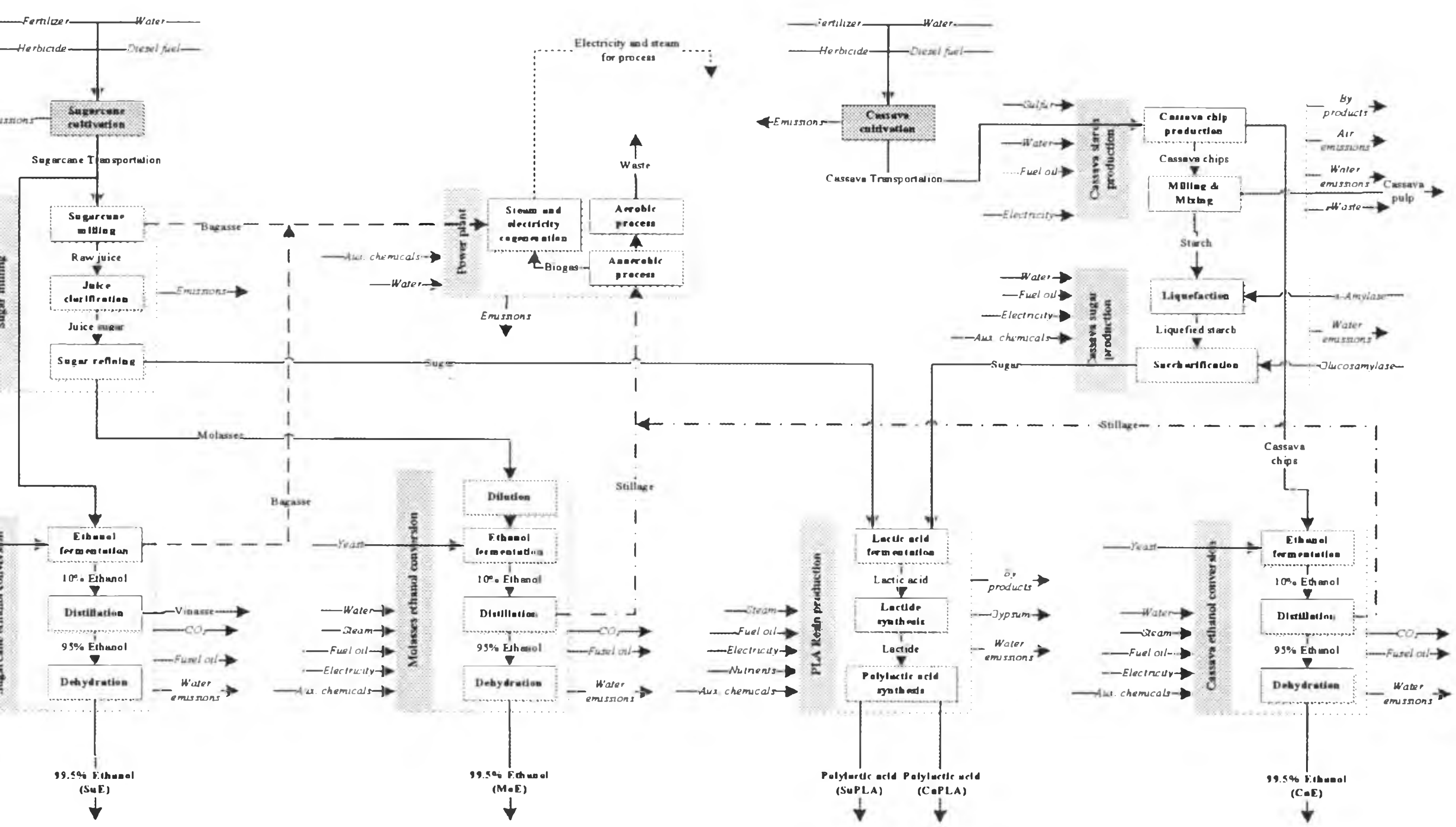
CHAPTER IV
RESULTS AND DISCUSSION

4.1 Biorefinery Model

According to biorefinery concept, a biorefinery model was created with ethanol production capacity 160 ton/day and PLA production capacity 300 ton/day includes 10 major processes which are sugarcane cultivation, sugarcane milling, cassava cultivation, cassava starch production, cassava sugar production, electrical energy cogeneration, PLA resin production, sugarcane ethanol conversion, molasses ethanol conversion, and cassava ethanol conversion. The biorefinery model is shown in Figure 4.1.

