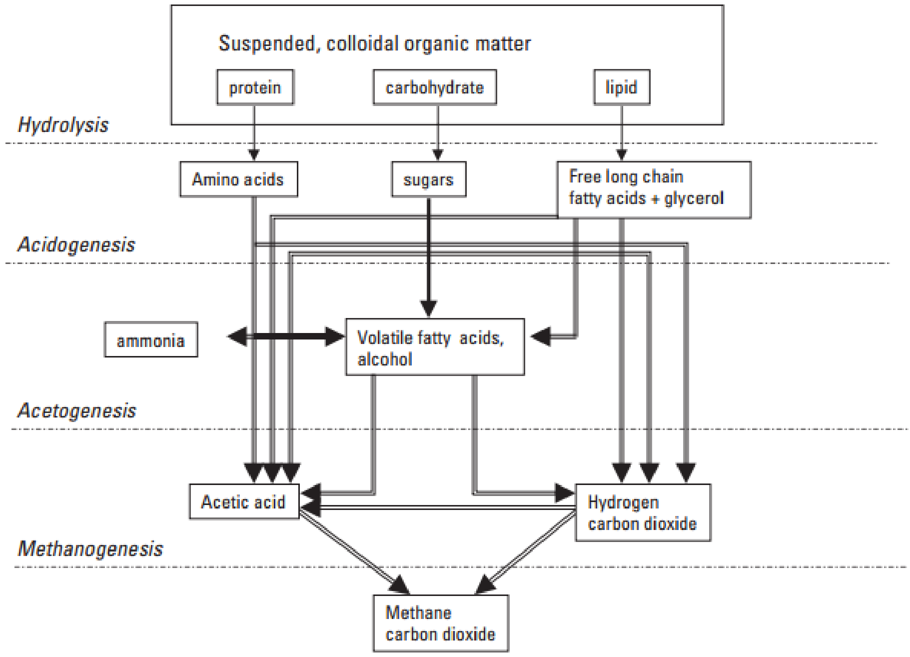

Figure 9: Conversion process of Biogas

(de Mes, et al., 2003)

1) **Hydrolysis** – The insoluble complex molecules in organic substrate that has been pretreated such as carbohydrates, lipids and proteins will be broken down by bacteria into smaller constituent parts, which are sugars, amino acids and fatty acids

2) **Acidogenesis** – The fatty acids and others remaining products from hydrolysis will be transformed by acidogenic bacteria into volatile fatty acid, alcohols, ammonia (NH_3), hydrogen and carbon dioxide (CO_2)

3) **Acetogenesis** – The volatile fatty acids are converted into acetate and hydrogen (H_2)

4) **Methanogenesis** – The intermediate products from previous stage are converted by methanogenic bacteria to produce biogas, CO_2 and water.

These conversion processes are done in the bioreactor with batch system or continuous system. The environmental factors that affected anaerobic digestion are temperature, pH and alkalinity and toxicity. For example; the suitable temperature for methanogenic bacteria to convert organic acid into biogas is above 70 °F and the suitable pH should be above 6 (Krich et al., 2005). The potential production of biogas can be determined by chemical oxygen demand (COD) which is the amount of organic matter in wastewater. While the aim of anaerobic digestion process is to reduce biochemical oxygen demand (BOD) which is the amount of oxygen acquired by microorganisms in the effluent (Krich et al., 2005).

In biogas production process, some amount of carbon dioxide is emitted, however, after replacing fossil fuels by biogas, the net carbon dioxide level in atmosphere is lower. Based on the US Environmental Protection Agency reports((BERC)), 2008)

"CO_2 from this source ((BERC))) is generally not counted as greenhouse gas emissions because it is considered part of the short-term CO_2 cycle of the biosphere"

This is because biomass that is the source of fuel can be produced within a human lifetime, so the carbon from burning biomass or its products can be harvested back into crops through photosynthesis. In comparison, fossil fuels which take several generations to form are extracted from an underground oil reservoir. Meaning that, burning fossil fuel will release the underground carbon to the atmosphere. Adding carbon that does not originally belong to the atmosphere will increase the net carbon dioxide level((BERC)), 2008).

Therefore, applying biogas technology to the waste water treatment process would help in reducing greenhouse gas emission and reducing the operating cost from reducing fossil fuel usage. Based on the study of (Papong, S., Rotwiroon, P., Chatchupong, T., & Malakul, P., 2014), by applying biogas generated from wastewater for stream production process in cassava ethanol production plant in Thailand, GHG emission is greatly affected by 96% reduction. Another study show that the bio-ethanol production from cassava and molasses have lower GHG emission than a single feedstock plant, however, a multi-feedstock plant has less profit, only effective in avoiding the risk of feedstock price fluctuation. After applying biogas for electricity generation, the profit is significantly improved. (Moriizumi, Y., Suksri, P., Hondo, S., & Wake, Y., 2013). In Thailand, there are large potential for producing biogas over one billion m^3 from agricultural industry. The benefits from utilizing biogas include improving health, reducing GHG, odours and land use, providing sustainable energy as well as organic fertilizers for soil conditioning (Aggarangsi, P., Tippayawong, N., Moran, J. C., & Rerkkriangkrai, P., 2013).

Chapter 3: Methodology

This chapter describes the method used to answer the research question in Chapter 1, "How would the utilization of biogas for electricity generation affect the profitability and emissions?"

In the first part, the reason for using quantitative design in this research will be explained; also, the hypothesis and the way to proof it will also be described in this section. In the second part, the steps that need to be taken to obtain the results will be explained thoroughly. In the third part, the sources that the data were acquired from will be described and explained. Lastly, for the fourth part, all the analysis methods in this work will be explained technically.

3.1. Research Approach

The research design of this study is a quantitative design as the determination of the biogas's effect on the profitability and GHG emission requires quantifiable results. There are some evidences from other studies which suggest that utilization of biogas in a bio-refinery will affect both, the profitability through the cost of energy and the greenhouse gas emission from the conventional fuel (Moriizumi et al., 2013; Papong, S. & Malakul, P., 2010; Papong et al., 2014). This research adopted the experimental approach which aims to establish a relationship between a cause (independent variable) and outcome (dependent variable). In this case, the independent variable is "the amount of biogas for generating electricity" and the dependent variable is "obtained profitability and obtained greenhouse gas emission". Additionally, a control variable is "the ratio of inputs between cassava-sugarcane-oil palm". This control variable should affect the final result, so variation of the ratios of each input materials will be required to see a correlation. As suggested above, this research was conducted with the following hypothesis:

"The utilization of biogas for generating electricity to multi-feedstock bio-refinery in Thailand will improve the profitability and minimize greenhouse gas emission"

To proof this hypothesis, there must be a base case which is the results of profitability and greenhouse gas emission from processes in bio-refinery which operate by without the utilization of biogas. The data were obtained from literature reviews to calculate the base results. After that, the final results of base case and controlled case were compared to proof the hypothesis, and then followed to answer the research questions further.

Rather than proving the hypothesis, this thesis also tries to analyse the ratio of feed stocks that give the highest profit and least greenhouse gas emission. In order to determine the best point, optimization analysis is utilized to find the profit and GHG emission at different ratio of feedstocks so that the point where the profit is maximized and the point where the GHG emission is minimized; also, the results from optimization will be useful to identify the trends for price and emission as a function with feedstock's ratio as inputs. Also, a useful test that can be used to determine the best location for bio-refinery is the regional analysis where the production yield of each region in Thailand are used to determine the possible profits and emissions.

3.2. Procedures

In order to determine the effect of biogas utilization on profit and GHG emission of a bio-refinery, the analysis have to cover energy analysis, profit analysis, and GHG emission analysis in order to confirm that biogas really helps in improving profit and reducing the emission; furthermore, after analysing individual's feedstock effect on profit and emission, an optimization analysis is done to see the effect of combined feedstock. In addition, the regional analysis is performed to find the best region to establish this bio-refinery

The methodology of this work adopts the procedure from Life Cycle Assessment (LCA) methodology, however, with adaptations in some parts. LCA accounts for the net energy gain or the emissions that were generated during the course of a particular product lifetime to see the environmental impacts it caused. However, the net energy gain analysis can only be conducted with energy products like biofuels; in this work, apart from biofuels, bioplastic is also included. That is why the net energy gain analysis will be overlook for this work.

The LCA was selected as an appropriate method; it is a comprehensive technique to assess the potential impact(s) on the environment and all aspects that associate with the processes (Luca De Benedetto, 2008). By understanding the impacts and benefits of products and service through the whole life cycle will help in utilizing resources more sustainably as well as gaining more market advantage (Hannele et al., 2011). The methodological framework of LCA consists of 4 main step according to ISO14040 (Finkbeiner, M., Inaba, A., Tan, R., Christiansen, K., & Klüppel, H. J., 2006)

1.) **Define the system boundary for the analysis –** Generally, the boundary of analysis must cover the processes or activities that are concerned based on the literature. These activities have their own materials inputs and outputs which are raw materials, products, fuels, emissions, or wastes; and each block of activities is connected to at least one or more blocks by the flows of materials. Any flows of materials of processes that are beyond the boundary will not be shown. Any input that comes from beyond the defined boundary is considered an input to the system; likewise, any output that goes beyond the defined boundary is an output to the system.

2.) **Collect the Life Cycle Inventory Database** – After identifying the processes and the flows, the next step is to determine the amount of material flows. Life cycle inventory database is a collection of material flow data of a particular feedstock-product system, for example, bio-ethanol production from sugarcane. These inventory data are often collected from actual plants in the real world by producers or researchers. Many life cycle studies often include tables of life cycle inventories as a reference. In this study, Life cycle energy inventory and Life cycle greenhouse gas inventory data were collected.

3.) **Conduct Analysis** –In this step, each feedstock was calculated for its total life cycle input energy, profitability, and life cycle GHG emission for no biogas utilization situation (base case) and another for the biogas utilization situation in order to check whether the biogas really helps increasing the profit and decreasing the GHG emission of bio-refinery. After that, the bio-refinery will be considered as a multi-feedstock, where the combination of cassava, sugarcane, and oil palm will be used to analyze the profit and GHG emission. Additionally, the regional crops yield will be applied to determine the potential best location for establishing the MFS bio-refinery.

- *Life Cycle Energy Analysis* – First, the all input energies are added according to each feedstock for totals. For the base case (no biogas utilization), all of the input energies, whether in forms of electricity, steam, diesel, or other materials, are accounted for. After that, the energies from biogas are determined. Then, the input energies are calculated again with reduction (substitution) by the biogas. This is the biogas utilization case. Normally, if a product is a certain kind of fuel, its net energy gain, its own energy minus the total input energy during production, would be calculated for; however, this study includes a bio-polymer product, poly-lactic acid, which its purposes is entirely unrelated to fuel, so calculating the net energy gain for PLA would not make any sense.

- *Profitability Analysis* – To determine the profitability the revenues from products and costs of the processes must be determined. The revenues are a product of the market price of products and the amount products produced, while the costs of processes are equal to costs price times the input energies and material from the entire process. Similar to the energy analysis, the profits are considered for two situations, when there is no biogas utilization and when there is the biogas utilization.

- *Life Cycle GHG Emission Analysis*- All processes, including production and wastewater treatment processes are accounted for the GHG emission they generated during the production process. Starting from cultivation, the emission came from the use of fertilizer and diesel machines for farming; in the production, emissions mainly came from the burning of coal or fuel for heat and electricity, and also the use of chemical products as well; lastly, wastewater treatment process is also another main contributor for GHG from the decomposing of organic material in wastewater. Both the scenario before and after applying biogas will be considered.

- *Optimization of Feedstock* – After determining an individual effect of each feedstock, they will be combined in order to see the effect the feedstocks will have in the multi-feedstock bio-refinery. The analysis is done for both the base case and biogas utilization case, and their results will be compared. The results are screened to find the trend or relationship between the profit or GHG emission with the feedstock. When the results are plotted on to a graph, the ratio with the highest point and lowest point can be identified visually. Moreover, by using the graph, it would be easier to tell the trend of profit and emission as function of feedstock ratio.

- *Regional Analysis* **-** The effect of regional production yield will be analysed in order to determine the best region to establish the bio-refinery plant. By using the product yield to estimate for the ratio of bio-refinery feedstock, it is possible to tell which area would give more profit and less GHG emission.

3.3. Sources of Data

The data used for calculation can be divided into 5 categories based on the types of analysis that are conducted in this research: Life cycle energy analysis, Profitability analysis, Life cycle GHG emission analysis, Optimization of feedstocks and Regional analysis. The data must be collected to cover all the activities of the three feedstocks that are within the boundary, which starts from cultivation and all the way to last step of production.

Since this study was conducted with Thailand as a location of interest, majority of the data are obtained from publications that studied about bio-refineries or their processes in Thailand. Other few data are obtained from studies that were conducted in other countries for parameters that cannot be obtained from publications from Thailand. The data on life cycle energies and GHG emission are obtainable from studies with LCI data published; while, for profitability, the prices and costs data were obtained from various institutional websites for utilities and commercial websites for prices of materials and products. Normally, most papers reported the energy according to the process that utilized it; however, they do not explicitly distinguish the energy for wastewater treatment process, but include it into the energy of main process.

For optimization analysis, the results from the profitability analysis and life cycle GHG emission analysis are used as an input to this part; therefore, there is no new input for this part. While, for the regional analysis, regional crops' production yields are used to calculate for feedstock ratio which is then used to calculate for profits and GHG emission based on the optimization method. The regional production yields data are collected and reported in the (Office of Agricultural Economics, 2015c).

Table 1: References of Analyses

Types of Analysis	References
Life Cycle Energy Analysis	(Silalertruksa, T. & Gheewala, S. H., 2009) (Chiarakorn et al., 2014) (Renó et al., 2011) (Pleanjai, S. & Gheewala, S. H., 2009)
Profitability Analysis	(EPPO, 2010) (Papong, S., Chom-In, T., Noksa-nga, S., & Malakul, P., 2010) (Nguyen et al., 2008) (Provincial Electricity Authority, 2015) (Plastics Institute of Thailand, 2013) (Thai Ethanol Manufacturing Association, 2015)
Life Cycle GHG Emission Analysis	(Papong, S. & Malakul, P., 2010) (Chiarakorn et al., 2014) (Nguyen et al., 2007) (Renó et al., 2011) (de Souza, S. P., Pacca, S., de Ávila, M. T., & Borges, J. L. B., 2010) (Harsono, S. S., 2014)
Optimization of Feedstock	*[Inputs of this analysis are results from three parts above]*
Regional Analysis	(Office of Agricultural Economics, 2014, 2015c, 2016)

3.4. Data Analysis

The data in this work were analyzed in Microsoft Excel 2007 and the graphs for optimization analysis were plotted by OriginPro 8.5. Methods that were applied to analyze the data in this work are listed as follow:

Before going into analysing the MFSB, each feedstock needs to be individually analyse to determine whether biogas utilization does improve the profits and GHG emission for them as other literatures have claimed.

3.4.1. Life Cycle Energy Analysis

Life cycle energy analysis is one variation of LCA that specifically identify the total energy involved in making of products. By performing this analysis, it is possible to identify the process that consumes energy which should be targeted for improvement. In addition, it will tell the room for improvement as well

In this analysis, the energy inputs of each feedstock that are required for production processes (starting from cultivation, all the way to final product) are identified. The total amount of energy that 1 kg of each feedstock is the sum of inputs energy of the process it has to go through. The total energy input before applying biogas is shown as the following;

$$E_{Total,before} = \Sigma\left(E_{input}\right)_i$$

While;

$E_{Total,before}$	=	Total energy input before applying biogas utilization of individual feedstock
E_{input}	=	Energy Input
i	=	Number of process

E_{input} are either the actual energy input (such as electricity or steam from coal or fuel oil) or the life-cycle energy of the input materials (such as fertilizer and chemicals). These individual inputs are obtainable from inventory data of similar process. This energy input will be considered as a total energy input before applying biogas

After determining total energy input, next step is to determine the energy of biogas. The energy of biogas is a product of amount of biogas (in cubic meter) from wastewater that can be found in literature, and the energy constant (or heat constant).

$$E_{Biogas} = V_{biogas} \cdot C_{biogas}$$

While;	V_{biogas}	=	Volume (amount) of biogas (m^3)
	C_{biogas}	=	Energy constant of biogas (MJ/m^3)

By using biogas to substitute the fuels for electricity and steam (both from fuel oil and from coal), the previous total energy input can be reduced. The remaining energy input after applying biogas is as the following:

Total biogas

$$E_{biogas} = E_{biogas,elec} + E_{biogas,steam} = E_{biogas,elec} + E_{biogas,fuel} + E_{biogas,coal}$$

Electricity:

$$E_{elec,after} = E_{elec,before} - E_{biogas,elec} (where\ E_{elec,after} \geq 0)$$

Steam (similar for fuel oil and coal):

$$E_{steam,after} = E_{steam,before} - E_{biogas,steam}(where\ E_{biogas,after} \geq 0)$$

Total Energy after applying biogas:

$$E_{Total,after} = E_{elec,after} + E_{steam(F),after} + E_{steam(C),after} + E_{other}$$

For each of the feedstock, it is necessary to identify the energy of electricity, steams, and other separately as their costs are different from each other, which they will affect the total cost of operation when doing the profitability analysis.

3.4.2. Profitability analysis

In the profitability analysis, the main purpose is to determine the costs of operation, the profit gains, and the change in costs (and profit) by applying biogas. For each feedstock, the equation for profit before applying biogas or base case (P_{before}) is shown as follow;

$$P_{before} = R - C_{total}$$

While;	R	=	Revenue
	C_{total}	=	Total cost of process

The profit will be determined separately for each feedstock. The revenue and the costs are a function of products time its unit price and the amount of energy inputs time their unit cost, respectively.

$$R = (Amount\ of\ Product)(Unit\ Price)$$

$$C_i = (Energy\ inputs)_i(Unit\ Cost)_i$$

While;	C_i	=	Cost of each materials or energy in the process
	i	=	Each materials or energy

Their total cost of process would be,

$$C_{total} = \Sigma C_i$$

The utilization of biogas will affect the costs of operation as it will reduce the need of energy from external sources that are electricity from national grid, and fuel and coal for steam. The term for the cost of recovery by biogas ($C_{recovery}$) is calculated as follow;

$$C_{recovery} = \left(E_{biogas,elec} * Price_{elec}\right) + \left(E_{biogas,fuel} * Price_{fuel}\right) + \left(E_{biogas,coal} * Price_{coal}\right)$$

After applying the biogas, the profit (P_{after}) equation will be,

$$P_{after} = P_{before} + C_{recovery} = R - C_{total} + C_{recovery} = R - C_{total,after}$$

While;	$C_{total,after}$	=	Remaining costs of process after applying the biogas for each feedstock

3.4.3. Life Cycle GHG Emission Analysis

Life cycle GHG emission analysis methodology is similar to the energy analysis. The GHG emission of a product life cycle includes the emissions from all the process involved in the production of each feedstock; before applying the biogas, the total GHG emission (GHG_{total}) can be computed by this equation:

$$GHG_{total} = \Sigma(GHG)_i$$

While; i = Each process involved in the bio-refinery

The GHG emission for each process can be found from the life cycle inventory. To account for the effect of biogas utilization on GHG emission, all the changes made by biogas must be accounted for. By producing biogas and burning them for the electricity:

- Anaerobic digestion of organic substances in wastewater into biogas reduces GHG emission from wastewater (GHG_{WW}).
- Burning biogas to produce heat for electricity and steam produces more GHG.
- Substitution of biogas electricity for grid electricity and biogas steam for coal and fuel oil steam reduces GHG emission.