Based on the biorefinery model developed in this study (Figure 4.1), sugarcane and cassava were co-utilized as feedstocks. Operation of a sugarcane plantation and harvesting were included in sugarcane cultivation process. After harvest, this sugarcane was transported to a sugar mill to extract sugarcane juice. The juice was then converted into sugar and molasses. These two products were used as raw materials for production of sugarcane-based PLA (SuPLA) and molasses-based ethanol (MoE). Moreover, some sugarcane juice could be used to produce sugarcane-based ethanol (SuE) directly by the sugarcane ethanol conversion process. After cultivate and transport of cassava, this cassava was divided into two parts. The first part was transformed to sugar via cassava starch and sugar production processes. This sugar was further used as the raw material for cassava-based PLA resin (CaPLA) by the PLA resin production process. The other part was chipped and used as a feedstock for cassava-based ethanol (CaE) production with dried distiller grains with solubles (DDGS) production line. Apart from the main feedstocks, bagasse produced from the sugar milling and sugarcane ethanol conversion process were used as fuel to generate electricity and steam for the biorefinery by using a highly efficient electrical and energy cogeneration process.



Biorefinery feedstocks: Sugarcane, Cassava
Biorefinery products: Bioethanol, Polylactic acid (PLA)
Biorefinery performance: Ethanol production capacity: 112-160 t/d
PLA production capacity: 210-300 t/d

iorefinery model.

All processes in the biorefinery model were divided into four stages include feedstock production, feedstock transportation, feedstock processing, and ethanol conversion / PLA resin production, as summarized in Table 4.1.

Table 4.1 Four major stages of the processes in the biorefinery model

	Feedstock production	**Feedstock transportation**	**Feedstock processing**	**Ethanol conversion / PLA resin production**
SuE	Sugarcane cultivation	Sugarcane transportation	-	Sugarcane ethanol conversion
MoE	Sugarcane cultivation	Sugarcane transportation	Sugar milling	Molasses ethanol conversion
CaE	Cassava cultivation	Cassava transportation	Cassava chips production	Cassava ethanol conversion
SuPLA	Sugarcane cultivation	Sugarcane transportation	Sugar milling	PLA resin production
CaPLA	Cassava cultivation	Cassava transportation	Cassava starch and sugar production	PLA resin production

Based on the stages and processes listed in Table 4.1, the life cycle inventory (LCI) was performed by collecting secondary data from existing bioethanol and biopolymer plants in Thailand and related studies. Details of each process are described in CHAPTER II (section 2.3.1, 2.3.2, 2.3.3, and 2.4.1) and their life cycle inventory is shown in appendix A.

4.2 Life Cycle Inventory

4.2.1 Sugarcane based Ethanol Production

Sugarcane based ethanol production was modeled by using national LCI database in sugarcane cultivation section. Relevant information on sugarcane plantation was extracted from Nguyen and Gheewala (2008). For both sugarcane and cassava roots transportation phases, we assume the location of biorefinery plant in Nakhon Ratchasima province. We also assume that biorefinery plant can receive biomass feedstocks (sugarcane and cassava roots) in 100 km. around the plant by using 10-wheel truck at full load 16 tons. The inventory data of feedstocks transportation phase was taken from MTEC. After sugarcane was transported to biorefinery, the sugarcane was forwarded to sugarcane ethanol conversion process. As a sugarcane based ethanol plant is already exist in Thailand, the information for sugarcane ethanol conversion from the plant might have high uncertainty. LCI data of sugarcane ethanol conversion section from Brazil (Ometto et al., 2010) was used in order to complete the model. The products of this process are hydrated alcohol, bagasse, and vinasse. However, the hydrated ethanol was not pure enough (96% ethanol). Thus, we must add the ethanol dehydration process into the model in order to reach dehydrated ethanol (99.5% ethanol). This process was completed by simulating with commercial software named ProII. Conditions of the molecular sieve adsorption unit were 93 degree Celsius and 1.77 atm. After hydrated ethanol was produced from sugarcane ethanol conversion, the hydrated ethanol was fed to the molecular sieve dehydration unit in order to purify the hydrated ethanol. The adsorption column removes 95% of the water and a small portion of ethanol. The 99.5% pure ethanol vapor was cooled by heat exchange against regenerate condensate and finally condensed and pumped to storage.

According to biorefinery concept, bagasse – residue from sugarcane processing – was used as fuel to generate electricity and steam by using cogeneration system. The system is used in industrial plants in Thailand. In order to improve the efficiency, the low pressure steam is replaced by higher pressure steam at 68 Bar_a which is used in Europe countries. The high pressure steam can generate more electricity than low pressure steam about 70% (Tossanaitada and Tia, 2008). The data of cogeneration system were collected by simulation with commercial software named ProII. The following assumptions were created for this simulation: inlet steam pressure 68 Bar_a 507 degree Celsius, outlet steam pressure at 10 Bar_a 303 degree Celsius, steam rate 60 ton/hour, 70% back-pressure steam turbine efficiency, 97%

generator efficiency, lower heating value of bagasse at 9.25 MJ/kg, 80% of bagasse heating value could be used in this process.

4.2.2 Molasses based Ethanol Production

Molasses based ethanol production process was modeled by using data from the national LCI database. Start with sugarcane cultivation and transportation phases (the data sources used are same as above). After sugarcane transported to sugarcane milling which is a process to produce sugar for sugarcane based PLA resin production process and to produce molasses for molasses ethanol conversion process. Residue of sugarcane milling process (bagasse) can be used as fuel to generate electricity and steam by using cogeneration system. The sugarcane milling information was retrieved from MTEC. After molasses from sugar milling was produced, it was transported to molasses ethanol conversion process. The products of this process are dehydrated ethanol (99.5% ethanol), and biogas. According to Department of Industrial Promotion, Ministry of Industry (2009), biogas 1 m^3 can produce electricity 1.2 kWh, CO_2 emission from biogas combustion, being of biogenic origin, are considered net zero as also bagasse combustion.

4.2.3 Cassava based Ethanol Production

Cassava based ethanol production process was start with cassava cultivation. The inventory average of cassava cultivation was taken from Khongsiri (2009). Next, cassava roots were transported to cassava chips production process. Cassava chips production data was extracted from Silalertruksa and Gheewala (2011). Then, the cassava chips were used to produce ethanol by cassava ethanol conversion process. Dried distiller grain with soluble (DDGS) and biogas are by-products of this process. Biogas could be used as fuel for electricity generation. Life cycle inventory of cassava ethanol conversion was extracted from KAPI (2007).

4.2.4 PLA Resin Production

After cassava roots were cultivated, they are transported to cassava starch production to produce starch and biogas for generate electricity. The inventory data of cassava starch with biogas production line was extracted from MTEC. Then, the starch forwarded to cassava sugar production process to produce glucose syrup. The inventory data for the sugar production were extracted from literatures (Chiarakorn *et al.*, 2011; Renouf *et al.*, 2008). The sugar from cassava and sugar from sugarcane, as described in section 4.2.2, were sent to PLA resin production stage. In this stage, the inventory data from Wim J. Groot & Tobias Borén (2010) were used as the secondary data for the production of PLA resin of PURAC (Thailand). Based on PURAC's inventory data, the inventory data of PLA resin production were constructed by carefully taken out the sugarcane production data from Purac's inventory data based on data from Nguyen (2007). From this data sugar from sugarcane and sugar from cassava could be used in the same process and slightly different condition. However, it should be separate process into two parts for SuPLA and CaPLA because it might be risk for reaction of each other.

After LCI was completed, five scenarios were created. They were divided into two groups; Group 1 (S1, S2 and S3) was obtained by the varying ratio of the two feedstocks while Group 2 (S1, S4 and S5) was obtained by varying the ratio of the products, as discussed in section 3.2.2.4. Then, the life cycle impact assessment (LCIA) was analyzed by using LCA software; SimaPro 7.1 with CML 2 baseline 2000 and Eco-indicator 95 methods, in order to evaluate the performance of all five scenarios of the biorefinery model in terms of GWP impact (CML 2 baseline 2000) and energy resource impact (Eco-indicator 95) as discussed in the following sections.

4.3 Life Cycle Impact Assessment

4.3.1 Global Warming Potential (GWP)

In the feedstock processing stage; the major source of GWP came from electricity and steam consumption in the cassava starch and sugar production processes of CaPLA production. In contrast, environmental benefit (negative impact) was obtained in sugar milling, which was the feedstock processing stage for MoE and SuPLA production. This was due to the surplus electricity and steam produced, which could be used in other processes. This energy integration could help reduce GWP as seen in scenarios S5, S4, and S1 which had much higher SuPLA production than S2 and S3. Thus, S5, S4, and S1 had less GWP impact than S2 and S3, as shown in Figure 4.2.

It can be seen that the ethanol conversion/PLA resin production stage contributed the highest GWP among all four stages (Figure 4.2). In this stage, major GWP was also caused by electricity and steam consumption in PLA resin production. The molasses and cassava ethanol conversion processes were shown to be the second and third contributors, respectively, to GWP impact, even though, there was biogas produced from these processes which was used to generate electricity to compensate for the energy consumption in the processes. On the contrary, the sugarcane-based ethanol conversion process for SuE production was shown to have better performance in regards to GWP impact due to the generation of surplus electricity and steam from the bagasse (as seen in S3 and S2). In the Group 1, S3 had the highest production of SuE, thus, S3 showed the lowest GWP. When considering the Group 2, S4 had the lowest total PLA production, thus S4 showed a lower GWP impact than that of S1 and S5 (S4<S1<S5). Figure 4.2 also shows the net GWP to be 402, 433, 458, 373, 430 t CO2 eq. for S1, S2, S3, S4, and S5, respectively. It can be seen that S4 has the lowest GWP among all five scenarios.