Therefore, the GHG equation to account for changes by biogas (GHG_{biogas}) is,

$$GHG_{biogas} = (-GHG_{WW}) + (GHG_{burning}) + (-GHG_{elec,sub}) + (-GHG_{fuel,sub}) + (-GHG_{coal,sub})$$

Finally, the GHG emission after substituting biogas for each feedstock(GHG_{after}) is given by,

$$GHG_{after} = GHG_{total} + GHG_{biogas}$$

3.4.4. Optimization analysis

In optimization analysis, the four feedstocks will be considered for the effect on profit and GHG emission; the calculations are divided in to two part: for base case and for biogas utilization case. The results will be calculated by varying the feedstock ratios. The optimization analysis is done to see the effect of biogas utilization on profits and GHG emission of a multi-feedstock. The total profit ($P_{total,FS}$) is equal to the sum of profits of cassava for ethanol production ($P_{CSV,EtOH}$), cassava for PLA production ($P_{CSV,PLA}$), sugarcane(P_{SGC}), and palm oil (P_{OP}) section.

$$P_{total,FS} = P_{CSV,EtOH} + P_{CSV,PLA} + P_{SGC} + P_{OP}$$

To perform optimization, the above equation can be rewrite to show the total profit as a function of feedstocks (FS) (in kg):

$$P_{total,FS} = FS_{CSV,EtOH}P_{CSV,EtOH} + FS_{CSV,PLA}P_{CSV,PLA} + FS_{SGC}P_{SGC} + FS_{OP}P_{OP}$$

By varying FS variables for inputs, the profits at different feedstock ratios are obtainable.

For GHG emission, the total GHG emission ($GHG_{Total,FS}$) is the sum of GHG from cassava for ethanol production ($GHG_{CSV,EtOH}$), cassava for PLA production ($GHG_{CSV,PLA}$), sugarcane (GHG_{SGC}), and palm oil (GHG_{OP}) section as well,

$$GHG_{Total,FS} = GHG_{CSV,EtOH} + GHG_{CSV,PLA} + GHG_{SGC} + GHG_{OP}$$

Similar to the profit, the GHG emission can be put in the function of feedstock ratios:

$$GHG_{Total,FS} = FS_{CSV,EtOH}GHG_{CSV,EtOH} + FS_{CSV,PLA}GHG_{CSV,PLA} + FS_{SGC}GHG_{SGC} + FS_{OP}GHG_{OP}$$

Profits and GHG emissions from this analysis can be tabulated or plotted on a graph. On a graph, it is easy to show the maximum and the minimum of profit and GHG emission, and the trend between the two parameters can be visually observed. For this work, the most preferable results is the ratio that will create low GHG emission while obtaining high profit. For analytical purpose, the sum of all feedstocks is limited to 100 kg in total.

3.4.5. Regional Analysis

In this part, the equations of profits and GHG emission from the optimization analysis will be used again with ratios of feedstock that represent each region in Thailand. These ratios are estimated from the regional production yields data from the Office of the Agricultural Economics. Using the same formula in the optimization analysis, ranges of profit and GHG emission will be estimated. The results are compared to find the best region, the one with the highest of profit range and lowest emission range. Similar to the optimization analysis, the sum of all feedstock is limited to 100 kg.

Chapter 4: Results& Discussion

4.1. Defining System Boundary

In order to analyze the profit and GHG emission related to the production of bio-ethanol, biodiesel, and poly-lactic acid, the analysis needs to cover the production and production-related process entirely in order to identify all the elements involved. The activities that are included within the boundary of this work are of cultivation of cassava, sugarcane, and oil palm; bio-ethanol, biodiesel, and poly-lactic acid (PLA) production; their wastewater treatment processes; and the biogas production.

The figure below shows the flow of materials within the boundary. On the top are the cultivations of the three energy crops. The activities that require energy and generate GHG emission are the application of fertilizers and herbicides, and the work of labours and diesel machinery for land preparing, planting, weeding, and harvesting.

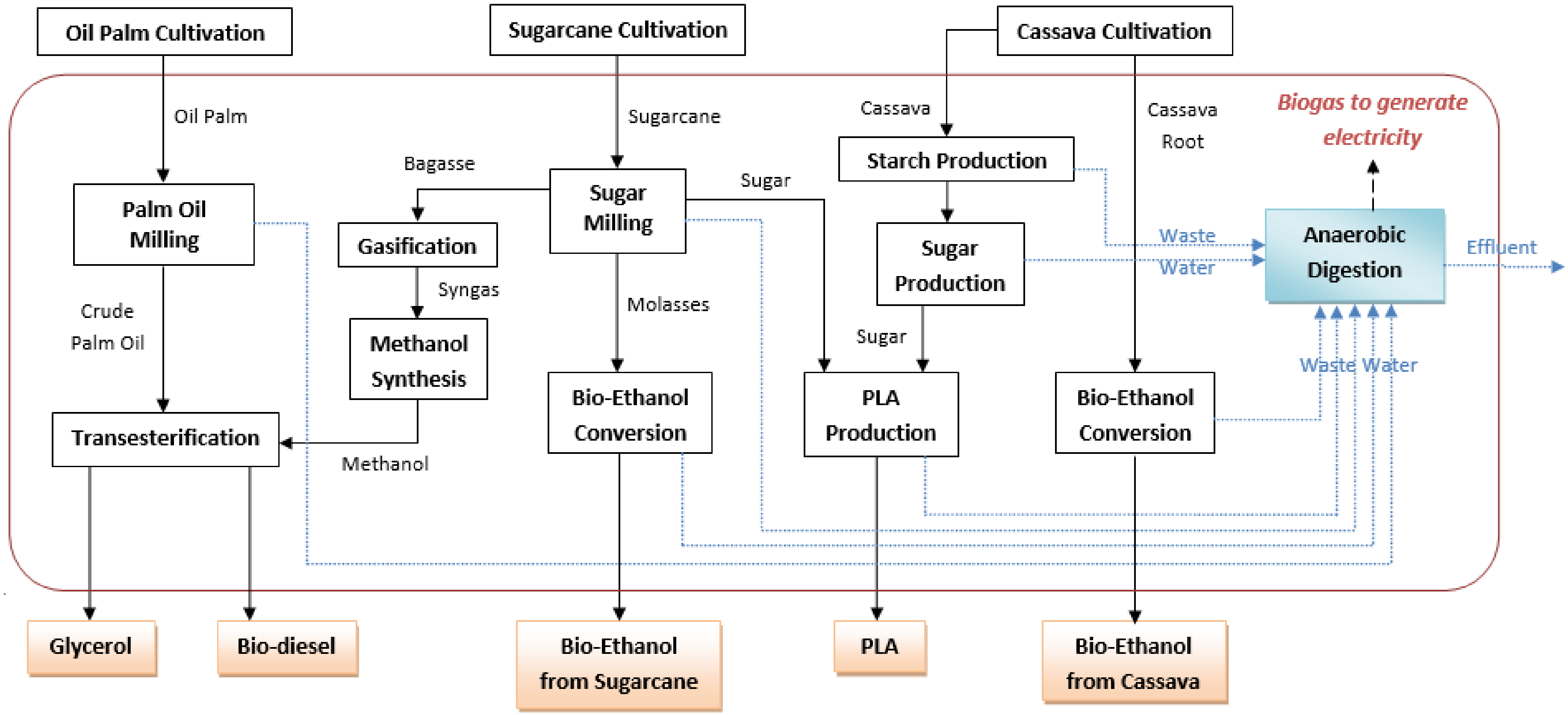

Figure 10: System Boundary of Multi-Feedstock Based Bio-Refinery Model

After cultivation, the crops are fed as feedstock to the main production processes where each of them is converted into the final products. The feedstock cassava involves with the production of two products, PLA and bio-ethanol. For PLA production, cassava is first converted in to starch by removing of sand and impurities, cleansing and chopping out root rails, removing protein and fibers, and drying by passing through the hot-aired dryer column. After that the starch is then converted in to glucose (sugar) by going through liquefaction, saccharification, and purification. Next, the sugar is converted into lactic acid by fermentation, and the lactic acid is chemically converted to lactide. Finally, lactide goes through polymerization process in tin catalyst to make poly-lactic acid. For bio-ethanol production, the cassava goes through milling, mixing and liquefaction, saccharification, fermentation, distillation, and dehydration in order to become 99.5 % purity of ethanol.

The second feedstock, sugarcane, is used to produce three products: PLA, bio-ethanol, and methanol. First, the fresh sugarcane goes through milling where it is crushed to extract sugar juice. The dry pulp of sugarcane after removing the juices called a bagasse. After removing impurities, the juice is concentrated into syrup by boiling off excess water, and the syrup is then crystallized for sugar crystals to form. After the sugar crystal has grown to a preferred size, they are separated from syrup by centrifugal process. Then, the remaining syrup is centrifuged further for more sugar. After the last time of centrifugal process, the remaining syrup is collected and is called as molasses.

The three intermediate products of sugarcane (sugar, bagasse, and molasses) are processed further in to the final products. The sugar that derived from sugarcane goes into the same PLA production processes as the sugar that derived from cassava. Molasses are an input to another bio-ethanol process; it has to go through fermentation by yeast, distillation, and dehydration in order to produce 99.5 % purity of ethanol. The last intermediary product of sugarcane, bagasse, is converted into methanol; to become methanol, bagasse has to go through drying, thermal treatment (gasification) into syngas, gas clean-up to remove particulate and sulphur, scrubbing to remove chlorine compounds, syngas conditioning to optimize syngas for methanol synthesis, and, finally, methanol synthesis itself. According to the planned scheme, this methanol will not be for sale but will be used for biodiesel production as an intermediary input instead.

The last feedstock, oil palm, is for the production of biodiesel another bio-fuel product. From the cultivating field, oil palm is cultivated as a fresh fruit bunch. The fresh fruit bunch, first, has to go in to the mill for the process of crude palm oil (CPO) extraction. Then, the extracted crude palm oil has to go into refinery where it is refined in to a refine palm oil (RPO). The refine palm oil then goes in to biodiesel plant for a transesterification in a batch reactor with methanol as an alcohol, and with either sodium hydroxide (NaOH) or potassium hydroxide (KOH) the catalyst. After 8 hours, palm methyl ester (PME) or biodiesel and glycerol are produced. PME and glycerol, then, are separated by gravity, and the ester is washed with water and dried by heating. Finally, biodiesel and glycerol are obtained.

Apart from the main products that are produced, several processes generate wastewater as well. Wastewater from biomass conversion process contains organic compounds which are sources for producing methane (CH_4). The streams of wastewater are collected toward the sewage treatment facility where the water is treated by anaerobic digestion for methane or biogas; then the biogas is collected and sent to fuel a reboiler for heating steam that will be used to generate electricity and to transfer heat to the production process. After treating the wastewater, the treated water is discharged as an effluent of the facility. This effluent cane be further utilized as a fertilizer for crops cultivation.

The data of all the electricity and heat generated in each process are collected from LCI for energy and profit analysis, as well as its GHG emission values. Other inputs, such as chemicals and water, are also included for profitability analysis as well.

Even though both sugarcane and cassava produce multiple products, cassava feedstock has to be divided to either PLA route or bio-ethanol route, unlike sugarcane which produced sugar, molasses, and bagasse simultaneously; therefore, the processes of cassava is divided into two as they are entirely unrelated.

4.2. Life Cycle Energy Analysis

After defining the boundary for this research, in order to analyse 'how the utilization of biogas for electricity generation will affect the profitability and emissions', values of Life cycle energy, Life cycle GHG emissions, costs of processes and revenues are needed.

In this part, the input energies of all processes mentioned in the boundary defining section are listed on the Table 2, according to the feedstock the process belongs to. Each feedstock will be individually analysed for its input energies, for both base case and biogas utilization case. They are the data collected from several life cycle inventories. For objects, like fertilizer, herbicide, and chemicals, their energies are accounted from the energies inputs in their own respective production processes; while for the energy inputs, like steam, electricity, and diesel, their energies are the actual amount that are consumed within the processes of the bio-refinery. For labours, it is the amount of energy that a human use to perform a specific task to produce the required output.

Steams are separated into steam from coal and steam from fuel oil for the purpose of distinguishing the amount of GHG emission impact and the cost related to them in the later analysis.

Table 2: Energy Input of Bio-refinery

Basis: 1 kg of Cassava (1 kg each for Ethanol production and PLA Production), 1 kg of Sugarcane, 1 kg of Oil Palm

Processes	Unit per kg of Feedstock	Cassava for EtOH *i*	Cassava for PLA *ii*	Sugarcane *iii*	Oil Palm *iv*
Cultivation					
Fertilizer	MJ	0.292	0.292	0.139	0.555
Herbicide	MJ	0.106	0.106	0.028	0.103
Diesel	MJ	0.052	0.052	0.171	0.424
Labor	MJ	0.062	0.062	0.018	
Ethanol Conversion					
Steam-Coal	MJ	2.825		0.373	
Electricity	MJ	0.724		0.373	
Starch Production					
Electricity	MJ		0.169		
Steam-Fuel Oil	MJ		0.286		
Steam-Coal	MJ		0.140		
Sugar Production					
Electricity	MJ		0.110		
Steam-Fuel Oil	MJ		0.057		
PLA Production					

Electricity	MJ		0.459	0.305	
Steam-Fuel Oil	MJ		1.676	1.112	
Sugarcane Milling					
Steam	MJ			0.794	
Gasification					
Electricity for Pre-treatment	MJ			0.056	
Electricity for Gasification	MJ			0.731	
Steam for Gasification	MJ			0.844	
Methanol Synthesis					
Electricity	MJ			0.048	
Steam	MJ			0.679	
Crude Palm Oil Extraction					
Electricity	MJ				0.003
Diesel	MJ				0.032
Biodiesel Production					
Electricity for Refining	MJ				0.001
Diesel for Refining	MJ				0.302
MeOH for Biodiesel	MJ				0.799
NaOH for Biodiesel	MJ				0.026
Electricity for Biodiesel	MJ				0.044
Diesel for Biodiesel	MJ				0.007
Total Energy Input (before applying biogas)	**MJ**	**4.060**	**3.410**	**5.673**	**2.297**
Total Electricity	MJ	0.724	0.739	1.513	0.048
Total Steam Fuel Oil	MJ		2.019		

Total Steam Coal	MJ	2.825	0.140	3.803	
Other	MJ	0.512	0.512	0.356	2.249

[i] (Silalertruksa, T., & Gheewala, S. H., 2009)
[ii] (Chiarakorn et al., 2014)
[iii] (Renó et al., 2011)
[iv] (Papong, S., Chom-In, T., Noksa-Nga, S., & Malakul, P., 2010)

Per 1 kg of the raw material, sugarcane feedstock for bio-ethanol and PLA processes consumed the most energy with 5.673 MJ. On the other hand, the lowest one is oil palm with the energy of 2.297 MJ per kg of oil palm. Among several items on the list, electricity and steam are the two major sources of life cycle energies for the process; their total values are shown separately from other items so that they are easier to compare between each feedstock. At the same time, other items that are not either electricity or steam are included in the 'Other'. They are distinguished from one another because biogas can only substitute the need of electricity and the steam.

In order to determine how much the energy input will be left after the utilization of biogas, the amount of energy of biogas must be determined. To get the values of the energies of biogas, the energy constant (heat) has to be multiplied to the amount in volume of biogas.

To calculate for the energy of biogas from the wastewater of each feedstock's processes we apply the same method; for example: For Cassava for Ethanol, the amount of biogas is 0.0664 m^3 per 1 kg of cassava feedstock. The energy constant is 20.93 MJ/ m^3 (Appendix A.7.).

$$Energy\ of\ Biogas_{CSV-Ethanol} = 0.0664\ m^3\ *\ 20.93\frac{MJ}{m^3} = 1.391\ MJ$$

After biogas is produced, it is sent to fuel reboiler to generate electricity and steam. The electricity and steam generated by biogas are substitutions to the conventional supplies, the electricity from grid and the steam from coal or fuel oil. To account for the substitution, the energy from biogas is used to eliminate, or subtract, the need of conventional supplies. For the priority of substitution, the need of electricity will be considered first as the price of electricity is costlier than steam.

Example: After the substitution, the needs of electricity and steam for cassava for ethanol production are going to decrease. Before the substitution by biogas, energy of electricity and stream are as follow;

$$Electricity:\ 0.724\ MJ$$

$$Steam_{Coal}: 2.825\ MJ$$

Out of 1.391 MJ of biogas energy from cassava for ethanol production, 0.724 MJ of biogas substitutes the electricity, and the rest 0.667 MJ substitutes steam from coal. After substitution,

$$Electricity:\ 0.724\ MJ - 0.724\ MJ = 0\ MJ$$

$$Steam_{Coal}:\ 2.825\ MJ - 0.667\ MJ =\ 2.158\ MJ$$

Table 3: Energy Produced from Biogas and Total Energy After Applying Biogas

Basis: 1 kg of Cassava (1 kg each for Ethanol production and PLA Production), 1 kg of Sugarcane, 1 kg of Oil Palm

	Unit per kg of Feedstock	Cassava for EtOH [i]	Cassava for PLA [ii]	Sugarcane [iii]	Oil Palm [iv]
Biogas, BG					
BG-Ethanol Production	MJ	1.391		0.851	
BG-PLA Production	MJ		0.974	0.646	
BG-Biodiesel Production	MJ				0.252
Energy After Appling Biogas					
(Priority: Electricity, Steam from Fuel Oil, Steam from Coal)					
Electricity	MJ			0.016	
Steam fuel Oil	MJ		1.784		
Steam Coal	MJ	2.158	0.140	3.803	
Other	MJ	0.512	0.512	0.356	2.249
Total Energy After Applying Biogas	**MJ**	**2.670**	**2.436**	**4.176**	**2.249**

[i] (Silalertruksa, T., & Gheewala, S. H., 2009)
[ii] (Chiarakorn et al., 2014)
[iii] (Renó et al., 2011)
[iv] (Papong et al., 2010)

The amount of energy obtained from biogas is listed on Table 3. The quantity of biogas depends on the amount and the quality of wastewater from each feedstock. From the calculated results, wastewater from cassava and sugarcane generates biogas energy more than oil palm; however, ranking wise, oil palm still consumes the least amount of energy per kg.

The substitution of biogas is limited to the portions that are electricity and steam; items in the portion of cultivation and other cannot be substituted by biogas. As shown in Table 3, after the substitution of biogas, electricity can be fully substituted, while some coal will still be needed to produce a steam.

As readers, might notice that the energy input of wastewater treatment is not presented in Table 3, they are actually included as partial energy inputs of the main processes. Most of the papers that are used as data sources of this research have the energy of wastewater treatment processes included within the energy of the main production processes.