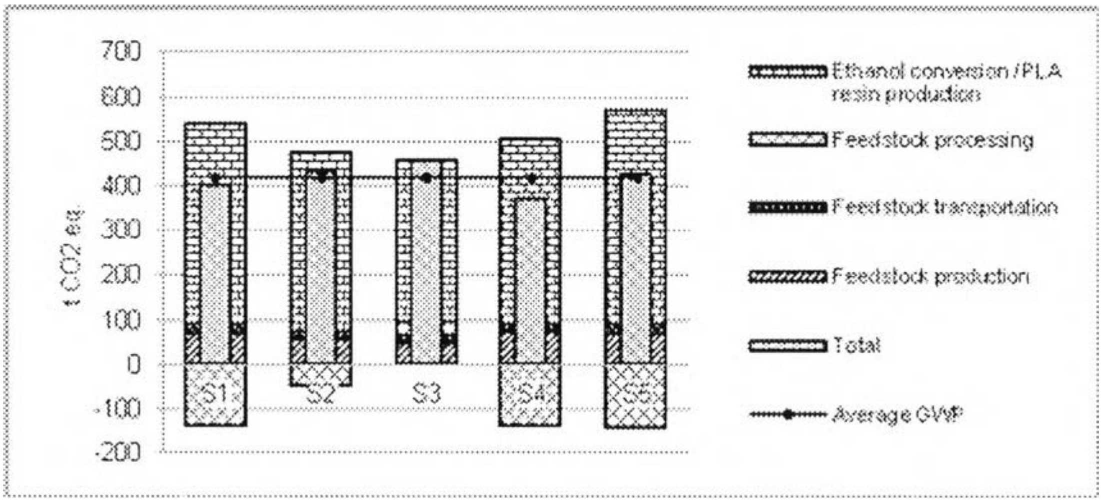


Figure 4.2 Global warming potential of scenarios in this study for each stage by using CML 2 baseline 2000.

4.3.2 Acidification Potential (AP)

From Figure 4.3, it can be seen that the most acidification impact comes from ethanol conversion/PLA resin production stage. When investigated in to the details the main acidification impact comes from sulfuric acid and electricity consumption in PLA resin production. From the Figure below, As S5 has the highest PLA resin production, it has shown to be the highest acidification impact which was equal to 4720 kg SO_2 eq. followed by S1, S2, S3, and S4, which were to be 4443, 4353, 4279, and 4166 kg SO_2 eq., respectively.

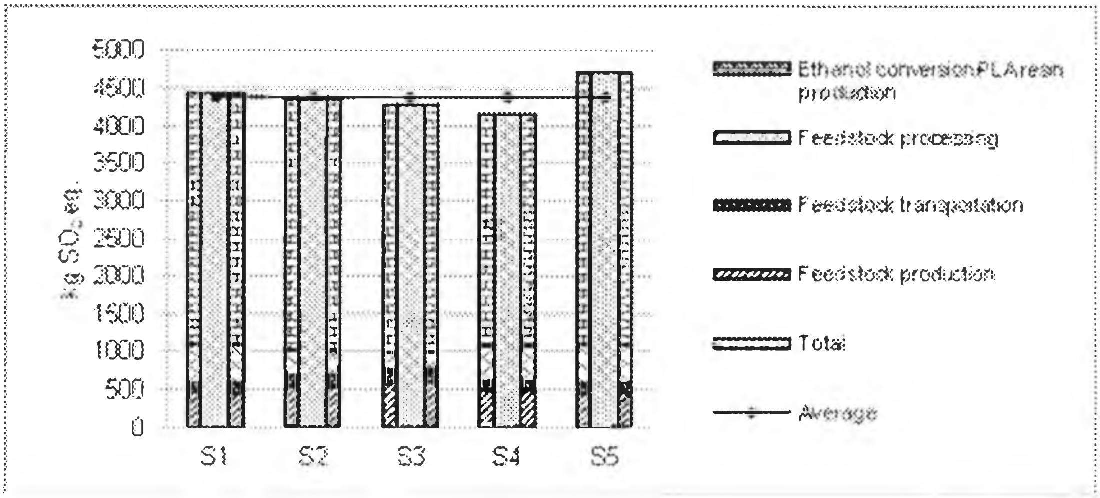


Figure 4.3 Acidification potential of scenarios in this study for each stage by using CML 2 baseline 2000.

4.3.3 Eutrophication Potential (EP)

From Figure 4.4, it can be seen that the most eutrophication impact comes from ethanol conversion/PLA resin production stage. Similar explanation to acidification impact, when investigated in to details the main eutrophication impact comes from waste water discharges of ethanol conversion process especially molasses ethanol conversion process and cassava ethanol conversion process. Although scenarios under study have production of MoE not much when compared with CaE and SuE production, its waste water has higher Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) than that of CaE and SuE. For SuE production, its waste water could be produced vinasse. So, SuE production was not affecting much for eutrophication impact. Figure 4.4 also shows the net EP for each scenario which was shown to be 2399, 1797, 1301, 2518, 2287 kg PO_4^{3-} eq. for S1, S2, S3, S4, and S5, respectively. It can be seen that S4 has shown to have the highest EP among all 5 scenarios studied as S4 was the highest ethanol production scenario.

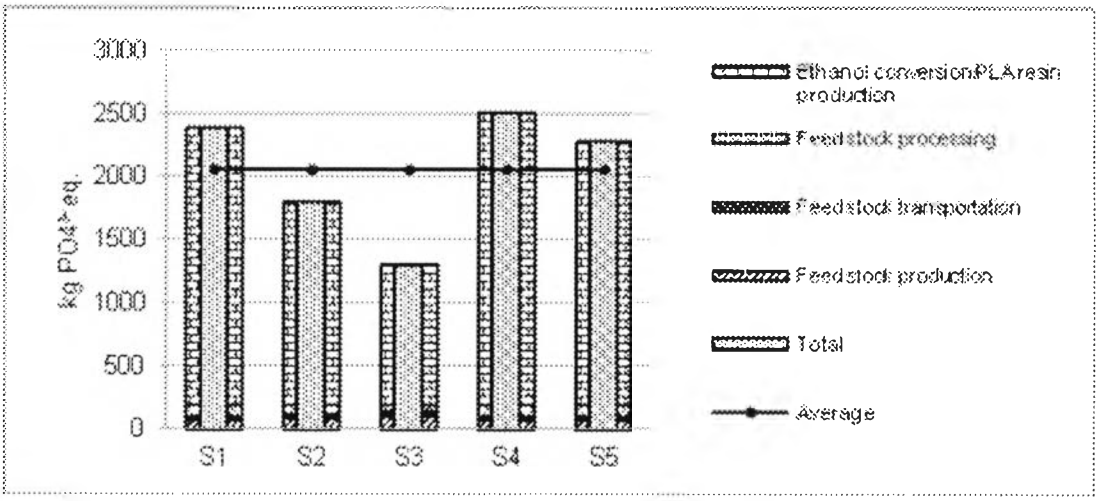


Figure 4.4 Eutrophication potential of scenarios in this study for each stage by using CML 2 baseline 2000.

4.3.4 Energy Resources

Figure 4.5 illustrates the energy resources results in each stage for all five scenarios. It can be seen that the ethanol conversion/PLA resin production stage consumed the highest amount of energy. In the feedstock processing stage, sugar milling generated surplus electricity and steam which could be used in other processes in the biorefinery. Therefore, scenarios S5, S4, and S1, which used more sugarcane (80% sugarcane) than the other scenarios (S2 and S3), could actually gain avoided energy (from surplus energy) as shown as negative values in Figure 4.5. When comparing Group 1, S5 had the highest PLA production followed by S1 and S4, thus, S4 showed the lowest total energy resources due to the least amount of PLA production. The net energy resources impact are shown to be 4128, 4561, 4902, 3706, 4526 GJ LHV for S1, S2, S3, S4, and S5, respectively (Figure 4.5).

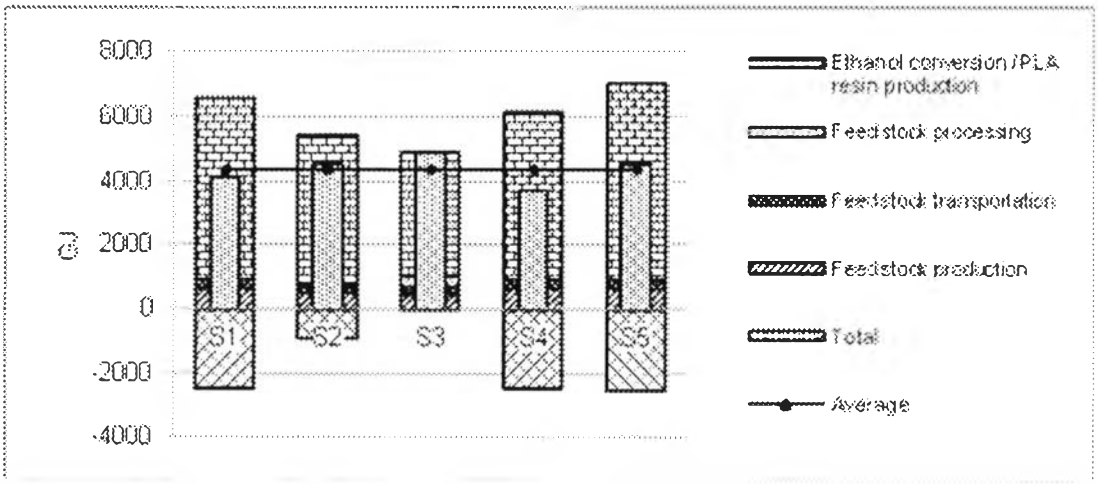


Figure 4.5 Energy resource of scenarios in this study for each stage by using Eco-indicator 95.