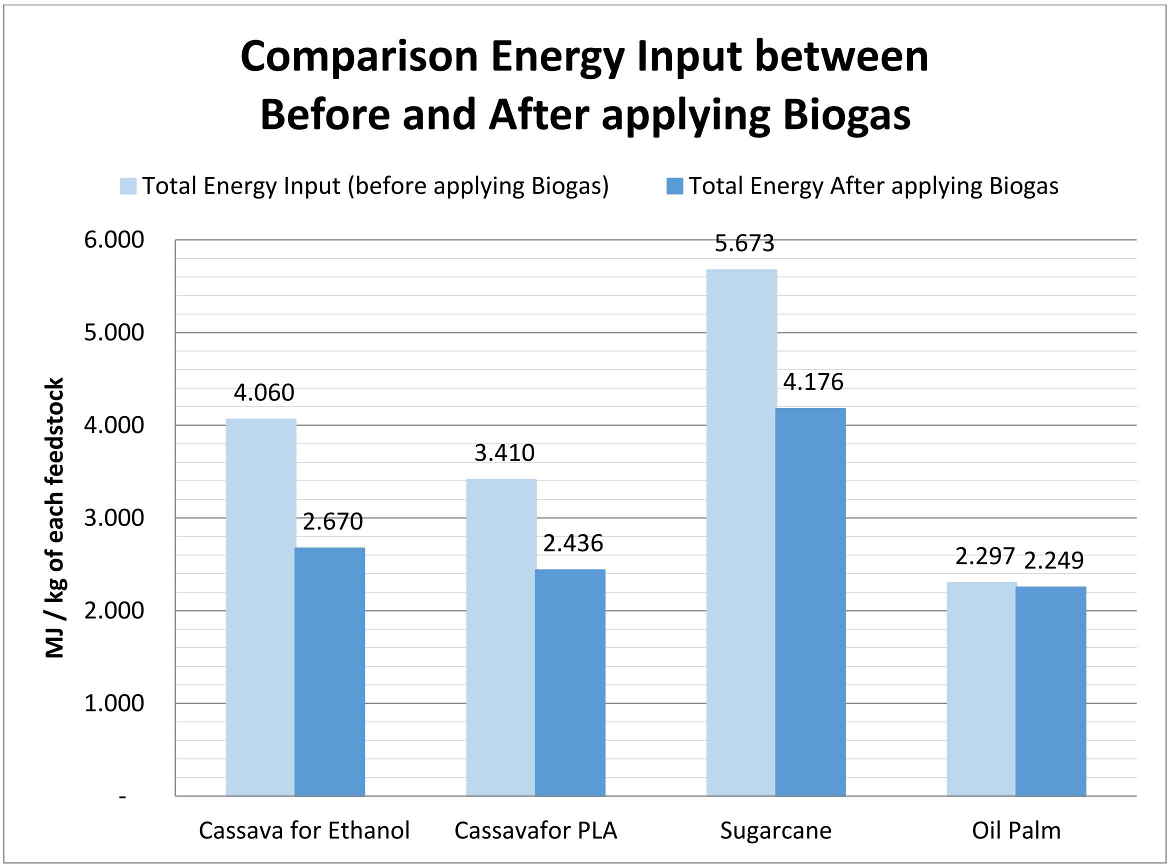

Figure 11: Graph of Comparison Energy Input between Before and After Applying Biogas

Table 4: Percentage Difference of Energy Input Between Before and After Applying Biogas

	Cassava for Ethanol	Cassava for PLA	Sugarcane	Oil Palm
% Difference	34.25	28.57	26.39	2.11

The results from comparing energy input of each of the individual feedstock suggested that the biogas produced from the wastewater will recover the energy for the process of each feedstock. For the processes of cassava for ethanol, cassava for PLA, and sugarcane, their energy inputs were recovered between 26 – 34 %, with cassava for ethanol having the highest and cassava for PLA as the second-highest; their amount energy (electricity, steam from fuel oil, and steam from coal) that can be replaced by biogas are substantial. Unlike the others, oil palm has only small electricity portion that can be substitute by biogas; so, it has the least energy recovered by biogas. Nevertheless, oil palm remains the lowest energy input.

After individually checking for the energy recovery of each feedstock, in the next section the changes in profit by biogas from each feedstock will be analysed.

4.3. Profitability Analysis

In other to determine the profit from the products of each of the feedstock, the total revenue and the total cost of production must be determined. The total revenue is calculated by multiplying the amount of products to their respectively unit prices and the total cost is determined by the cost of operation, including the cost of energy input and other materials.

Profit Formula:

$$Profit = Revenue - Operating\ Cost$$

Table 5: Products from Bio-refinery

Basis: 1 kg of Cassava (1 kg each for Ethanol production and PLA Production), 1 kg of Sugarcane, 1 kg of Oil Palm

Products	Unit per kg of Feedstock	Cassava for EtOH [i]	Cassava for PLA [ii]	Sugarcane [iii]	Oil Palm [iv]
Final Products					
Ethanol	L	0.163		0.043	
PLA	kg		0.132	0.087	
Biodiesel	kg				0.147
Glycerol	kg				0.026
Intermediate Products					
Starch from Cassava	kg		0.224		
Sugar from Cassava	kg		0.213		
Sugar from Sugarcane	kg			0.141	
Molasses	kg			0.197	
Bagasse	kg			0.284	
Syngas	kg			0.597	
Methanol	L			0.142	
CPO	kg				0.163

[i] (Silalertruksa, T., & Gheewala, S. H., 2009)
[ii] (Chiarakorn et al., 2014)
[iii] (Renó et al., 2011)
[iv] (Papong et al., 2010)

One kilogram of different feedstock generates different amount of benefits (revenues) as the price of product and the amount of product differ from each other. For sugarcane and oil palm which have more than one final product, the total revenue is the sum of two or more products.

Table 6: Revenue from Products

Basis: 1 kg of Cassava (1 kg each for Ethanol production and PLA Production), 1 kg of Sugarcane, 1 kg of Oil Palm

Benefits from Products	Unit per kg of Feedstock	Cassava for EthOH	Cassava for PLA	Sugarcane	Oil Palm
Ethanol [i]	THB	4.302		1.132	
PLA [ii]	THB		12.500	8.293	
Methanol [iii]	THB				
Biodiesel [iv]	THB				2.969
Glycerol [v]	THB				1.180
Total Revenue	**THB**	**4.302**	**12.500**	**9.425**	**4.149**

[i] (Energy Policy Committee, 2015)
[ii] (Plastics Institute of Thailand, 2013)
[iii] (CHEMIPAN, 2016a)
[iv] (Kung Krabaen Bay Royal Development Study Center, 2016)
[v] (Promchuer, S., Aomsabsin, W., Jamratchai, P., & Sriruksa W., 2015)

As shown on the Table 6, revenue from cassava for PLA production and sugarcane are higher than the other two, mainly because of the high revenue of PLA. However, without considering the cost of the processes it is not yet possible to judge the feedstock with best profits.

4.3.1. Cost of Processes

Similar to Table 2 in the previous part, the costs of processes for each feedstock are the addition of cost of energy and materials involved. The costs of processes or the operational costs in this study is limited to the costs of fertilizers, herbicides, labours, electricity, coal, fuel oil, diesel, and chemicals. As the main concern of this study is to deal with the high cost of operation, the investment cost is not included in the analysis. Moreover, the bio-refinery of this particular configuration does not currently exist in Thailand, so, estimating the accurate cost of investment would be extremely difficult.

To determine the cost of processes for each feedstock, the market prices are used for all items. The cost is a product between the price in Thai Baht per MJ and the energy input from Table 2. The prices that are used are converted from per unit of mass or volume into per unit of MJ.

Example: The energy input of coal for steam for ethanol conversion process for sugarcane is 0.373 MJ per kg of sugarcane. The market price of coal is 0.073 THB per MJ. The cost of coal for this process is equal to

$$Cost = 0.373\,\frac{MJ}{kg\ SGC} * 0.073\,\frac{THB}{MJ} = 0.027\,\frac{THB}{kg\ SGC}$$

The market prices of other items are in (Appendix B.1.).

Most of the prices can directly be found from vendors or from announcements by governmental authority, like fuel prices; these prices are simply announced as per unit of that particular product. Unlike the rest, electricity cost comes in the form of formula; it would require several inputs to calculate the cost of electricity which some of them would require assumptions and some of them has to be eliminated as they could be difficult to make an estimation for. Water cost is also one of the cost that requires assumption, which depends on the amount of water consume in each production. The calculation of electricity cost and water cost are explained below.

4.3.1.1. Calculating for the Cost of Electricity (per 1 MJ)

Generally, electricity cost formula (excluding VAT) is as follow (Building Division Pattani Campus, Thaialnd., 2011);

$$Cost_{Elec} = Energy\ Cost + Electricity\ Demand\ Cost + \ Factor\ of\ Tariff\ (Ft)$$

Energy cost is a cost based on the actual amount of energy consumed in the unit of kilowatt-hour. Electricity demand cost or demand cost is a cost for the highest electricity demand in kilowatts unit during a course of time, known as on-peak period and off-peak period. On-peak is a time during Monday to Friday, from 9:00 to 22:00 (13-hour); and off-peak is a time during Monday to Friday, from 22:00 to 9:00 (11-hour), and the whole weekend. Finally, Factor of tariff (Ft) is the cost that changes according to the fluctuation of the cost of fuel for electricity generation and electricity buying rates (Provincial Electricity Authority, 2015).

$$\begin{aligned} Energy\ Cost\ &= Units\ of\ Electricity_{On-Peak} * Rate_{On-Peak} \\ &+ Units\ of\ Electricity_{Off-Peak} * Rate_{Off-Peak} \end{aligned}$$

$$Demand\ Cost = Demand_{On-Peak} * Demand\ Rate_{On-Peak} + Demand_{Off-Peak} * Demand\ Rate_{Off-Peak}$$

$$Ft = \left(Units\ of\ Electricity_{On-Peak} + Units\ of\ Electricity_{Off-Peak}\right) * Ft\ Rate$$

Few assumptions are required in order to calculate electricity cost; (1) The bio-refinery operates 7 days a week continuously, (2) The electricity consumption is constant all the time. Moreover, the demands for on-peak and off-peak can only be obtained when all the power consumption rate (kW) of all electricity consuming appliances are known; as the power consumption rates vary from one model of appliances to another, the electricity demands are difficult to estimate. This point is considered one of the limitations for this study. The last assumption is (3) Omitting the calculation for demand of electricity.

The rates that are required for calculation are given as the following;

Table 7: Rates for Electricity Cost Calculation

Type of Rate	Rate
Rate $_{On-Peak}$	2.6136 THB/kWh
Rate $_{Off-Peak}$	1.1726 THB/kWh
Ft Rate	-0.333 THB/kWh

(EGAT, 2015a)

Therefore, Energy cost formula is as follow;

$$Energy\ Cost\ = Units\ of\ Electricity_{On-Peak} * 2.6136\ \left[\frac{THB}{kWh}\right]$$
$$+ Units\ of\ Electricity_{Off-Peak} * 1.1726\ \left[\frac{THB}{kWh}\right]$$

Based on the assumption number 1 and 2, and the definition of on-peak and off-peak periods, the formula can be simplified further into

$$Energy\ Cost = \left(\left(\frac{13\ h}{24\ h}\right) Total\ Units\ of\ Electricity * 2.6136\ \left[\frac{THB}{kWh}\right]\right.$$
$$\left. + \left(\frac{11\ h}{24\ h}\right) Total\ Units\ of\ Electricity * 1.1726\ \left[\frac{THB}{kWh}\right]\right) * \frac{5\ days}{7\ days}$$
$$+ Total\ Units\ of\ Electricity * \ 1.1726\ \left[\frac{THB}{kWh}\right] * \frac{2\ days}{7\ days}$$
$$Energy\ Cost = Total\ Units\ of\ Electricity * 1.7301\ \left[\frac{THB}{kWh}\right]$$

For the consistency in this work, kilowatts-hour should be converted into MJ. The unit conversion of kilowatts-hour to MJ is 1 kWh = 3.6 MJ.

$$Energy\ Cost = Total\ Units\ of\ Electricity\ in\ MJ * 0.4806\ \left[\frac{THB}{MJ}\right]$$

Factor of tariff or Ft cost formula is as follow;

$$Ft = \left(Units\ of\ Electricity_{On-Peak} + Units\ of\ Electricity_{Off-Peak}\right)$$
$$* \left(-0.333\ \left[\frac{THB}{kWh}\right]\right)$$

Based on assumption 1, 2, and the definition of on-peak and off-peak periods, the formula can be further simplified into

$$Ft = \left(\frac{13\ h}{24\ h} * Total\ Units\ of\ Electricity + \frac{11\ h}{24\ h} * Total\ Units\ of\ Electricity\right) * \left(-0.333\ \left[\frac{THB}{kWh}\right]\right)$$

$$Ft = Total\ Units\ of\ Electricity * \left(-0.333\ \left[\frac{THB}{kWh}\right]\right)$$

For consistency, this formula should be converted in to MJ instead of kWh as well.

$$Ft = Total\ Units\ of\ Electricity\ in\ MJ * \left(-0.093\ \left[\frac{THB}{MJ}\right]\right)$$

Therefore, cost of electricity formulas are as follow;

$$Cost_{elec} = Energy\ Cost + Ft$$

$$Cost_{elec} = Total\ Units\ of\ Electricity\ in\ MJ * (0.4806 - 0.093)\ \left[\frac{THB}{MJ}\right]$$

$$Cost_{elec} = Total\ Units\ of\ Electricity\ in\ MJ * 0.338 \left[\frac{THB}{MJ}\right]$$

Thus, the cost of 1 MJ of electricity is 0.338 THB. It is important to note that this cost price is calculated based on the assumptions given; the accuracy of price is only good for estimation.

4.3.1.2. Calculating for the Cost of Water

In the order to estimate the cost of water, the amount of water used in each process and the unit price of water must be known.

Table 8: References of the Amount of Water Consumption Based on Each Types of Feedstocks

Feedstock-Product	Water	Unit/kg of feedstock	Reference
Cassava for PLA	0.094	m^3/kg of Cassava	(Chiarakorn et al., 2014)
Cassava for Ethanol	0.163	m^3/kg of Cassava	(Gheewala et al., 2013)
Sugarcane PLA	0.002	m^3/kg of Sugarcane	(Chiarakorn et al., 2014)
Sugarcane Ethanol	0.021	m^3/kg of Sugarcane	(Gheewala et al., 2013)
Biodiesel	0.166	m^3/kg of Oil Palm	(Pleanjai, S., Gheewala, S. H., & Garivait S., 2007)

Current bulk sales unit price for non-household is 13.00 THB per cubic meter (MWA, 1999). The cost of water can be calculated by the following equation.

Cost of water is shown as the following;

$$Cost_{Water} = Price_{Water} * Q\ (amount\ in\ volume)$$

For example, per 1 kg of sugarcane the cost of water will be,

$$Cost_{Water} = 13.00 \left[\frac{THB}{m^3}\right] * (0.021 + 0.002) \left[\frac{m^3}{kg\ SGC}\right]$$

$$Cost_{Water} = 0.295 \left[\frac{THB}{kg\ SGC}\right]$$

As already mentioned, the energy input of wastewater treatment process is included to the energy input of the main process; therefore, their costs of wastewater treatment is also partial of the cost of the main processes as well.

Table 9: Costs of Processes in Bio-refinery

Basis: 1 kg of Cassava (1 kg each for Ethanol production and PLA Production), 1 kg of Sugarcane, 1 kg of Oil Palm

Processes	Unit per kg of Feedstock	Cassava EtOH	Cassava PLA	Sugarcane	Oil Palm
Cultivation					
Fertilizer	THB	0.119	0.119	0.056	0.226
Herbicide	THB	0.018	0.018	0.005	0.017
Diesel	THB	0.027	0.027	0.089	0.220
Labor	THB	0.670	0.670	0.201	
Ethanol Conversion					
Steam-Coal	THB	0.206		0.027	
Electricity	THB	0.281		0.145	
Starch Production					
Electricity	THB		0.066		
Steam-Fuel Oil	THB		0.057		
Steam-Coal	THB		0.010		
Sugar Production					
Electricity	THB		0.043		
Steam-Fuel Oil	THB		0.011		
PLA Production					
Electricity	THB		0.178	0.118	
Steam-Fuel Oil	THB		0.333	0.221	
-					

Sugarcane Milling					
Steam-Coal	THB			0.058	
Gasification					
Electricity for Pre-treatment	THB			0.022	
Electricity for Gasification	THB			0.284	
Steam-Coal for Gasification	THB			0.062	
Methanol Synthesis					
Electricity	THB			0.018	
Steam-Coal	THB			0.050	
Crude Palm Oil Extraction					
Electricity	THB				0.001
Diesel	THB				0.017
Biodiesel Production					
Electricity for Refining	THB				0.001
Diesel for Refining	THB				0.157
MeOH for Biodiesel	THB				
NaOH for Biodiesel	THB				0.045
Electricity for Biodiesel	THB				0.017
Diesel for Biodiesel	THB				0.004
Water	THB	1.122	1.228	0.295	2.157
Total Cost (before recovery)	**THB**	**2.442**	**2.760**	**1.650**	**2.861**
Total Electricity	THB	0.281	0.287	0.587	0.019
Total Steam Fuel Oil	THB		0.401	0.221	
Total Steam Coal	THB	0.206	0.010	0.196	
Other	THB	1.956	2.062	0.645	2.825

[i] (Nguyen, T. L. T., Gheewala, S. H., & Garivait, S., 2007b; Office of Agricultural Economics, 2015b)
[ii] (Nguyen et al., 2007b; Office of Agricultural Economics, 2015a)
[iii] (EPPO, 2015)
[iv] (Nguyen et al., 2007b)
[v] (EPPO, 2010; Wancham, K., 2015)
[vi] (National Energy Policy Office, 2000)
[vii] (EPPO, 2010, 2015)
[viii] (CHEMIPAN, 2016b)

As shown, the total operational cost of oil palm processes is the highest among the four productions, mainly, due to the cost of water. The total costs of processes of cassava for PLA and cassava for bio-ethanol are second and third, respectively, with higher costs of electricity and steam than the processes of oil palm. For sugarcane, total operational cost is the least, but sugarcane's cost of energy (electricity + steam) portion is the highest. How the cost is distributed will affect the profits after biogas recovery, as biogas can only help reduce the cost that comes from energy only.

Table 10: Costs of Processes After Applying Biogas

Basis: 1 kg of Cassava (1 kg each for Ethanol production and PLA Production), 1 kg of Sugarcane, 1 kg of Oil Palm

	Unit per kg of Feedstock	**Cassava EtOH**	**Cassava PLA**	**Sugarcane**	**Oil Palm**
Costs of Energy Remain After Recovery					
Total Electricity	THB			0.006	
Total Steam Fuel Oil	THB		0.35		
Total Steam Coal	THB	0.157	0.010	0.196	
Other	THB	1.956	2.062	0.645	2.825
Total Cost of Energy Remain	**THB**	**2.113**	**2.426**	**0.848**	**2.825**

By using the remaining energy from Table 10, the cost of energy remain can be determined multiplying the remaining energy to the price of electricity, coal, and fuel oil. If the biogas can fully replace the used of electricity or fuel oil, then, that cost disappear. It is clear that the costs of energy remaining will be less than the total cost before the recovery. To calculate for the new profit, it is simply the difference between the revenue and the new cost, the cost of energy remains.