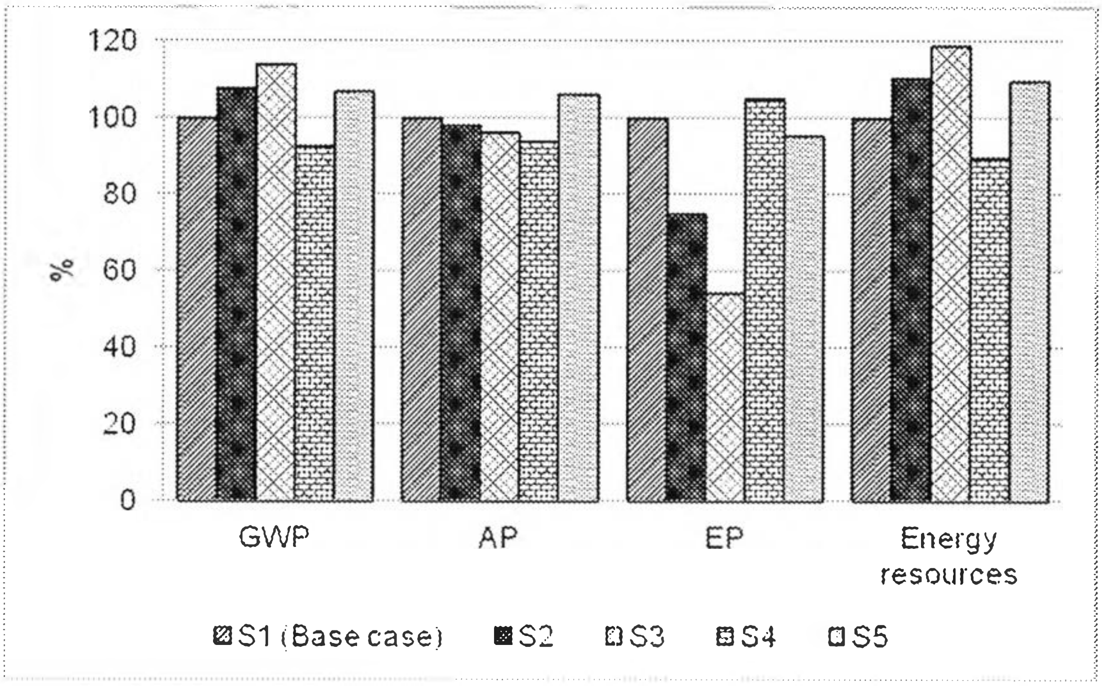


Figure 4.6 Comparison of life cycle energy use and environmental performance for 5 scenarios.

Based on Figure 4.6, it present the summarized of comparison of life cycle energy use and environmental performance for 5 scenarios. In comparison, the base case (S1) is set at 100%. As shown in the figure, S4 has shown to have the best environmental performance in GWP, AP, and energy consumption, among all 5 scenarios studied due to high sugarcane usage and low PLA resin production. However, S4 has shown to have the worst environmental performance in EP. Moreover, from Table 3.1, S4 was not the best scenario in profit generation which made us question that which scenario would be the best in both environmental and economic aspects. Thus, in the next section, Eco-efficiency parameter has been developed in order to combine the two aspects, environment and economic, together.

4.4 Eco-Efficiency

Eco-efficiency is an indicator that is used to help businesses to be more effective efficient and responsible for natural resources and the environment. This indicator has been shown to be relevant to both economic and environmental aspects towards sustainable development. Eco-efficiency can be expressed as the ratio of economic creation to ecological destruction as shown in equation 1, thus the higher the Eco-efficiency parameter the better it is.

$$Eco - efficiency = \frac{Value\ of\ a\ product\ or\ service}{Environmen\ tal\ impact\ of\ a\ product\ or\ service} \qquad (1)$$

In this study, four Eco-efficiency parameters were developed specifically to combine environmental (GWP, AP, EP, and energy resources) and economic (profit) aspects by using ratio of normalized profit and normalized environmental impacts. The normalized values were calculated by dividing the profit and environmental impact in each scenario with the average values obtained from all scenarios studied as shown in Figure 4.7.

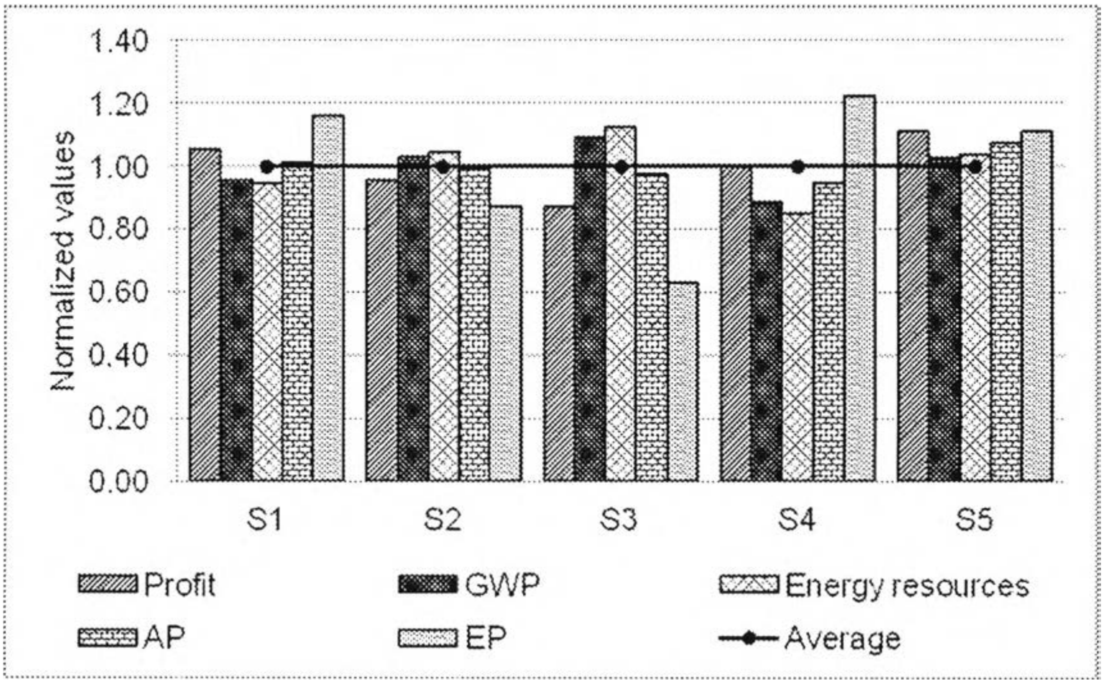


Figure 4.7 Normalized values for eco-efficiency parameter calculation.

These normalized values were used as benchmark to aid in fair comparison between scenarios studied. The four Eco-efficiency parameters (Eco-efficiency$_{GWP}$ was for GWP impact, Eco-efficiancy$_{AP}$ was for AP impact, Eco-efficiancy$_{EP}$ was for EP impact, and Eco-efficiency$_{Energy\ resources}$ was for energy resource impact) as calculated from normalized values are shown in Table 4.2.

Table 4.2 Eco-efficiencies of scenarios in this study

Scenario	**S1**	**S2**	**S3**	**S4**	**S5**
Eco-efficiancy$_{GWP}$	1.10	0.92	0.80	1.13	1.08
Eco-efficiancy$_{AP}$	1.04	0.96	0.90	1.06	1.03
Eco-efficiancy$_{EP}$	0.91	1.10	1.38	0.82	0.99
Eco-efficiancy$_{Energy\ resources}$	1.12	0.91	0.78	1.18	1.07

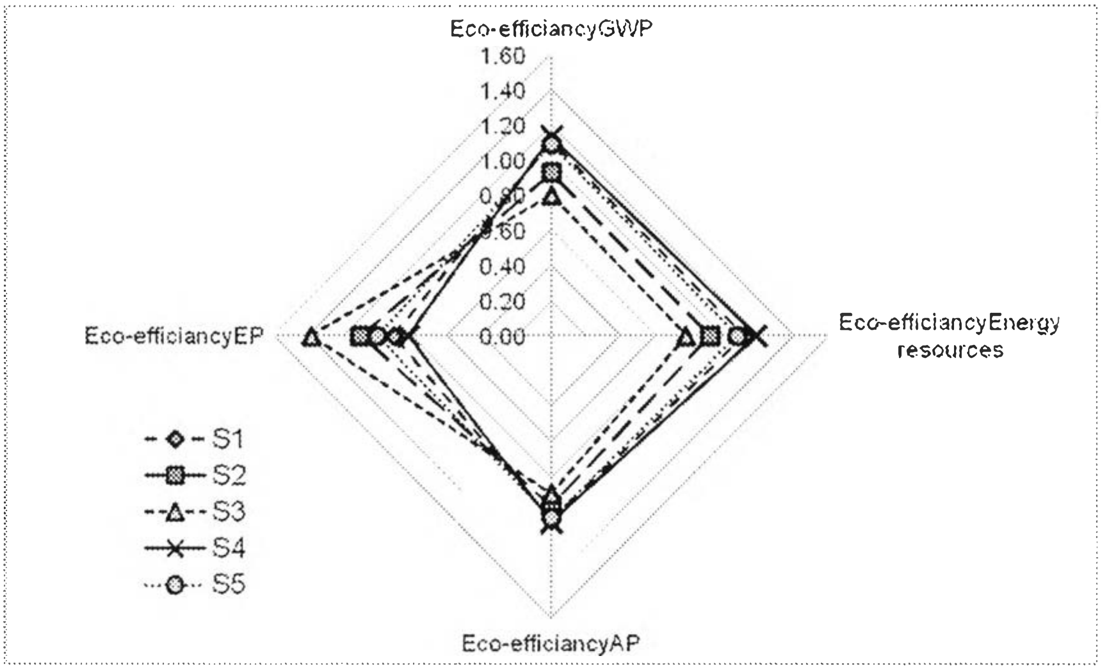


Figure 4.8 Relationship between the four Eco-efficiency.