4.3.2. Profits Between Before and After Applying Biogas

Table 11: Profits Between Before and After Applying Biogas

Basis: 1 kg of Cassava (1 kg each for Ethanol production and PLA Production), 1 kg of Sugarcane, 1 kg of Oil Palm

Profits per Feed	Unit per kg of Feedstock	Cassava EtOH	Cassava PLA	Sugarcane	Oil Palm
Profits Before Applying Biogas *(Total Revenue - Cost of Energy before recovery)*	THB	1.860	9.740	7.775	1.288
Profits After Applying Biogas *(Total Revenue - Cost of Energy Remain after recovery)*	THB	2.189	10.074	8.577	1.324

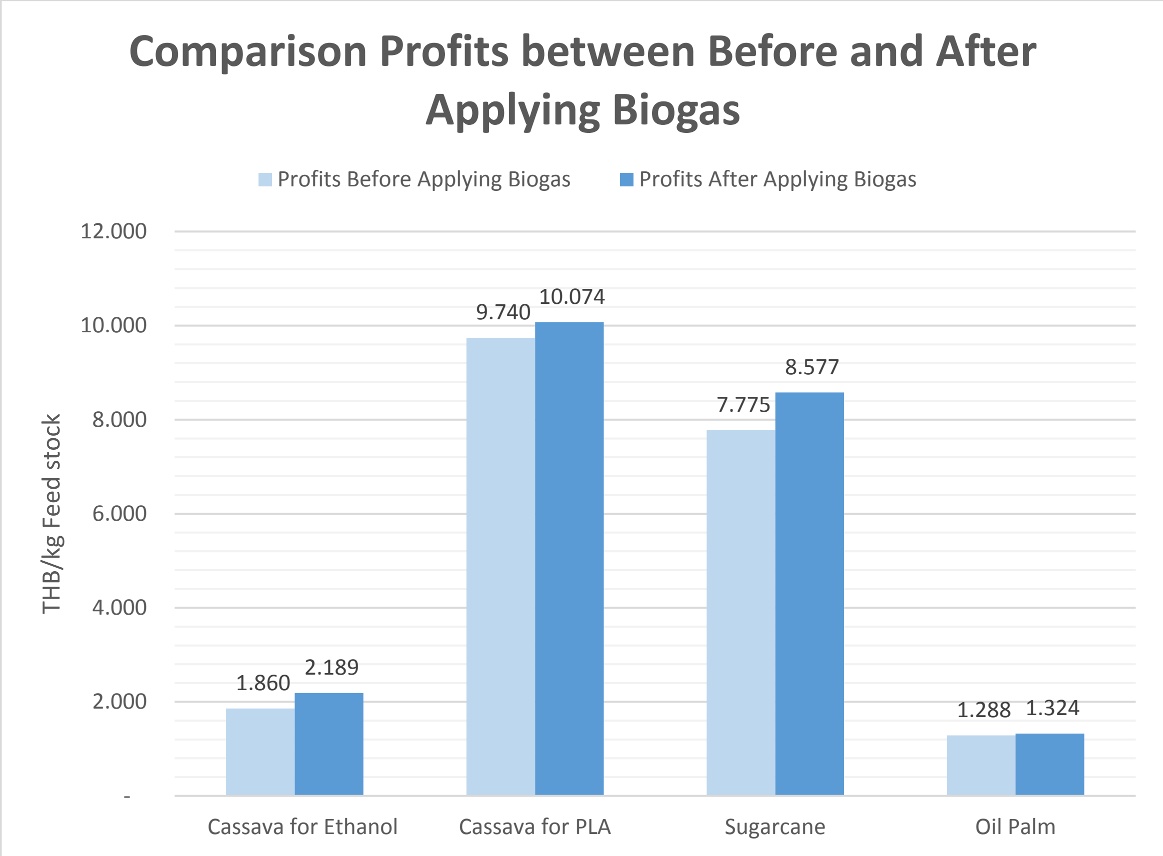

Figure 12: Graph of Comparion Profits between Before and After Applying Biogas

Table 12: Percentage Difference of Profits Between Before and After Applying Biogas

	Cassava for Ethanol	Cassava for PLA	Sugarcane	Oil Palm
% Difference	17.72	3.42	10.32	2.79

As the costs of energy for each feedstock processes decreases, thanks to biogas substitution for fuels, their profits are increasing. From the results, cassava for PLA generates the highest profit per 1 kg of feedstock both before and after applying biogas utilization with 9.740 and 10.074 THB per kg respectively; while, among the four, cassava for ethanol has the most improvement by percentages. By the amount in Thai Baht, sugarcane increases the most by 0.802 THB per kg of sugarcane. For the case of oil palm, since most of the cost came from the ‘other’ category, the biogas did not increase much of the profit.

After calculating profits for an individual feedstock, in the next section, GHG emission from each of the feedstock will be calculated.

4.4. Life Cycle Greenhouse Gas Emission Analysis

GHG emissions of each feedstock are distinguished according to the processes involved. Apart from the main production processes, wastewater treatment processes are also included as well as they also emit GHG. They are shown separately because, firstly, their sources of GHG emissions are different from each other, and, secondly, the GHG emission of wastewater will be eliminated after it is treated for biogas.

Table 13: Life Cycle Greenhouse Gas Emission of Bio-refinery

Basis: 1 kg of Cassava (1 kg each for Ethanol production and PLA Production), 1 kg of Sugarcane, 1 kg of Oil Palm

Processes	Unit per kg of Feedstock	Cassava EtOH [i]	Cassava PLA [ii]	Sugar-cane [iii]	Oil Palm [iv]
1.) Cultivation	kg CO2 eq.	0.04	0.04	0.01	0.05
2.) Ethanol Conversion	kg CO2 eq.	0.23		0.05	
3.) PLA Production*	kg CO2 eq.		0.59	0.39	
4.) Sugarcane Milling	kg CO2 eq.			0.0002	
5.) Gasification	kg CO2 eq.				
6.) Syngas & Methanol Synthesis	kg CO2 eq.			0.26	

7.) Crude Palm Oil Extraction	kg CO2 eq.				0.003
8.) Biodiesel Production	kg CO2 eq.				0.01
WW Treatment (2)	kg CO2 eq.	0.18			
WW Treatment (2) + (4)	kg CO2 eq.			0.08	
WW Treatment (3)	kg CO2 eq.		0.70	0.46	
WW Treatment (7) + (8)	kg CO2 eq.				0.263
Total GHG Emission before applying biogas	kg CO2 eq.	**0.455**	**1.326**	**1.252**	**0.329**

* PLA Production from cassava include greenhouse gas emission from starch and sugar production

[i] (Papong, S. & Malakul, P., 2010)
[ii] (Chiarakorn et al., 2014)
[iii] (Nguyen et al., 2007b; Renó et al., 2011; Chiarakorn et al., 2014)
[iv] (de Souza et al., 2010; Harsono et al., 2014)

As shown on the Table 13, GHG emission from the processes of cassava for PLA and sugarcane are significantly higher than the other two. The main contributors for the high GHG emissions are the processes of PLA production and their respective wastewater treatment processes. Emission of wastewater from some processes are combined because some of the data that were obtained as a single value. Even though the emission of wastewater is included, the emission from biogas production stage itself is not as the carbon dioxides from biogas are short-cycle carbons (these carbons are from the organic materials in wastewater that came from processing biomass, or crops); so these carbons can be easily harvested back into nature if the crops is planted again, and, therefore, not accounted for the emission.

After applying the biogas to produce own electricity and steam, three phenomena related to GHG emission will occurred. First, as biogas is extracted from organic wastewater, the GHG emission from wastewater treatment process would decreases. In this work, it is assumed that the emission from wastewater is entirely gone after the treatment process. Therefore, the amount for this one will be equal to the emission from wastewater. Second, by burning biogas for steam and electricity, the GHG emission from combustion will be created. Finally, by using biogas for electricity, the emission that came from electricity grid is decreased as well.

Table 14: Greenhouse Gas Emission After Applying Biogas

Processes	**Unit per kg of Feedstock**	**Cassava EtOH**	**Cassava PLA**	**Sugarcane**	**Oil Palm**
GHG Emission from WW treatment (reduced)	kg CO2 eq.	-0.180	-0.700	-0.545	-0.263
GHG Emission from Burning Biogas [i]	kg CO2 eq.	0.030	0.030	0.062	0.002
GHG Emission from electricity grid and stream (reduced) [ii]	kg CO2 eq.	-0.016	-0.017	-0.034	-0.001
Total GHG Emission after applying Biogas	**kg CO2 eq.**	**0.288**	**0.640**	**0.735**	**0.067**

[i] *(*Yu, L., Yaoqiu, K., Ningsheng, H., Zhifeng, W., & Lianzhong, X., 2008*)*
[ii] (EGAT, 2015a)

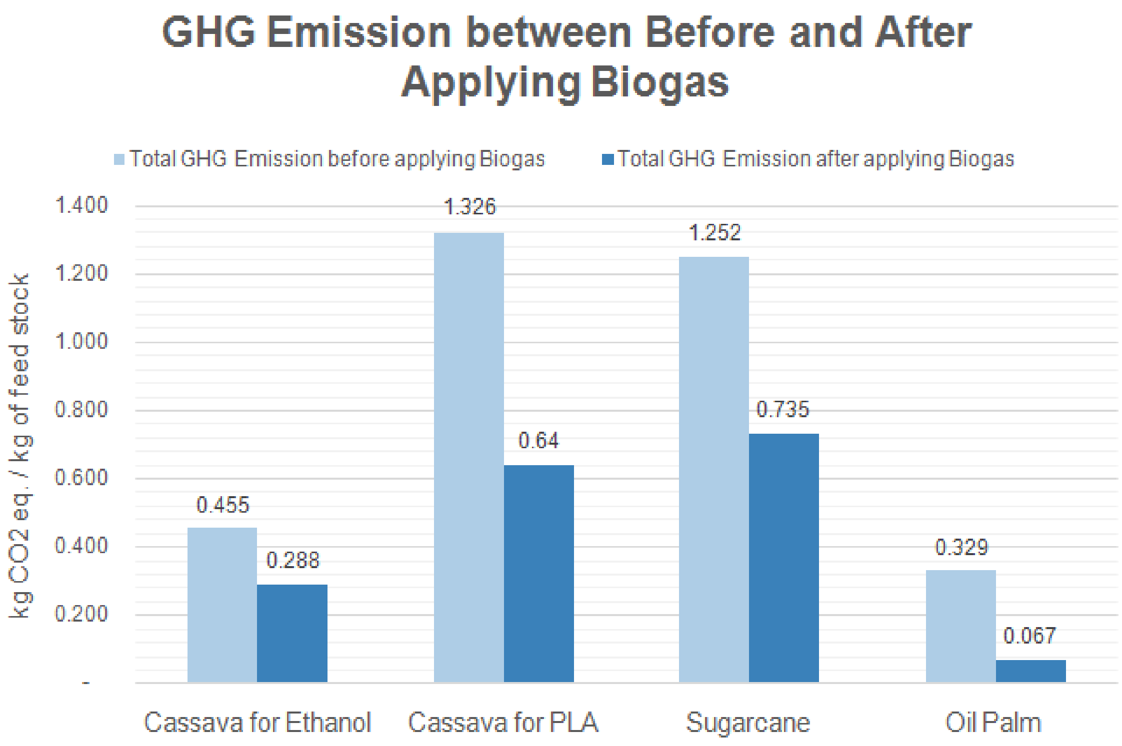

Figure 13: Graph of GHG Emission Between Before and After Applying Biogas

Table 15: Percentage Difference of GHG Emission Between Before and After Applying Biogas

	Cassava for Ethanol	Cassava for PLA	Sugarcane	Oil Palm
% Difference	36.7	51.7	41.3	79.6

From the GHG emission analysis, it is confirmed that biogas utilization for electricity generation from each feedstock helps in reducing the GHG emission. The ranking of GHG emission per kg of feedstock changes slightly after applying biogas; cassava for PLA dropped to the second ranking. From the percentages, it can be seen that all of them had their emission reduced significantly. Initially, the processes of cassava for PLA before applying biogas (base case) produce high GHG during PLA production and the wastewater treatment process due to the high amount of organic material that are residues of the production processes of PLA, however, as biogas is applied the emission from energy usage drop significantly, even lower that the after-recovery emission from sugarcane. This is also the same case with the sugarcane; however, the main processes of sugarcane deliver higher amount of GHG than the cassava for PLA. While, the processes of cassava for ethanol initially produce quite low GHG emission, after the treatment it is reduced further by 36.7 %. However, by percentage wise, oil palm achieves the highest with 79.6 % of GHG reduced, mainly due to the whole processes of oil palm do not generate much GHG except for the wastewater. Since most of oil palm's GHG emission comes from the wastewater, once the water is treated, the emission of oil palm reduced significantly.

4.5. Optimization of Feedstock

Up until this point, the previous analysis considered each feedstock individually and all the results (energy, profit, emission) are per 1 kg of each feedstock. In this step the optimization analysis is performed in order to see the total effect of all feedstock together. The profits and GHG emission of multi-feedstock will be calculated at various ratios for both base-case and biogas utilization case which the results will be compared. As each feedstock generated unequal profit and GHG, changing their ratios would also affect the combined output as well. The best result, if possible, is a ratio where the profit is the highest and the GHG emission is at the lowest. Low GHG emission from the facility is a preferable result as it excessive emission of GHG is deemed irresponsible and unacceptable by the modern norms of society. On the other hand, the workers of bio-refinery should be making high profit in order to maintain the business and be as profitable as any profit organization would which is their responsibility toward shareholders.

The first step for optimization is to derive the equations with the feedstock as inputs, profits and GHG emission as outputs. The equation for profit is shown as follow;

$$Total\ Profit = Profit_{CSV,E} + Profit_{CSV,P} + Profit_{SGC} + Profit_{Palm}$$

Then, profit can be substituted with the product of profit per unit of feedstock (as determined in the profitability analysis) and the feedstock in kg.

Table 16: Profits per Feed After Applying Biogas

Profits per Feed	Unit per kg of Feedstock	Cassava EtOH	Cassava PLA	Sugarcane	Oil Palm
Profits After Applying Biogas *(Total Revenue - Cost of Energy Remain after recovery)*	THB	2.189	10.074	8.577	1.324

$$Total\ Profit = \left(2.189 * F_{CSV,E} + 10.074 * F_{CSV,P} + 8.577 * F_{SGC} + 1.324 * F_{Palm}\right)[THB]$$

In similar manner, the GHG emission equation can be derived the same way. Equation for GHG Emission:

$$Total\ GHG = GHG_{CSV,E} + GHG_{CSV,P} + GHG_{SGC} + GHG_{Palm}$$

Each term can be substituted with the product of emission per unit of feedstock as determined in the previous section, and the feedstock in kg.

$$Total\ GHG = \left(0.288 * F_{CSV,E} + 0.640 * F_{CSV,P} + 0.735 * F_{SGC} + 0.067 * F_{Palm}\right)[CO_2\ eq.]$$

Initially, there are four types of feedstock for determining the profit and emission; however, as cassava for ethanol generates rather low profit when compare to other feedstock, it was chosen to be omitted from the optimization. Moreover, ethanol can be produced from sugarcane, so there would not be a problem if we omit the cassava for sugarcane. Therefore, with three types of feedstock left, the optimization became simpler. The amount of feedstock in kg is varied by 10 at a time, with the range from 10 kg to 80 kg and a total of 100 kg of three feedstocks.

Table 17: Profits between Before and After applying Biogas at MFSB

Feedstock Ratio (kg)	Profit before Biogas (THB)	Profit after Biogas (THB)	% Difference
10:10:80	278.2	292.4	5.12%
10:20:70	343.0	364.9	6.38%
10:30:60	407.9	437.5	7.24%
10:40:50	472.8	510.0	7.87%
10:50:40	537.7	582.5	8.35%
10:60:30	602.5	655.1	8.72%
10:70:20	667.4	727.6	9.02%
10:80:10	732.3	800.1	9.27%
20:10:70	362.7	379.9	4.74%
20:20:60	427.6	452.4	5.82%
20:30:50	492.4	525.0	6.61%
20:40:40	557.3	597.5	7.21%
20:50:30	622.2	670.0	7.69%
20:60:20	687.1	742.6	8.08%
20:70:10	751.9	815.1	8.40%
30:10:60	447.2	467.4	4.51%
30:20:50	512.1	539.9	5.44%
30:30:40	577.0	612.5	6.15%
30:40:30	641.8	685.0	6.73%
30:50:20	706.7	757.5	7.19%
30:60:10	771.6	830.1	7.58%
40:10:50	531.7	554.9	4.36%
40:20:40	596.6	627.4	5.17%
40:30:30	661.5	700.0	5.82%
40:40:20	726.4	772.5	6.35%
40:50:10	791.2	845.0	6.80%
50:10:40	616.3	642.4	4.24%
50:20:30	681.1	714.9	4.96%
50:30:20	746.0	787.5	5.56%
50:40:10	810.9	860.0	6.06%
60:10:30	700.8	729.9	4.15%
60:20:20	765.7	802.4	4.80%
60:30:10	830.5	875.0	5.35%
70:10:20	785.3	817.4	4.09%
70:20:10	850.2	889.9	4.67%
80:10:10	869.8	904.9	4.03%

*Feedstock Ratio = Cassava for PLA : Sugarcane : Oil palm

Figure 14: Graph of Profits between Before and After applying Biogas at MFSB

Table 17 and Figure 15 show the results of profits from the MFSB, before and after applying biogas for electricity generation. The profits increase after biogas utilization at all ratios; this confirms that biogas really help in increasing the profit. The maximum profit is 904.9 THB at the ratio of 80:10:10. From the graph, the trend would suggest that increasing cassava for PLA would increase profit the most. On the other hand, the lowest profit is 292.4 THB at the ratio of 10:10:80, suggesting that oil palm have a very low profit.

In term of percentage, biogas utilization helps increasing the profit by 9.27 % at maximum, at the feedstock ratio of 10:80:10; this point suggested that biogas from sugarcane section increases profit most effectively. The reason that the point of highest profit (80:10:10) and the point where profit increases the most in percentage (10:80:10) are not the same point is because the selling price of PLA from cassava has more effect on the total profit than the reducing cost by biogas utilization of sugarcane feedstock.

Table 18: GHG emissions between Before and After applying Biogas at MFSB

Feedstock Ratio (kg)	GHG Emission (kg CO_2 eq.)	GHG Emission (kg CO_2 eq.)	% Difference
10:10:80	52.12	19.10	-63.34%
10:20:70	61.35	25.78	-57.97%
10:30:60	70.57	32.46	-54.00%
10:40:50	79.80	39.15	-50.95%
10:50:40	89.03	45.83	-48.53%
10:60:30	98.26	52.51	-46.56%
10:70:20	107.49	59.19	-44.94%
10:80:10	116.72	65.87	-43.57%
20:10:70	62.08	24.83	-60.00%
20:20:60	71.31	31.51	-55.81%
20:30:50	80.54	38.19	-52.58%
20:40:40	89.77	44.87	-50.01%
20:50:30	99.00	51.55	-47.93%
20:60:20	108.23	58.23	-46.19%
20:70:10	117.45	64.91	-44.73%
30:10:60	72.05	30.56	-57.59%
30:20:50	81.28	37.24	-54.19%
30:30:40	90.51	43.92	-51.48%
30:40:30	99.74	50.60	-49.27%
30:50:20	108.96	57.28	-47.43%
30:60:10	118.19	63.96	-45.89%
40:10:50	82.02	36.28	-55.76%
40:20:40	91.25	42.96	-52.92%
40:30:30	100.47	49.64	-50.59%
40:40:20	109.70	56.32	-48.66%
40:50:10	118.93	63.00	-47.03%
50:10:40	91.98	42.01	-54.33%
50:20:30	101.21	48.69	-51.89%
50:30:20	110.44	55.37	-49.87%
50:40:10	119.67	62.05	-48.15%
60:10:30	101.95	47.73	-53.18%
60:20:20	111.18	54.41	-51.06%
60:30:10	120.41	61.09	-49.26%
70:10:20	111.92	53.46	-52.23%
70:20:10	121.15	60.14	-50.36%
80:10:10	121.88	59.19	-51.44%

*Feedstock Ratio = Cassava for PLA : Sugarcane : Oil palm

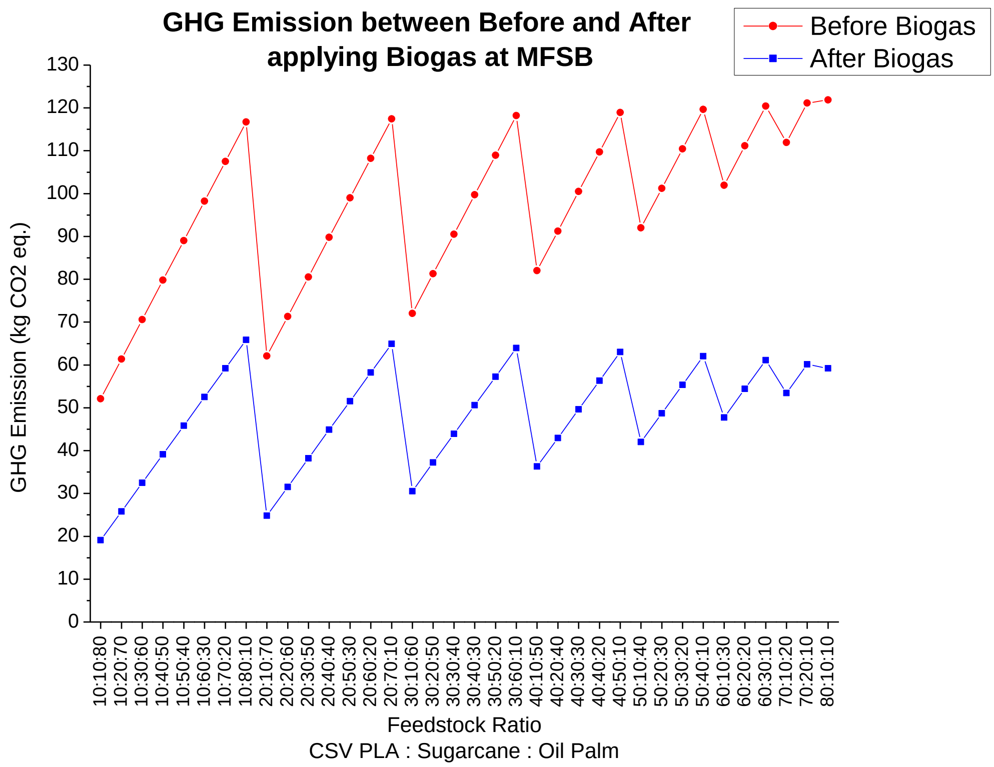

Figure 15: Graph of GHG Emission between Before and After applying Biogas at MFSB

Table 18 and Figure 16 show the results of GHG emission at MFSB, before and after applying biogas for electricity generation. The results show that the GHG emission at any feedstock ratios decreases after the utilization of biogas, confirming that biogas does really help in decreasing the GHG emission in bio-refinery. The lowest GHG emission after biogas utilization is 19.10 kg CO_2 eq. at the ratio 10:10:80. In term of percentage difference, the most difference is -63.34 % at the ratio 10:10:80, suggesting that biogas utilization is most effective at reducing GHG for oil palm process. The reason for this is that oil palm produces lowest GHG emission when compare with other feedstocks; when biogas is applied, the GHG emission becomes even lower than before, when used in multi-feedstock, oil palm will pull down the total GHG emission. The trend suggesting that by increasing oil palm ratio, the GHG emission will decreases. On the other hand, by increasing the sugarcane, the emission will increase, because sugarcane has the highest portion of GHG emission that cannot be reduced after the biogas utilization. The highest GHG emission is 65.87 kg CO_2 eq. at 10:80:10.

Table 19: The Relationship of Three Feedstocks with Profits and GHG Emission

	Increasing Cassava for PLA	Increasing Sugarcane	Increasing Oil Palm
Profits	↑	Δ	↓
GHG Emissions	Δ	↑	↓

↑ = Increasing profits or GHG emissions,
Δ = Moderately increasing profits or GHG emissions,
↓ = Reducing profits or GHG emissions

Based on the results of profit and GHG emission, the relationship of the three feedstocks with profits and GHG emission are summarized on the Table 19. Cassava for PLA gives the best profits due to the high price of PLA; increasing the portion of cassava for PLA would give a higher profit. Sugarcane feedstock gives the second-best profit amount the three; while, profit from oil palm is the smallest. In term of GHG emission, oil palm produces the least GHG emission, very small when compare with the other two. Cassava for PLA produces second most GHG and Sugarcane is the first, although both of them generate quite high GHG when compare to oil palm.

Table 20: Profits and GHG Emission from Varied Feedstock Ratio

Feedstock Ratio (kg)	Profit (THB)	GHG Emission (kg CO_2 eq.)
10:10:80	292.4	19.10
10:20:70	364.9	25.78
10:30:60	437.5	32.46
10:40:50	510.0	39.15
10:50:40	582.5	45.83
10:60:30	655.1	52.51
10:70:20	727.6	59.19
10:80:10	800.1	65.87
20:10:70	379.9	24.83
20:20:60	452.4	31.51
20:30:50	525.0	38.19
20:40:40	597.5	44.87
20:50:30	670.0	51.55
20:60:20	742.6	58.23
20:70:10	815.1	64.91
30:10:60	467.4	30.56
30:20:50	539.9	37.24
30:30:40	612.5	43.92
30:40:30	685.0	50.60
30:50:20	757.5	57.28
30:60:10	830.1	63.96
40:10:50	554.9	36.28
40:20:40	627.4	42.96
40:30:30	700.0	49.64
40:40:20	772.5	56.32
40:50:10	845.0	63.00
50:10:40	642.4	42.01
50:20:30	714.9	48.69
50:30:20	787.5	55.37
50:40:10	860.0	62.05
60:10:30	729.9	47.73
60:20:20	802.4	54.41
60:30:10	875.0	61.09
70:10:20	817.4	53.46
70:20:10	889.9	60.14
80:10:10	904.9	59.19

*Feedstock Ratio = Cassava for PLA : Sugarcane : Oil palm

The data on this Table 20 is plotted on the graph below.

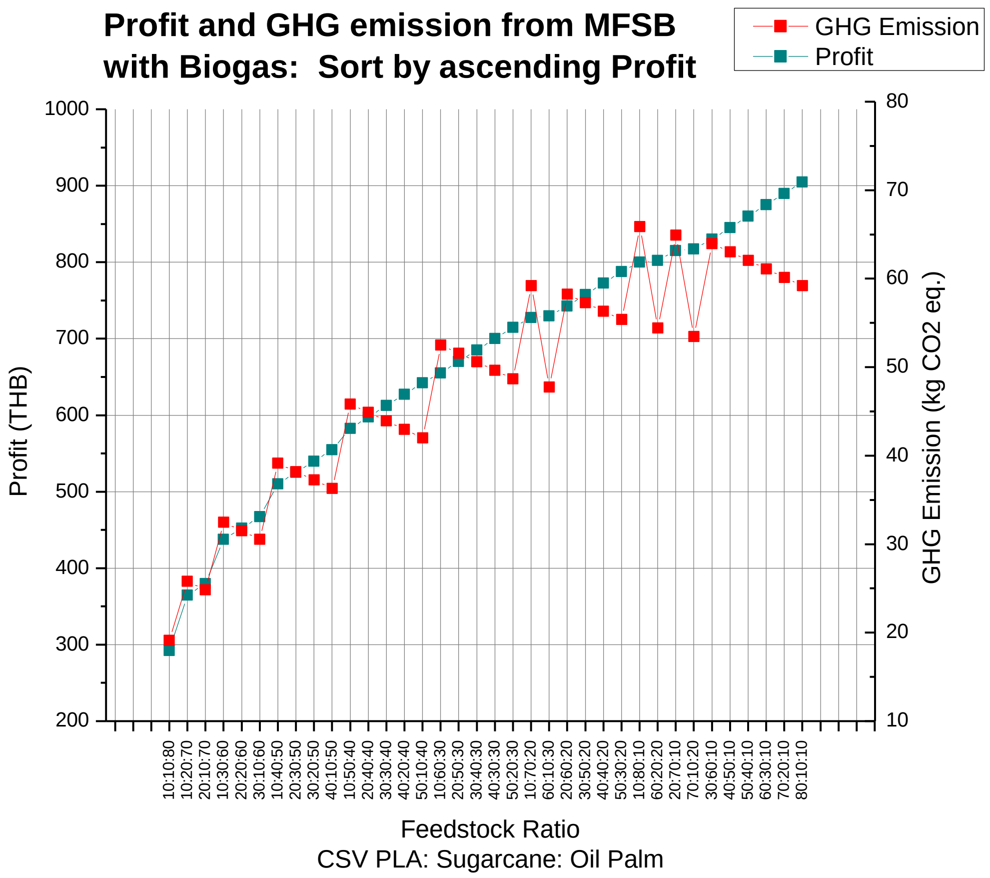

Figure 16: Graph of Profits and Emission when Applying Biogas sorted by Ascending Profit order

The data in Figure 17 are arranged according to the ascending profits. In general, the GHG emission is directly proportional to the profit; however, the data congregated into smaller groups and showed a slightly decreasing trend within groups. Therefore, within certain ranges of profit, there is a data point which has lower GHG emission than the other points.

Table 21: Feedstock Ratios that Generate the Least GHG Emission within Different Price Range

Feedstock Ratio (kg)	Profit Range (THB)	Profit (THB)	GHG Emission (kg CO_2 eq.)
10:10:80	< 300	292.39	19.10
20:10:70	300-399	379.89	24.83
30:10:60	400-499	467.39	30.56
40:10:50	500-599	554.89	36.28
50:10:40	600-699	642.39	42.01
60:10:30	700-799	729.89	47.73
70:10:20	800-899	817.39	53.46
80:10:10	> 900	904.89	59.19

*Feedstock Ratio = Cassava for PLA : Sugarcane : Oil palm

Based on Table 21, eight points from graph exhibit lowest GHG emission in each of their profit range. Two things can be observed from these points: first, the ratio either have high cassava for PLA ratio or high oil palm ratio and second, the sugarcane ratio is at the minimum (10 kg). While both cassava for PLA and sugarcane have quite high profit, sugarcane generated the most GHG emission in comparison to other feedstocks which explains why the ratio for sugarcane are at the lowest. In order to determine which points among the selected points is best one, they will be judged by how much profit generated per the GHG emission they cause, aka an eco-efficiency.

Table 22: Profit per GHG emission of the selected feedstock ratios

Feedstock Ratio (kg)	Profit (THB)	GHG Emission (kg CO_2 eq.)	Profit per GHG emission (THB/ kg CO_2 eq.)
10:10:80	292.39	19.10	15.3048
20:10:70	379.89	24.83	15.2994
30:10:60	467.39	30.56	15.2961
40:10:50	554.89	36.28	15.2938
50:10:40	642.39	42.01	15.2921
60:10:30	729.89	47.73	15.2908
70:10:20	817.39	53.46	15.2898
80:10:10	904.89	59.19	15.2890

*Feedstock Ratio = Cassava for PLA : Sugarcane : Oil palm

As shown on the Table 22, the profit per GHG emission for each feedstock ratio are approximately 15.29 – 15.30; thus, the results imply that these feedstock ratios generated profit with equal efficiency for the GHG emission they produced, or in simpler manner, these feedstock ratios are equally eco-efficient.

As the profit per GHG emission showed that the eight feedstock ratios are equally efficient, the decision then had to be made on the next most logical choice. The selection of the best ratio is, then, judge by giving equal importance between profit and GHG emission; therefore, by the order, the feedstock ratio in the middle, or 50:10:40 is selected.

The feedstock ratio of 50:10:40 satisfied in term of how the feedstock is efficiently used; it is the optimal choice for production of our choices of feedstock and products. However, if concerning the demand of bioethanol and biofuel based on the target of AEDP (2015-2036), the project consumptions of bio-ethanol and bio-diesel are 4.1 billion and 5.1 billion litres in 2036 (references). The products are about 4:5 in ratio. From the optimal feedstock ratio 50:10:40, it can produce less bio-ethanol than biodiesel. Therefore, if optimizing the feedstock ratio by concerning the demand of bio-ethanol : biodiesel to be 4:5, the results are varied as shown in Table 23.

Table 23: Profit, GHG Emission and Amount of Products from the Feedstock Ratio based on Biofuels Demand.

Feedstock Ratio (kg)	Profit (THB)	GHG Emission (kg CO_2 eq.)	PLA (kg)	Bio-ethanol (L)	Biodiesel (L)
4:72:24	689.60	57.09	6.81	3.09	4.00
12:66:22	716.08	57.66	7.34	2.84	3.67
20:60:20	742.56	58.23	7.87	2.58	3.33
28:54:18	769.04	58.80	8.40	2.32	3.00
36:48:16	795.52	59.38	8.93	2.06	2.67
44:42:14	822.00	59.95	9.46	1.81	2.33
52:36:12	848.48	60.52	9.98	1.55	2.00
60:30:10	874.96	61.09	10.51	1.29	1.67
68:24:8	901.44	61.67	11.04	1.03	1.33
76:18:6	927.92	62.24	11.57	0.77	1.00
84:12:4	954.40	62.81	12.10	0.52	0.67
92:6:2	980.88	63.38	12.63	0.26	0.33

*Feedstock Ratio = Cassava for PLA : Sugarcane : Oil palm

As shown on the Table 23, for every feedstock ratio used, the ratio of bio-ethanol to biodiesel is always 4:5. The profit and GHG emission increases with each other; the selection of the ratio is judge by giving equal importance to both profit and GHG emission. Therefore, by the order the ratio 60:30:10 is selected. The ratio 60:30:10 has both average profit per GHG emission and the amount of bio-ethanol and biodiesel, making it a favourable choice for selection. After doing both analyses, the ratio of 50:10:40 is the best when concerning with the eco-efficiency of the way to utilize the feedstock; however, the feedstock ratio 60:30:10 takes in the concern on the demand for biofuels as well.

As we can see, the relationship between the profits and GHG emission is directly proportional with each other. For producers to be highly profitable, they would have to emit lots of GHG emission as well. To solve this dilemma, the suggested solutions can be divided in to two ways: first, apply for government incentives program or other similar programs, and, second, adopt new technology that minimize the GHG emission of the processes. Government incentive programs reward producers who use environmental friendly methods; these incentives are often subsidies or carbon credits. While, some producers may also try to improve their production process for lowering the GHG emission and the operational cost.

To increase the profit for low GHG case, low profit case, FiT, or feed-in-tariff, is a payment made to entities generating their own electricity from renewable resources, such as biomass, or biogas in this place. The FiT rate for biogas from wastewater is 3.76 THB/ kWh, plus FiT premium 0.50 THB/ kWh for bio-fuel projects (EGAT, 2015b). Some profit can be gained if the electricity from biogas is sold for FiT; however, if the electricity is sold, the bio-refinery would have to acquire that portion of electricity from national grid which would mean that the biogas did not help in reducing the GHG emission.

Apart from FiT, another method to increase the profit for low GHG case is by applying for a Clean Development Mechanism (CDM) project. Participants of CDM are rewarded with carbon credits for contributing to emission reduction. Interested producers can establish their CDM projects in Thailand to earn carbon credits which they can sell the credits for money; however, as Thailand's Carbon market has yet to be established, the seller of credits have to sell it directly, by over-the-counter (OTC) approach, to the ones who wanted to buy. Unlike the FiT method, the bio-refinery can be utilized the biogas for internal usage (electricity and steam generation) and, still, able to sell carbon credits for money. This way, the profit increased while the emission is minimized.

Apart from increasing the profit, producers should also try to minimize GHG emission by relying on techniques or technology that can capture GHG emission or reducing energy consumption. Insulating boiler to increase the energy efficiency which would require less fuel is one way of reducing GHG emission. Technology such as cogeneration process where a steam line is used for both electricity generation and heating processes, also improves the energy efficiency and reducing GHG emission from less required fuel as well. In this work, processes that should require the improvement of energy efficiency would be the ethanol production, PLA production, and methanol synthesis processes as they consumed a lot of energy input; reducing fuel usage on boiler and other combustion device can help in reducing energy cost and GHG emission as well. Installing insulating boiler or cogeneration process are the example techniques that can achieve this purpose.

4.6. Regional Analysis

This analysis is conducted- to find the potential regions for establishing multi-feedstock bio-refinery in Thailand. The country can be divided in to 6 regions; Northern, North-eastern, Central, Eastern, Western and Southern. Among these six, northern, north-eastern, and central regions can grow all the three crops together. However, the growth rate may differ from one place to another; the difference in growth rate could mean differences in profit and GHG emission as well. In order to determine the availability of crops in each region, the parameter of production yield is used to express as how well crops can grow in that regions, in a way implies how easily certain crops can be acquired in relative to other crops. The 3-year average production yields of crops are converted into percentage to estimate as a feedstock ratio.

Table 24: Percentage of Feedstock Based on Production Yield of North Region

North Region	Annual Production Yield	Percentage
Cassava	3,678 kg/ rai	22 %
Sugarcane	11,822 kg/ rai	72 %
Oil palm	993 kg/ rai	6 %

Table 25: Percentage of Feedstock Based on Production Yield of Northeast Region

Northeast Region	Annual Production Yield	Percentage
Cassava	3,517 kg/ rai	22 %
Sugarcane	11,247 kg/ rai	70 %
Oil palm	1,294 kg/rai	8 %

Table 26: Percentage of Feedstock Based on Production Yield of Central Region

Central Region	Annual Production Yield	Percentage
Cassava	3,506 kg/ rai	20 %
Sugarcane	11,460 kg/ rai	65 %
Oil palm	2,537 kg/ rai	14 %

Comparing the three regions, there are not much differences between them, except, the fact that the yield of oil palm in central regions are almost double of the other two regions. The feedstock ratios are either rounded-up or rounded-down to the closest tens. From these results, the bio-refinery should have the same potential regardless of which one of the three regions it operates in. On averages, the feedstock ratio of three regions is 20:70:10. Therefore, the three regions showed equal potential for establishing bio-refinery.

Table 27: Eco-efficiency of the Feedstock ratio based on the production yield and the optimized ratio based on the demand of biofuels

	Feedstock Ratio (kg)	**Profit per GHG emission (THB/ kg CO2 eq.)**
Feedstock ratio based on the production yield of all 3 regions	20:70:10	12.557
Optimized Feedstock ratio based on the demand of biofuels	60:30:10	14.322

*Feedstock Ratio = Cassava for PLA : Sugarcane : Oil palm

The profit per GHG emission of the feedstock ratio based on the production yield of the 3 regions is lower than the optimized feedstock ratio based on the demand of biofuels; the feedstock production of the three regions can be changed in order to become more eco-efficient. In the three regions, the production of cassava for PLA should increase by 200% of the original cassava amount (from 20 to 60) and the production of sugarcane should be decreased by 133% of the original sugarcane amount (from 70 to 30). The production of oil palm can remain the same. By increasing cassava for PLA in feedstock, the total profit will increase, and by decreasing the sugarcane, the GHG emission will decrease; together, both effects will increase the eco-efficiency.

Chapter 5: Conclusion

In this report, the effect of biogas on profitability and the GHG emission are analysed for a bio-refinery with feedstock of cassava, sugarcane, and oil palm producing bio-ethanol, PLA, and biodiesel. The role of biogas in the bio-refinery is to substitute the conventional fuel for energy generation, namely, electricity and steam. By analysing each feedstock separately, it is confirmed that biogas helps improving the energy, profit, and reducing GHG emission as reviewed from other literatures. As MFSB, the utilization of biogas for electricity generation successfully improved the profit and minimized GHG emissions, with the ratio being [cassava for PLA: sugarcane: oil palm], the best ratio is at 50:10:40 which achieve the highest eco-efficiency possible with profit per GHG emission of 15.30. However, when concerning the Thailand's demand of bio-ethanol and biodiesel, the alternative best ratio is at 60:30:10. This ratio shows potential to achieved government's target for biofuel production, which consider to be eco-efficient at 14.32. Based on regional analysis, it is found that Northern, North-Eastern and Central region have equal potential for establishment of MFSB. However, the productional yield of energy crops in the three regions still need to regulated for biofuels and bioplastic production with higher eco-efficiency.

As a contribution toward policymakers, this study recommends the regulation over the crops production to meet the finding of this work which is at the ratio 60:30:10; crop production at recommended ratio will be able to achieve the target for biofuels production of Thailand with equal concerns for profit and GHG emission. By doing so, it will be possible the producers to expand the bio-refineries in Thailand. Also, farmers will gain more income for producing the crops based on this ratio as it will be on demand and job related with plantation will also be generated as well.

Even though the optimized feedstock ratio was determined, the eco-efficiency of the ratio can be improved further by either increasing profit or decreasing the GHG emission. Two possible solutions to this problem are the provision of incentives by policy-makers and the technological improvement by the manufacturers. As Thailand has no market for carbon-credit trading, members of CDM project could benefit from earning carbon credits which can be traded for money by directly selling them to manufacturer that needs it. Another kind of incentives is a subsidy provided by government to producers of biomass electricity for commercial use; in Thailand, it is called feed-in-tariff (FiT). For technological improvement approach, manufacturers can investigate their own facilities for process whose energy efficiency can be improved; thus, improving the energy efficiency means that the less fuel is used to generate the same amount of work or heat which, then the GHG emission and profit will also improve as a result. As for this work, bio-ethanol conversion, PLA production, and methanol synthesis processes have high energy input. So to improve them, fuel usage should be reduced for boiler and combustion devices. For example, installing insulating boiler could help in fuel reduction effort. Another common approach to reduce fuel usage is the cogeneration process where a steam line is used for both electricity generation and heating processes.

There are several limitations in this thesis. Some of the data are unobtainable. As the boundary of bio-refinery includes four productions together, raw data collection from field would have required time to conduct as the facilities for the productions are located on different locations. Moreover, access to manufacturer's data can be quite difficult to obtain as they are confidential and classified. This study, then, collected the secondary data which are more readily available through other academic articles; nevertheless, not all the required parameters are available from a single source. In addition, some parameters required assumptions to calculate, as already clarified in the discussion. Therefore, data are gathered from several articles which lead to concern about the consistency of data. The inconsistency in data could result in some inaccuracies of calculation.

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Appendices

Appendix A: Life-cycle energy analysis

A.1. Conversion Rate of Products

The data of energy inputs often comes in product basis. For the analysis in this work, the basis of energy needs to be per kg of feedstock. A formula to change basis of energy for any process (denoted by i) is

$$Energyperfeedstock_i = Energyperproduct_i * ConversionRateofaproduct$$

Therefore, to calculate for the energy per feedstock, *conversion rate* of products are needed. From Financial and Economic Viability of Bioplastic Production in Thailand (2014), 1,000 of ethanol is produced from 6.21 tons of cassava. The conversion rate of cassava for ethanol is calculated by

$$Conversion\ rate_{cassava,ethanol} = \frac{1{,}000\ Lofethanol}{6{,}210\ kgofcassava} = 0.161\frac{Lofethanol}{kgofcassava}$$

By the same definition, the conversion rates of other processes can be calculated as well.

Table A-1: Conversion rates of all products-feedstock

Feedstock	Product	Conversion rate	Reference
Cassava [kg]	Bio-ethanol [L]	0.161	(Silalertruksa, T. & Gheewala, S. H., 2009)
	PLA [kg]	0.132	(Chiarakorn et al., 2014)
Sugarcane [kg]	Bio-ethanol [L]	0.043	(Silalertruksa, T. & Gheewala, S. H., 2009)
	PLA [kg]	0.087	(Renó et al., 2011)
Oil Palm [kg]	Biodiesel [kg]	0.147	(Pleanjai, S. & Gheewala, S. H., 2009)

A.2. LCI Data of Cassava Feedstock for Bio-ethanol Production

Table 2
Energy balance (MJ) for production of 1000 L cassava based ethanol.[a]

Items	Unit	Scenario I: Current operation		Scenario II: Designed operation	
		Total energy	Fossil energy	Total energy	Fossil energy
1) Cassava farming/processing					
1a. Cassava farming					
NPK fertilizers	MJ	1790	1703	1779	1693
Herbicide	MJ	649	617	645	612
Diesel (farm machinery)	MJ	317	317	315	315
Labor	MJ	377		375	
1b. Cassava processing					
Diesel (chip processing)	MJ	–	–	761	761
2) Transport					
Fresh cassava	MJ	885	885	880	880
3) Ethanol conversion					
Coal (steam production)	MJ	16,495	16,495	8104	8104
Energy recovered from biogas used for steam production)	MJ	792	–	1760	–
Electricity	MJ	4430	4297	3130	3036
Net energy inputs	MJ	25,735	24,314	17,749	15,401
NEV[b]	MJ	(−4535)		3827	
NRnEV[c]	MJ		(−3114)		5799
Net Energy Ratio (NER)[d]		0.82	1.19		
Renewability[e]		0.87	1.38		

[a] Energy content of ethanol = 21,200 MJ/1000 L ethanol.
[b] Net Energy Value (NEV) = energy content of ethanol – net energy inputs.
[c] NRnEV = energy content of ethanol – fossil energy inputs.
[d] Net Energy Ratio (NER) = net energy outputs/net energy inputs.
[e] Renewability = net bioenergy outputs/net fossil energy inputs.

Figure A-1: Energy balance (MJ) for production of 1000 L cassava based ethanol

(Silalertruksa, T. & Gheewala, S. H., 2009)

For bio-ethanol production from cassava, scenario 1 from the figure above will be used as data for energy input.

To calculate for the energy input per kg of feedstock, the energy per product is multiplied to the conversion rate of products

$$For fertilizer: 1.790 \frac{MJ}{L of ethanol} * 0.161 \frac{L of ethanol}{kg of cassava} = 0.292 \frac{MJ}{kg of cassava}$$

Below is Table A-2 for energy inputs per kg of cassava for bio-ethanol production from cassava

Table A-2: Energy input per 1 kg of cassava for cassava-ethanol process

	Energy per 1000 L of ethanol [MJ/ 1000 L of ethanol]	Energy per 1 kg of cassava [MJ/ kg of cassava]
Cultivation		

Fertilizer	1,790	0.292
Herbicide	649	0.106
Diesel	317	0.052
Labour	377	0.062
Conversion		
Steam - Coal	16,495	2.825
Electricity	4,430	0.724

The same process is repeated to the data of other production to find the energy input per kg of feedstock for other feedstock.

A.3. LCI Data of Cassava Feedstock for PLA Production

Some energy inputs of cassava for PLA production requires the conversion rate for intermediary products as well.

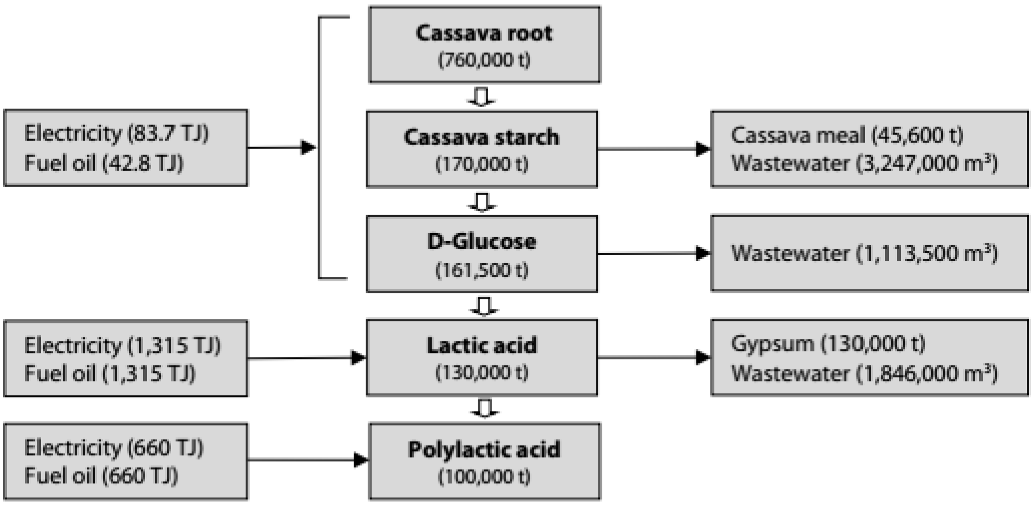

Figure A-2: Scheme of mass and energy flow for PLA production from cassava root

(Chiarakorn et al., 2014)

Table A-3: Conversion rate for starch, glucose, and lactic acid

Intermediary Products	**Amount in kg per kg of cassava [kg/ kg of cassava]**
Cassava Starch	0.224
Glucose	0.213
Lactic acid	0.171

Table 3
Inventory data of cassava starch production stage.

Flow	Unit	Amount		Type	Related activities
		Base case	Option I		
Inputs					
Cassava root	kg/kg starch	4.33 ± 0.39	4.33 ± 0.39	Material input	Farming
Water	l/kg starch	18.65 ± 7.16	18.65 ± 7.16	Material input	Processing water and steam production
Fuel oil	MJ/kg starch	1.28 ± 0.67	0	Energy input	Burning for steam and electricity production
Biogas	m^3/kg starch	0.03 ± 0.03	0.06 ± 0.01	Internal flow	Burning for steam and electricity production
Electricity	kg/kg starch	0.21 ± 0.04	0.18 ± 0.01	Energy input	In process electricity use
Outputs					
Cassava starch (13% MC)	kg/kg starch	1.00	1.00	Product output	Allocation by starch content
Cassava pulp (dry mass)	kg/kg starch	0.39	0.39	By-product	Allocation by starch content

Figure A-3: Inventory data of cassava starch production stage

(Papong et al., 2014)

To change the unit of electricity from kWh to MJ, multiply by 3.6.

To change the unit of biogas from m^3 to MJ, multiply by20.93. In this case, biogas is treated as coal instead.

To obtain the energy input per 1 kg of cassava, multiply the amount in the table by the conversion rate of starch from cassava.

Table A-4: Energy input per 1 kg of cassava for cassava starch production process

	Energy per 1 kg of PLA [MJ/ kg of PLA]	Energy per 1 kg of cassava [MJ/ kg of cassava]
Starch Production		
Electricity	1.285	0.169
Fuel Oil	2.176	0.286
Steam -Coal	1.067	0.140

2.3.3. Glucose production stage

Commercially, glucose is produced via the enzymatic hydrolysis starch for which many crops can be used as the source of starch such as corn, wheat, cassava, rice, etc. Glucose production from cassava starch consists of three steps: liquefaction, saccharification, and purification. Because information on energy used in glucose production from cassava in Thailand has not been published, this study has gathered the inventory data from the report on the financial and economic viability of bioplastics production in Thailand (Chiarakorn et al., 2011), and Renouf et al. (2008). One kilogram of glucose production requires 0.144 kWh of electricity and 0.0067 L of fuel oil.

2.3.4. Lactic acid, lactide and PLA production stage

Glucose is converted to lactic acid by fermentation, followed by purification. The fermentation process requires energy use (steam and electricity) and contributes substantially to the fossil energy demand of PLA. Sulfuric acid, calcium carbonate, and auxiliary chemicals are required as operating supplies. The PLA manufacturing from lactic acid occurs in two steps. The first step is the conversion of lactic acid into the lactide, and then purification by distillation. In the second step the polymerization of lactide to polylactide takes place in the presence of a tin catalyst. Inventory data on the energy use and process chemical demand for the lactic acid, lactide, and polylactide production were extracted from Groot and Borén (2010). Based on 1 kg of PLA, the production requires 0.97 kWh of electricity and 12.74 MJ of steam. This study considered two different scenarios as described below:

Figure A-4: Paragraphs on glucose production stage and PLA production stage from cassava (Papong et al., 2014)

To change the unit of electricity from kWh to MJ, multiply by 3.6.

To change the unit of fuel oil from L to MJ, multiply by 39.77.

Table A-5: Energy input per 1 kg of cassava for glucose and PLA production processes

	Energy per 1 kg of PLA [MJ/ kg of PLA]	Energy per 1 kg of cassava [MJ/ kg of cassava]
Sugar (glucose) production		
Electricity	0.837	0.110
Fuel Oil	0.430	0.057
PLA Production		
Electricity	3.492	0.459
Steam- Fuel Oil	12.740	1.676

A.4. LCI Data of Sugarcane Feedstock for Bio-ethanol Production

Table 5
Energy balance (MJ) for production of 1000 L molasses based ethanol (MoE).

Items	MoE Plant-1		MoE Plant-2		MoE Plant-3	
	Total energy	Fossil energy	Total energy	Fossil energy	Total energy	Fossil energy
1) Sugarcane farming						
NPK fertilizers	3228	3069	3089	2937	2932	2788
Herbicide	662	626	634	599	601	569
Diesel (farm machinery)	3968	3968	3798	3798	3604	3604
Labor	429		418		397	
2) Sugar milling						
Surplus electricity during normal operation (to grid)	(−2608)		(−2496)		(−2369)	
Surplus bagasse (converted to electricity to grid)	(−7047)		(−6745)		(−6401)	
3) Ethanol conversion						
Steam and electricity	17,378		16,412		23,491	2173
4) Transport						
Sugarcane	1955	1955	1871	1871	1775	1775
Molasses	238		869	869	1155	1155
Net energy inputs	27,858	9618	27,091	10,074	33,955	12,064
Net energy outputs (ethanol and surplus electricity)	30,855		30,441		29,970	
NEV	2997		3350		(−3985)	
NRnEV		21,237		20,367		17,906
Net energy ratio (NER)	1.11		1.12		0.88	
Renewability	3.21		3.02		2.48	

Figure A-5: Energy balance (MJ) for production of 1000 L molasses based ethanol (MoE)

(Silalertruksa, T. & Gheewala, S. H., 2009)

Table A-6: Energy input per 1 kg of sugarcane for cultivation and conversion processes

	Energy per 1000 L of ethanol [MJ/ 1000 L of ethanol]	Energy per 1 kg of sugarcane [MJ/ kg of sugarcane]
Cultivation		
Fertilizer	3,228	0.139
Herbicide	662	0.028
Diesel	3,968	0.171
Labour	429	0.018
Conversion		
Steam - Coal	8,689	0.373
Electricity	8,689	0.373

A.5. LCI Data of Sugarcane Feedstock for PLA Production

The LCI data for PLA production from sugarcane has never been published in any articles before; therefore, energy inputs involving in sugarcane PLA production are calculated by using the energy inputs of cassava PLA production multiplying with the weight ratio of sugarcane PLA to cassava PLA (both are per 1 kg of their respective feedstock).

The weight ratio is (0.087 kg of PLA per kg of sugarcane / 0.132 kg of PLA per kg of cassava) or 0.663.

Table A-7: Energy input per 1 kg of sugarcane for PLA production process

	Energy per 1 kg of cassava [MJ/ kg of cassava]	Energy per 1 kg of sugarcane [MJ/ kg of sugarcane]
PLA Production		
Electricity	0.459	0.305
Steam- Fuel Oil	1.676	1.112

A.6. LCI Data of Oil Palm Feedstock for Biodiesel Production

Table 1
Energy inputs and energy outputs in PME system.

Life cycle biodiesel production	Per ton PME	MJ/kg PME
Input		
Oil palm plantation		
N-fertilizer (kg)	54.01	3.10
P_2O_5-fertilizer (kg)	0.35	0.0024
K_2O-fertilizer (kg)	99.90	0.68
Glyphosate (kg)	1.94	0.52
Paraquat (kg)	0.69	0.18
Seed (kg)	67.77	0.07
Diesel used (for transport FFB) (kg)	69.16	2.89
(a) Sub-total		7.45
Crude palm oil extraction		
Electricity (MJ)	22.58	0.02
Diesel used (for starting turbine) (kg)	5.25	0.22
(b) Sub-total		0.24
Palm oil refining		
Electricity (MJ)	12.20	0.01
Diesel used (for transport RPO) (kg)	49.16	2.06
(c) Sub-total		2.07
Biodiesel production		
MeOH (kg)	180.00	5.45
NaOH (100%) (kg)	10.00	0.18
Electricity (MJ)	297.00	0.30
Diesel used (for transport PME) (kg)	1.23	0.05
(d) Sub-total		5.98
Total (a + b + c + d)		15.75
Output		
Palm methyl ester (PME) (kg)	1000.00	38.07
Glycerol (kg)	180.00	3.42
Palm kernel (kg)	374.38	6.36
Shell (kg)	457.58	8.45
Total		56.30

Figure A - 6: Energy inputs and energy outputs in PME system

From: (Pleanjai, S. & Gheewala, S. H., 2009)

Table A-8: Energy input per 1 kg of oil palm for cultivation, extraction, and biodiesel production processes

	Energy per kg of biodiesel [MJ/ 1000 L of ethanol]	Energy per 1 kg of oil palm [MJ/ kg of cassava]
Cultivation		
Fertilizer	3.782	0.555
Herbicide	0.700	0.103
Diesel	2.890	0.424
Crude Palm Oil Extraction		
Electricity	0.020	0.003
Diesel	0.220	0.032
Biodiesel Production		

Electricity for Refining	0.010	0.001
Diesel for Refining	2.060	0.302
MeOH for Biodiesel	5.450	0.799
NaOH for Biodiesel	0.180	0.026
Electricity for Biodiesel	0.300	0.044
Diesel for Biodiesel	0.050	0.007

A.7. Biogas Energy Calculation

CSV: Cassava

SGC: Sugarcane

OP: Oil palm

EtOH: Ethanol

BD: Biodiesel

The energy constant of biogas is 20.930 MJ/m^3 of biogas.

[C] = [A] x [B] x 20.930 MJ/ m^3 of biogas

Table A-9: Energy of biogas from wastewater per 1 kg of feedstock

Production	[A] Amount of product per kg of feedstock	[B] Volume of biogas (m^3) per product	[C] Energy of biogas per kg of feedstock
Cassava-Ethanol	0.163 L EtOH/kg CSV	0.407 m^3/L EtOH	1.391 MJ/kg CSV
Cassava-PLA	0.132 kg PLA/kg CSV	0.354 m^3/kg PLA	0.974 MJ/ kg CSV
Sugarcane-Ethanol	0.043 L EtOH/kg SGC	0.946 m^3/L EtOH	0.851 MJ/kg SGC
Sugarcane-PLA	0.087 kg PLA/kg SGC	0.354 m^3/kg PLA	0.646 MJ/kg SGC
Biodiesel-Oil palm	0.147 kg BD/kg PO	0.082 m^3/kg BD	0.252 MJ/kg PO

The volume of biogas per product [B] (or parameters that can be used to calculate for it) are obtained from articles.

Volume of Biogas for Cassava-Ethanol

> For each liter of ethanol produced, up to 20 liters of stillage may be generated (Wilkie et al., 2000). The characteristics of the stillage vary considerably according to the fermentation feedstock and to location. In addition to this, wash water used to clean the fermenters, cooling water blow down might contribute as well to stillage variability (Wilkie et al., 2000; Sheehan and Greenfield, 1980; Pant and Adholeya, 2007).

Figure A-7: Part of text about wastewater (stillage) for fermentation

(Kuiper et al. 2007)

Table 8 Characteristics of distillery waste water for cassava feedstock

Characteristics	Cassava	
	(Jackman, 1977; Sheehan and Greenfield, 1980)	(de Menezes, 1989; Wilkie et al., 2000)
Stillage Yield (L/L EtOH)	-	16 - 20
BOD (mg/L)	-	31,400
COD (mg/L)	-	81,100
pH	-	3.5
Organic Matter (g/L)	21,800	-
Total Nitrogen (mg/L)	400	650
Sulphate (SO_4^{2-}) (mg/L)	100	-
Calcium (CaO) (mg/L)	100	-
Phosphorus (P_2O_5) (mg/L)	200	-
Total Phosphorus (mg/L)	-	124
Magnesium (MgO) (mg/L)	100	
Potassium (K_2O) (mg/L)	1,100	-

Figure A-8: Characteristics of distillery wastewater for cassava feedstock

(Kuiper et al. 2007)

Table 10 Summary of anaerobic treatment of stillage from conventional feed-stocks (Modified data from Wilkie et al., 2000)

Temperature/Feedstock	OLR (g COD/L/day)	Treatment Efficiency % removed BOD	Treatment efficiency % removed COD	Methane Yield (L/ g COD)	Methane Productivity (L/L/day)
Mesophilic/molasses	12.25	79.33	71.20	0.26	3.84
Mesophilic/other	12.16	nd	87.25	0.25	2.90
Thermophilic/molasses	23.50	89.20	60.73	0.17	3.37
Mixed/cellulosic	9.48	93.73	83.56	0.30	2.37

Figure A-9: Summary of anaerobic treatment of stillage from conventional feedstocks

(Kuiper et al. 2007)

The parameters obtained for calculating the volume of biogas are 20 L of wastewater per L of ethanol; 81,100 mg (or 81.1 g) of COD per L of wastewater; 83.56 % of COD removal (unitless); 0.3 L of biogas per g of COD. Multiplying all of them together and convert L to m^3 gives 0.407 m^3/L of ethanol.

Volume of Biogas for Cassava-PLA

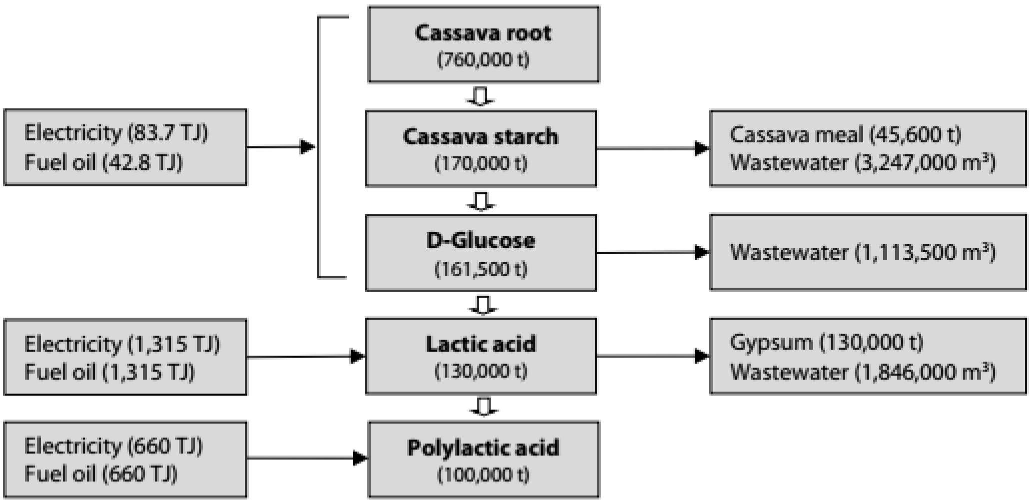

Figure A-10: Scheme of mass and energy flow for PLA production from cassava root

(Chiarakorn et al., 2014)

The calculation of CH_4 emissions from wastewater was adapted from the Project Design Document (PDD) for Clean Development Mechanism (CDM): #2556, #2645 and #2678. The calculation was based on the assumption that wastewater treatment was carried out using an aerated lagoon with a COD removal capacity of 0.019 t/m^3, a B_0 of 0.8, and a MCF of 0.21. It was also assumed that there was no CH_4 emission from the sludge. Wastewater produced 0.19 t and 0.09 t CH_4/t of PLA for the first and second scenario, respectively.

Figure A-11: Part of text about COD removal capacity

(Chiarakorn et al., 2014)

The parameters obtained are 62.07 L of wastewater per kg of PLA (obtained by adding all wastewater together); 0.019 ton of COD removal per m^3. By using the same amount of biogas yield as cassava ethanol production (0.3 L/g COD), the volume of biogas is 0.354 m^3/kg PLA.

Volume of Biogas for Sugarcane-Ethanol

Data for biogas production of sugarcane ethanol is unobtainable from any literature; so for this study, it is proportional to the biogas from cassava ethanol by the products.

Volume of Biogas for Sugarcane-PLA

Data for biogas production of sugarcane PLA is unobtainable from any literature; so for this study, it is proportional to the biogas from cassava PLA by the products.

Volume of Biogas for Biodiesel-Oil palm

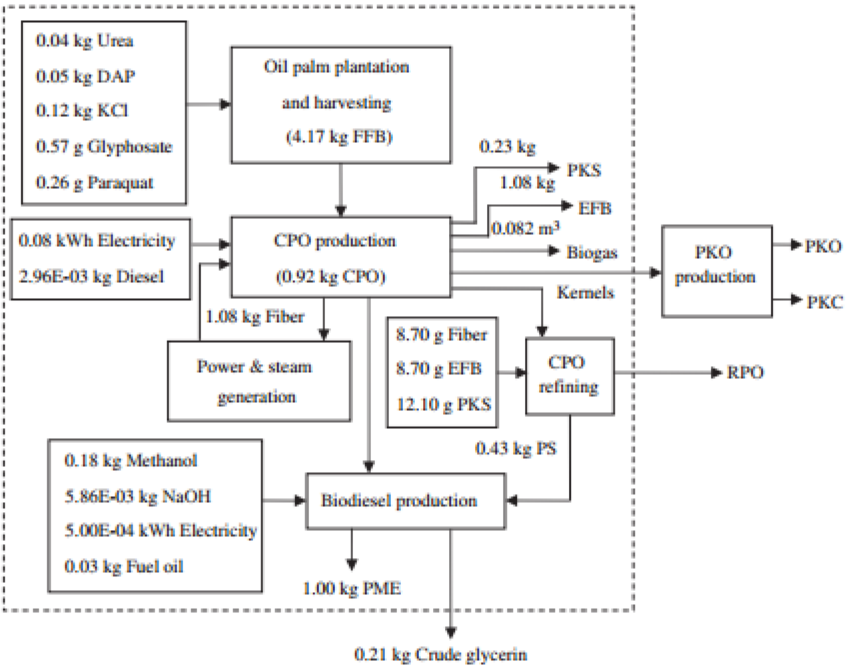

Figure A-12: Scheme of biodiesel production processes with biogas production (Papong et al., 2010)

For oil palm biodiesel production, 0.082 m^3 of biogas is produced per kg of biodiesel.

Appendix B: Profitability Analysis

B.1. Costs in Productions

Table B-1: Cost in THB of input per MJ of energy

Input	Unit	Energy per unit [MJ]	Cost per unit * [THB]	Cost per MJ [THB/MJ]
Cultivation				
Fertilizer	kg	43.174	17.578	0.407
Herbicide	kg	632.586	105.690	0.167
Diesel	L diesel	36.420	18.901	0.519
Labor	man hours	3.446	37.500	10.882
Bio-ethanol Conversion				
Steam - Coal	kg coal	28.880	2.105	0.073
Electricity		-	-	0.388
Peak	kWh	3.600	2.614	0.726
Off-peak	kWh	3.600	1.173	0.326
FT	kWh	3.600	-0.333	-0.092
Starch Production				
Electricity		-	-	0.388
Peak	kWh	3.600	2.614	0.726
Off-peak	kWh	3.600	1.173	0.326
FT	kWh	3.600	-0.333	-0.092
Steam Fuel Oil	L fuel oil	39.770	7.901	0.199
Steam - Coal	kg coal	28.880	2.105	0.073
Sugar (glucose) production				
Electricity		-	-	0.388
Peak	kWh	3.600	2.614	0.726
Off-peak	kWh	3.600	1.173	0.326
FT	kWh	3.600	-0.333	-0.092
Steam Fuel Oil	L fuel oil	39.770	7.901	0.199
PLA Production				
Electricity		-	-	0.388
Peak	kWh	3.600	2.614	0.726
Off-peak	kWh	3.600	1.173	0.326
FT	kWh	3.600	-0.333	-0.092
Steam - Fuel Oil	L fuel oil	39.770	7.901	0.199

Methanol-Sugarcane Milling				
Steam - Coal	kg coal	28.880	2.105	0.073
Gasification				
Electricity		-	-	0.388
Peak	kWh	3.600	2.614	0.726
Off-peak	kWh	3.600	1.173	0.326
FT	kWh	3.600	-0.333	-0.092
Steam - Coal	kg coal	28.880	2.105	0.073
Syngas Conditioning + Methanol synthesis				
Electricity		-	-	0.388
Peak	kWh	3.600	2.614	0.726
Off-peak	kWh	3.600	1.173	0.326
FT	kWh	3.600	-0.333	-0.092
Steam - Coal	kg coal	28.880	2.105	0.073
Crude palm oil extraction				
Electricity		-	-	0.388
Peak	kWh	3.600	2.614	0.726
Off-peak	kWh	3.600	1.173	0.326
FT	kWh	3.600	-0.333	-0.092
Diesel	L diesel	36.420	18.901	0.519
Biodiesel Production				
Electricity		-	-	0.388
Peak	kWh	3.600	2.614	0.726
Off-peak	kWh	3.600	1.173	0.326
FT	kWh	3.600	-0.333	-0.092
Diesel	L diesel	36.420	18.901	0.519
NaOH	kg	19.070	32.650	1.712
Methanol	kg	38.000	35.370	0.931

*Cost per unit = Market prices

B.2. Revenue from Products

Table B-2: Revenue in THB per kg of product

	Unit	Price per unit [THB]
PLA	kg	95
Ethanol	L	26.33
Biodiesel	L	23
Glycerin	kg	44.7

B.3. References for Energy Conversion

ค่าการแปลงหน่วย CONVERSION FACTORS
ปริมาณพลังงานของเชื้อเพลิง (ค่าความร้อนสุทธิ)
ENERGY CONTENT OF FUEL (NET CALORIFIC VALUE)

ประเภท (หน่วย)	กิโลแคลอรี/หน่วย kcal/UNIT	ตันเทียบเท่าน้ำมันดิบ/ล้านหน่วย toe/10^6UNIT	เมกะจูล/หน่วย MJ/UNIT	พันบีทียู/หน่วย 10^3Btu/UNIT	TYPE (UNIT)
พลังงานเชิงพาณิชย์					COMMERCIAL ENERGY
1. น้ำมันดิบ (ลิตร)	8680	860.00	36.33	34.44	1. CRUDE OIL (litre)
2. คอนเดนเสท (ลิตร)	7900	782.72	33.07	31.35	2. CONDENSATE (litre)
3. ก๊าซธรรมชาติ					3. NATURAL GAS
3.1 ชื้น (ลูกบาศก์ฟุต)	248	24.57	1.04	0.98	3.1 WET (scf.)
3.2 แห้ง (ลูกบาศก์ฟุต)	244	24.18	1.02	0.97	3.2 DRY (scf.)
4. ผลิตภัณฑ์ปิโตรเลียม					4. PETROLEUM PRODUCTS
4.1 ก๊าซปิโตรเลียมเหลว (ลิตร)	6360	630.14	26.62	25.24	4.1 LPG (litre)
4.2 น้ำมันเบนซิน (ลิตร)	7520	745.07	31.48	29.84	4.2 GASOLINE (litre)
4.3 น้ำมันเครื่องบิน (ลิตร)	8250	817.40	34.53	32.74	4.3 JET FUEL (litre)
4.5 น้ำมันดีเซล (ลิตร)	8700	861.98	36.42	34.52	4.5 DIESEL (litre)
4.6 น้ำมันเตา (ลิตร) (FUEL OIL)	9500	941.24	39.77	37.70	4.6 FUEL OIL (litre)
4.7 ยางมะตอย (ลิตร)	9840	974.93	41.19	39.05	4.7 BITUMEN (litre)
พลังงานใหม่และหมุนเวียน					NEW & RENEWABLE ENERGY
1. ฟืน (กก.)	3820	378.48	15.99	15.16	1. FUEL WOOD (kg.)
2. ถ่าน (กก.)	6900	683.64	28.88	27.38	2. CHARCOAL (kg.)
3. แกลบ (กก.)	3440	340.83	14.40	13.65	3. PADDY HUSK (kg.)
4. กากอ้อย (กก.)	1800	178.34	7.53	7.14	4. BAGASSE (kg.)
5. ขยะ (กก.)	1160	114.93	4.86	4.60	5. GARBAGE (kg.)
6. ขี้เลื่อย (กก.)	2600	257.60	10.88	10.32	6. SAW DUST (kg.)
7. วัสดุเหลือใช้ทางการเกษตร (กก.)	3030	300.21	12.68	12.02	7. AGRICULTURAL WASTE (kg.)
8. ก๊าซชีวภาพ (ลูกบาศก์เมตร)	5000	495.39	20.93	19.84	8. BIOGAS (m^3)

Figure B-1: Energy content of fuel (net calorific value)

(EPPO, 2010)

Table 2
Factors for energy calculations along the life cycle of palm oil biodiesel production.

Subject	Energy factor (MJ/kg)	Source
Diammonium phosphate	19.80	Ecoinvent (2006)
Urea	62.20	Ecoinvent (2006)
KCl	5.93	Ecoinvent (2006)
Boron	30.00	Ecoinvent (2006)
Paraquat	458.4	Pimentel (1992)
Glyphosate	452.5	Pimentel (1992)
Carbofuran	405	Ecoinvent (2006)
Bipyridylium	353	Ecoinvent (2006)
Methanol	38.00	Tobin (2005)
NaOH	19.70	Tobin (2005)
Diesel	43.10	TEI (2001)
Fuel oil	52.50	IPCC (2006)
Electricity (MJ/kWh)	9.5	TEI (2003)
Palm fiber	11.40	Biomass Clearinghouse (2008)
Crude glycerin	25.6	JGSEE laboratory (2007)

Figure B-2: Factors for energy calculations along the life cycle of palm oil biodiesel production (Papong et al., 2010)

TABLE 1. Direct Material and Energy Inputs in Cassava Ethanol System

Item	Consumption per 100,000 L ethanol	
	Unit	Amount
1) Cassava farming/processing		
Fertilizer		
Nitrogen	kg	1,328
Phosphorous as P_2O_5	kg	1,249
Potassium as K_2O	kg	1,569
Herbicide		
Paraquat (Gramozone)	kg	46
Glyphosate	kg	58
Diesel used for farm machinery	L	1,241
Diesel used for chip processing	L	1,126
Labour used for farming	man-hours	10,940

Figure B-3: Direct material and energy inputs in cassava farming process (Nguyen et al., 2008)

TABLE 2. NEV and NRnEV of Cassava-Based Fuel Ethanol System

Items	Energy inputs (MJ/L ethanol)	Fossil energy inputs (MJ/L ethanol)
I) Cassava farming	*4.24[a] (3.09)[b] (2.82)[c]*	*3.90*
NPK fertilizers	1.22	1.16
N	0.96	0.93
P	0.13	0.11
K	0.13	0.12
Herbicide	0.55	0.52
Diesel fuel (used for farming operation)	1.05	1.05
Labour	1.42[d] (0.27)[b] (0)[c]	1.17[d]

Figure B-4: Net energy value and Net renewable energy value of cassava-based fuel ethanol system

(Nguyen et al., 2008)

B.4. References for Costs and Prices

PRICE STRUCTURE OF PETROLEUM PRODUCT IN BANGKOK

30-Dec-15

UNIT:BAHT/LITRE	EX-REFIN. (AVG)	TAX B./LITRE	M. TAX B./LITRE	OIL FUND	CONSV. FUND	WHOLESALE PRICE(WS)	VAT	WS&VAT
ULG	13.4857	5.6000	0.5600	6.1500	0.2500	26.0457	1.8232	27.8689
GASOHOL95 E10	14.8424	5.0400	0.5040	0.0500	0.2500	20.6864	1.4480	22.1344
GASOHOL91	14.5944	5.0400	0.5040	0.0050	0.2500	20.3934	1.4275	21.8210
GASOHOL95 E20	16.0987	4.4800	0.4480	-2.4000	0.2500	18.8767	1.3214	20.1981
GASOHOL95 E85	23.2729	0.8400	0.0840	-9.2300	0.2500	15.2169	1.0652	16.2820
H-DIESEL	11.9895	4.9500	0.4950	-0.0200	0.2500	17.6645	1.2365	18.9010
FO 600 (1) 2%S	6.7419	0.4660	0.0466	0.0600	0.0700	7.3844	0.5169	7.9013
FO 1500 (2) 2%S	6.5075	0.4426	0.0443	0.0600	0.0700	7.1244	0.4987	7.6231
LPG (BAHT/KILO)	16.5051	2.1700	0.2170	-1.3170	0.0000	17.5751	1.2303	18.8054

Figure B-5: Price structure of petroleum product in Bangkok

(EPPO, 2015)

4.2 อัตราตามช่วงเวลาของการใช้ (Time of Use Rate : TOU)

	ค่าความต้องการพลังไฟฟ้า (บาท/กิโลวัตต์)	ค่าพลังงานไฟฟ้า (บาท/หน่วย)	
	Peak	Peak	Off Peak
4.2.1 แรงดันตั้งแต่ 69 กิโลโวลท์ขึ้นไป	74.14	2.6136	1.1726
4.2.2 แรงดัน 22-33 กิโลโวลท์	132.93	2.6950	1.1914
4.2.3 แรงดันต่ำกว่า 22 กิโลโวลท์	210.00	2.8408	1.2246
Peak : วันจันทร์ -ศุกร์ 09.00 น. - 22.00 น.			
Off Peak : วันจันทร์ -ศุกร์ 22.00 น. - 09.00 น. และวันเสาร์ วันอาทิตย์ วันหยุดราชการตามปกติ (ไม่รวมวันหยุดชดเชย) ทั้งวัน			

Figure B - 6: Electricity rate of Thailand

(Provincial Electricity Authority, 2015)

ขายส่ง กรุงเทพฯ	16,567	16,867	16,700	16,700	16,700	16,400	16,333	16,333	16,333	16,333	16,467	16,467	16,667
ขายปลีกท้องถิ่น	17,818	17,936	17,455	17,542	17,655	17,578	17,528	17,599	17,549	17,485	17,466	17,438	17,471

Figure B-7: 12-month price of fertilizer in Thailand in 2015

(Office of Agricultural Economics, 2015b)

First row: Retail price in Bangkok;

Second Row: Wholesales price

Price of Fertilizer: 17.578 THB/kg after average

สารกำจัดวัชพืช (Herbicide)	
ปริมาณ	มูลค่า
80,278	8,845
112,177	11,480
106,860	11,294

Figure B-8: Amount in L and value in THB of herbicide in Thailand in 2015

(Office of Agricultural Economics, 2016a)

First column: Amount; Second column: Value

ประกาศการไฟฟ้าฝ่ายผลิตแห่งประเทศไทย
เรื่อง ราคาถ่านหินอ้างอิงสำหรับคำนวณอัตราค่ารับซื้อไฟฟ้าจากผู้ผลิตไฟฟ้ารายเล็ก
ประเภทสัญญา Firm

การไฟฟ้าฝ่ายผลิตแห่งประเทศไทย (กฟผ.) ขอแจ้งราคาถ่านหินอ้างอิงสำหรับการคิดอัตรารับซื้อไฟฟ้าจากผู้ผลิตไฟฟ้ารายเล็ก (SPP) ประเภทสัญญา Firm ที่ใช้ถ่านหินเป็นเชื้อเพลิงประจำปี ๒๕๕๗ ซึ่งกำหนดให้ใช้ค่าเฉลี่ยของราคาถ่านหินอ้างอิง Barlow Jonker : Japanese Power Utilities (BJ JPU) และ Bureau of Resource and Energy Economics (BREE) ซึ่งปัจจุบันรัฐบาลออสเตรเลียมอบหมายให้ Department of Industry and Science ทำหน้าที่คาดการณ์ตัวเลขต่างๆ แทน ดังนี้

BJ JPU Reference	=	๘๑.๐๓	เหรียญสหรัฐ/ตัน
BREE Reference	=	๘๒.๐๐	เหรียญสหรัฐ/ตัน
ราคาถ่านหินอ้างอิง	=	(๘๑.๐๓+๘๒.๐๐) / ๒	เหรียญสหรัฐ/ตัน
	=	๘๑.๕๑๕	เหรียญสหรัฐ/ตัน

โดยให้ใช้เฉพาะเดือนมกราคม ๒๕๕๘ ถึง เดือนมีนาคม ๒๕๕๘

Figure B-9: Announcement from EGAT on referential price of coal for calculating electricity buying rate for small producers

(EGAT, 2015a)

The price of coal in the announcement 81.515 USD/tonne (or 0.081515 USD/kg); using currency exchange rate of 25.82 THB/USD, the coal price is 2.105 THB/kg.

Table B-2: Sources of products' prices

Products	Source	Visited
PLA	(Plastics Institute of Thailand, 2013)	2015/11/16
Ethanol	(Thai Ethanol, 2015)	2015/11/16
Biodiesel	(Kung Krabaen Bay Royal Development Study Center, 2016)	2016/1/13
Glycerin	(Oil Palm Research Institute of Surathani, 2015)	2016/1/17

Appendix C: GHG Emission Analysis

C.1. GHG Emission Data

Table C-1: GHG emission from processes according to feedstock type

Processes	Cassava for Ethanol [kg CO_2/kg]	Cassava for PLA [kg CO_2/kg]	Sugarcane [kg CO_2/kg]	Oil palm [kg CO_2/kg]
Cultivation				
+ Fertilizers & Herbicides	0.039	0.039	0.003	0.049
+ Others	0.006	0.006	0.006	0.000
Ethanol Conversion				
+ Coal for steam	0.203	-	0.049	-
+ Others	0.031	-	-	-
PLA Production				
+ Electricity	-	0.380	0.252	-
+ Other	-	0.205	0.136	-
Sugarcane Milling	-	-	0.0002	-
Gasification	-	-	0.000	-
Syngas & Methanol Synthesis				
+ Electricity	-	-	0.001	-
+ Others	-	-	0.261	-
Crude Palm Oil Extraction	-	-	-	0.003
Biodiesel Production	-	-	-	0.014
Wastewater Treatment	0.180	0.700	Ethanol 0.080	0.263
			PLA 0.464	
Total	**0.455**	**1.326**	**1.252**	**0.329**

C.2. Reference for GHG Emission Analysis

Table 2
Life-cycle GHG emission of 1 L anhydrous ethanol production.

Items contribution	Ethanol (without allocation)		Ethanol (with 25% allocated to co-products)	
	g CO_2 eq. per L	%	g CO_2 eq. per L	%
Coal combustion	1243	43.4	932	66.5
CH_4 from ethanol wastewater treatment pond	1104	38.6	83	5.9
Electricity	186	6.5	138	9.8
Fertilizers	182	6.4	137	9.8
Transport	62	2.2	47	3.4
N-Fertilizer emission	52	1.8	39	2.8
Cassava chip production	17	0.6	13	0.9
Herbicides	7	0.2	5	0.4
Diesel in cultivation	6	0.2	5	0.4
Chemical in ethanol conversion	4	0.1	3	0.2
Total	2863	100	1402	100

Figure C-1: Life-cycle GHG emission 1 L anhydrous ethanol production

(Papong, S. & Malakul, P., 2010)

Table 14. Environmental impacts of PLA production

Environmental impacts	Scenario 1 Cassava root to PLA (kg/kg PLA)
GHG emission	
a) CH_4 from wastewater	0.19
b) CO_2 from electricity	2.89
c) CO_2 from fuel oil	1.56

Figure C-2: Environmental impacts of PLA production

(Chiarakorn et al., 2014)

Table 5
Molasses-based ethanol life cycle GHG emissions, scenario 1 (base case)

Activity	g CO_2 eq[a]/L ethanol	
	2005: $AR_{Sug-Mo} = 15:1$	Base year 2006: $AR_{Sug-Mo} = 8.6:1$
Sugar cane farming	*260.2*	454.6
Fertilizers and herbicides	66.8	116.7
Diesel fuel (farming operation)	21.3	37.3
Labour	38.2	66.7
Diesel fuel (transportation)	39.0	68.2
Soil N_2O	69.4	121.2
Cane trash burning	25.5	44.5
Sugar milling	*5.8*	*10.2*
Bagasse, rice husk and wood waste use as fuels	3.7	6.6
Diesel fuel (transportation)	2.1	3.6
Electricity sold to the grid	*−71.8*	*−125.4*
Ethanol conversion	*3119.4*	*3119.4*
Coal use as fuel	*1150.1*	*1150.1*
Rice husk use as fuel	2.1	2.1
Biogas use as fuel	0.3	0.3
CH_4 emissions from anaerobic pond	1870	1870
Diesel fuel (transportation)	96.9	96.9
Total emissions	*3313.5*	*3458.7*
Gross avoided emissions	*−2638.9*	*−2638.9*
Net increase in emissions	*674.6*	*819.8*
% Increase	*25.6*	*31.3*

Figure C-3: Molasses-based ethanol life cycle GHG emissions

(Nguyen et al., 2007)

Table 4
Outputs data of methanol production referred to 1 kg of methanol [11,41–46,48,49].

	Value	Units
Sugarcane cultivation, harvesting and transportation		
Truck emissions from diesel combustion engines		
CO_2	6.58	g
NO_x	5.4×10^{-2}	g
CO	1.24×10^{-2}	g
Fine particles	1.3×10^{-3}	g
Organic carbon	2.5×10^{-4}	g
Nitrate	2.8×10^{-3}	mg
Silicon	8.4×10^{-3}	mg
Ammonium	9.2×10^{-3}	mg
Sulfate	1.3×10^{-2}	mg
Alkanes	1.1×10^{-4}	g
Olefins	1.2×10^{-4}	mg
Aromatics	9.8×10^{-2}	mg
Formaldehyde	1.5×10^{-4}	g
Acetaldehyde	2.9×10^{-4}	g
Propanal	9.8×10^{-2}	g
Acetone	1.5×10^{-4}	g
Aromatic acids	1.4×10^{-2}	mg
Tractor emissions from diesel consumption		
CO_2	30	g
HC	9.9×10^{-2}	g
CO	2.7×10^{-1}	g
NO_x	6.8×10^{-1}	g
SO_x	4.8×10^{-2}	g
PM10	7.2×10^{-2}	g
Emissions from soil under sugarcane cultivation		
N_2O from denitrification[a]	1.37	g
N_2 from denitrification	2.28	g
NH_3 from volatization	3.6×10^{-1}	g
Emissions to air from pre-harvest sugarcane burning		
N_2O	4.0×10^{-2}	g
NO_x	2.51	g
CH_4	6.8×10^{-1}	g
SOx	3.1×10^{-1}	g
NMVOC	1.54	g
Emissions to water		
Phosphorous	2.8×10^{-2}	g
Nitrate	1.48×10^{-1}	g

Figure C - 4: Outputs data of methanol production referred to 1 kg of methanol (Renó et al., 2011)

Table 4
Greenhouse gas emission balance.

	This study
Output (kg CO_2e/ha year)	
1. Agricultural phase	
1.1. Fertilizer	
Nitrogen (N)	903.76
Phosphate (P_2O_5)	161.83
Potassium (K_2O)	74.69
Magnesium (MgO)	12.14
Boron (B)	9.15
Total	1165.08[a]
1.2. Pesticides	
Herbicide	38.75
Insecticide	16.44
Rondeticide	–
Total	55.19
Total	*1220.27*
2. Fuel	
Harvesting (field)	Manual
Transport (as far as field)	54.91
Transport (as far as mill)	219.63
Total transport (mill-field-mill)	274.54
Personnel transport	–
Total	*274.54*
3. Industrial phase	
3.1. Oil extraction	
Electricity from power plant	–
Electricity from grid	*0.01*
Steam from power plant	–
Diesel for start-up	65.07
Total	65.08
3.2. Transesterification	
Methanol	*311.50*
Catalyst (NaOH)	*28.53*
Electricity from grid	*1.30*
Steam	–
Total	341.34
Total	406.42
Total GHG emission	1901.23
Total GHG emission allocated	1436.51

Figure C-5: Greenhouse gas emission balance for biodiesel production (de Souza et al., 2010)

3.2. *GHC emissions*

3.2.1. Baseline GHG emissions from aerobic treatment of POME in open ponds

The total GHG emissions from the aerobic treatment of POME in open ponds amount to 7583 kg $CO_{2\text{-eq}}$ ha^{-1} yr^{-1} as shown in Table 5 below. The largest share of the GHG emissions comes from the POME stored in the open ponds (91.7%), followed by the emissions from the POME discharged (8.2%) and the emissions from the generation of electricity for pumping and stirring the POME (0.1%). The GHG emission is shown in Table 5 below.

Related to the unit of biodiesel, the total GHG emissions from the treatment of POME in open ponds are 1634 g $CO_{2\text{-eq}}$ kg^{-1} biodiesel, based on a biodiesel yield of 4640 kg ha^{-1} yr^{-1}. This is equivalent to 39.63 g $CO_{2\text{-eq}}$ MJ^{-1} biodiesel, based on an energy

Figure C-6: GHG emission of biodiesel production (open pond)

(Harsono et al., 2014)

Appendix D: Regional Analysis

D.1. Reference for Regional Analysis

มันสำปะหลังโรงงาน : เนื้อที่เพาะปลูก เนื้อที่เก็บเกี่ยว ผลผลิต และผลผลิตต่อไร่ รายอำเภอ ปีเพาะปลูก 2556

จังหวัด/อำเภอ	เนื้อที่เพาะปลูก (ไร่)	เนื้อที่เก็บเกี่ยว (ไร่)	ผลผลิต (ตัน)	ผลผลิตต่อไร่(กก.)	
				เนื้อที่เพาะปลูก	เนื้อที่เก็บเกี่ยว
รวมทั้งประเทศ	**9,037,273**	**8,656,942**	**30,227,542**	**3,345**	**3,492**
ภาคเหนือ	1,947,213	1,876,311	6,714,546	3,448	3,579
ตะวันออกเฉียงเหนือ	4,714,713	4,493,264	15,387,256	3,264	3,425
ภาคกลาง	2,375,347	2,287,367	8,125,740	3,421	3,552

Figure D-1: Cassava, planted area, harvested area, products, and production yield per rai, 2013

(Office of Agricultural Economics, 2014)

* First row: Northern region; Second row: North-eastern region; Third row: Central region

มันสำปะหลังโรงงาน : เนื้อที่เพาะปลูก เนื้อที่เก็บเกี่ยว ผลผลิต ผลผลิตต่อไร่ รายอำเภอ ปี 2557

จังหวัด	เนื้อที่ปลูก (ไร่)	เนื้อที่เก็บ (ไร่)	ผลผลิต (ตัน)	ผลผลิตต่อไร่(กก.)	
				เพาะปลูก	เก็บเกี่ยว
รวมทั้งประเทศ	**8,975,865**	**8,431,223**	**30,022,052**	**3,345**	**3,561**
ภาคเหนือ	1,961,992	1,843,080	6,700,328	3,415	3,635
ตะวันออกเฉียงเหนือ	4,604,972	4,359,677	15,465,916	3,359	3,547
ภาคกลาง	2,408,901	2,228,466	7,855,808	3,261	3,525

Figure D-2: Cassava, planted area, harvested area, products, and production yield per rai, 2014

(Office of Agricultural Economics, 2015c)

* First row: Northern region; Second row: North-eastern region; Third row: Central region

มันสำปะหลังโรงงาน : เนื้อที่ปลูก เนื้อที่เก็บเกี่ยว ผลผลิต และผลผลิตต่อไร่ ปี 2558-2560 (ปี 2559-2560 พยากรณ์ไตรมาสที่ 2 เดือนมิถุนายน 2559)

จังหวัด	เนื้อที่เพาะปลูก (ไร่)			เนื้อที่เก็บเกี่ยว (ไร่)			ผลผลิต (ตัน)			ผลผลิตต่อเนื้อที่เก็บเกี่ยว (กก.		
	2558	2559	2560	2558	2559	2560	2558	2559	2560	2558	2559	2560
รวมทั้งประเทศ	9,319,718	-	-	8,961,344	8,899,140	9,038,605	32,357,741	30,909,871	32,224,145	3,611	3,473	3,565
ภาคเหนือ	2,052,879	-	-	1,944,387	1,945,513	1,971,190	7,177,595	7,037,922	7,344,084	3,691	3,618	3,726
ตะวันออกเฉียงเหนือ	4,891,792	-	-	4,685,481	4,702,040	4,762,045	16,863,447	16,140,428	16,769,333	3,599	3,433	3,521
ภาคกลาง	2,375,047	-	-	2,331,476	2,251,587	2,305,370	8,316,699	7,731,521	8,110,728	3,567	3,434	3,518

Figure D-3: Cassava, planted area, harvested area, products, and production yield per rai, 2015

(Office of Agricultural Economics, 2016).

* First row: Northern region; Second row: North-eastern region; Third row: Central region

ตารางที่ 15 อ้อยโรงงาน : เนื้อที่เก็บเกี่ยว ผลผลิต และผลผลิตต่อไร่ เป็นรายภาค และรายจังหวัด ปี 2557-2559

Table 15 Sugarcane : Harvested area, production and yield per rai by region and province, 2014-2016

ภาค/จังหวัด	เนื้อที่เก็บเกี่ยว (ไร่) Harvested area (Rais)			ผลผลิต (ตัน) Production (Tons)			ผลผลิตต่อไร่ (กก.) Yield per rai (Kgs.)			Region/ Province
	2557 2014	2558 2015	2559 2016	2557 2014	2558 2015	2559 2016	2557 2014	2558 2015	2559 2016	
รวมทั้งประเทศ	8,456,409	9,591,448	9,961,164	103,697,005	106,333,451	109,857,017	12,263	11,086	11,029	Whole Kingdom
เหนือ	2,192,888	2,552,982	2,628,836	29,338,263	28,228,798	28,999,589	13,379	11,057	11,031	Northern
ตะวันออกเฉียงเหนือ	3,780,963	4,242,197	4,401,990	43,613,650	47,380,528	48,593,886	11,535	11,169	11,039	Northeastern
กลาง	2,482,558	2,796,269	2,930,338	30,745,092	30,724,125	32,263,542	12,384	10,988	11,010	Central

Figure D-4: Sugarcane: Harvested area, production and yield per rai by region and province, 2014-2016

(Office of Agricultural Economics, 2016)

* First row: Northern region; Second row: North-eastern region; Third row: Central region

ตารางที่ 18 ปาล์มน้ำมัน : เนื้อที่ ผลผลิต และผลผลิตต่อไร่ เป็นรายภาค และรายจังหวัด ปี 2556-2558

Table 18 Oil palm : Area, production and yield per rai by region and province, 2013-2015

ภาค/จังหวัด	เนื้อที่ยืนต้น (ไร่) Planted area (Rais)			เนื้อที่ให้ผล (ไร่) Harvested area (Rais)			ผลผลิต (ตัน) Production (Tons)			ผลผลิตต่อไร่ (กก.) Yield per rai (Kgs.)			Region/Province
	2556 2013	2557 (p) 2014	2558 (f) 2015	2556 2013	2557 (p) 2014	2558 (f) 2015	2556 2013	2557 (p) 2014	2558 (f) 2015	2556 2013	2557 (p) 2014	2558 (f) 2015	
รวมทั้งประเทศ	4,489,119	4,621,253	4,696,559	3,773,123	4,023,819	4,276,240	12,434,520	12,472,505	11,015,872	3,296	3,100	2,576	Whole Kingdom
เหนือ	54,626	67,952	67,497	12,556	29,701	41,761	13,941	31,405	33,864	1,110	1,057	811	Northern
ตะวันออกเฉียงเหนือ	120,183	137,940	135,266	45,462	64,610	94,556	66,775	90,210	96,141	1,469	1,396	1,017	Northeastern
กลาง	443,285	468,530	482,293	335,108	381,201	441,762	914,708	1,004,399	992,031	2,730	2,635	2,246	Central
ใต้	3,871,025	3,946,831	4,011,503	3,379,997	3,548,308	3,698,161	11,439,096	11,346,491	9,893,836	3,384	3,198	2,675	Southern

Figure D - 5: Oil palm: Area, production and yield per rai by region an province, 2013-2015

(Office of Agricultural Economics, 2015c).

* First row: Northern region; Second row: North-eastern region; Third row: Central region; Fourth row: Southern region

Table D-1: 3-year average of production yield of cassava, sugarcane, and oil palm in North, Northeast, and Central regions of Thailand

Yield	Year 1	Year 2	Year 3	3 Yr Avg.
Cassava				
North	3691	3618	3726	3678.3
Northeast	3599	3433	3521	3517.7
Central	3567	3434	3518	3506.3
Sugarcane				
North	13379	11057	11031	11822.3
Northeast	11535	11169	11039	11247.7
Central	12384	10988	11010	11460.7
Oil Palm				
North	1110	1057	811	992.7
Northeast	1469	1396	1017	1294.0
Central	2730	2635	2246	2537.0

Table D-2: Production yield in ratio

	Cassava	Sugarcane	Oil Palm
North	0.223	0.717	0.060
Northeast	0.219	0.700	0.081
Central	0.200	0.655	0.145