Figure 4.8 illustrates the relationship among the four Eco-efficiency parameters. It can be used to identify the best scenario. When being normalized, an Eco-efficiency value higher than 1 should be considered efficient in terms of both environmental and economic aspects. In addition, the higher the Eco-efficiency value (>1) the better the performance it is. Since four Eco-efficiency parameters (Eco-efficiency$_{GWP}$, Eco-efficiancy$_{AP}$, Eco-efficiancy$_{EP}$, and Eco-efficiency$_{Energy\ resources}$) have been developed in this study, the best scenario should have high values in all parameters. Based on these criteria, S1, S4 and S5 have three parameter values which more than 1 (Eco-efficiency$_{GWP}$, Eco-efficiancy$_{AP}$, and Eco-efficiency$_{Energy\ resources}$). If we focus mainly on GWP and energy resources impacts, S4 have shown to be the best scenario while S1 and S5 was the second and third best.

4.5 Biorefinery Performance Analysis

In this study, biorefinery performace was evaluated in many aspects consist of raw materials consumption, fuel and biopolymer production, and profit generation.

4.5.1 Raw Materials Consumption

The model biorefinery would have better performance in both GWP and energy resources with increased sugarcane usage. The more sugarcane used the more energy that could be produced by bagasse. The more energy produces the greater avoids greenhouse gas (GHG) emissions. As seen in scenario S1, S4, and S5 which have the same ratio of raw materials consumption with 80% sugarcane and 20% cassava usage. The three scenarios have clearly better performance in both impacts than that in S2 (60% sugarcane and 40% cassava usage), and S3 (40% sugarcane and 60% cassava usage). The results show that sugarcane ethanol conversion for SuE production could produce more electricity and steam than sugar milling. Thus, in the case that the biorefinery require the more energy or desire to reduce the GWP and energy resource impacts the SuE production would be considered.

4.5.2 Fuel and Biopolymer Production

Increasing PLA production led to higher GWP and energy resource impacts because of higher electricity and steam consumption in the bioplastic production process. When we compare in Group 2, S5 has the highest in both impacts (GWP, energy resources) due to it has the highest PLA resin production. In contrast, the production of ethanol, especially MoE and CaE, could increase EP impact. This was due to the waste water that released in environment. If we focus on GWP and energy resource impacts, the biorefinery should not produce PLA resin and turned to ethanol production.

4.5.3 Profit Generation

It seems that the use of the sugarcane is better than cassava in term of the utilization of bagasse to generate electricity and steam. This could reduce the cost of energy consumption. Although, PLA resin production gives high GWP and energy resource impacts, it gains more profit than the ethanol production. In order to maximize the profit, the biorefinery should use sugarcane as feedstock to produce PLA resin.

It can be seen that each feedstock usage and product production provide the differences in the pros and cons. Finally, we should hold the principle of the biorefinery concept - Taking maximum benefit of intermediate and by-products to generate additional chemicals and materials, and Maintaining balance of high-value / low-volume bio-based chemicals and materials with high-volume/low value biofuels - A biorefinery might produce one or several low volume, but high-value, chemical products and a low-value, but high-volume liquid transportation fuel, at the same time generating electricity and process heat for its own use and perhaps enough for the sale of electricity. The high-value products enhance the profitability, the high-volume fuel helps meet the national energy needs, and the power production reduces costs and avoids GHG emissions. For the high-value chemical products, the local market value for the products will decide which products will be produced.

4.6 Comparison with Conventional Process

It can be seen that the GWP and energy consumption of each product has the same trend (Figure 4.9, 4.10). This was due to the main GWP of each product comes from energy consumption.

4.6.1 Sugarcane based Ethanol

At present, Thailand has already sugarcane based ethanol plant. Thus no information of SuE production in Thailand is publicly available. The conventional sugarcane based ethanol (CSuE) was retrieve from Brazil paper (Macedo *et.al*, 2008). The plant is produce ethanol from direct juice using bagasse as a fuel and generating surplus electricity with high pressure boiler and export to national grid. The difference between SuE and CSuE is that SuE count surplus steam credit due to the steam can use in other processes in biorefinery while CSuE cannot do that. Thus, SuE has GWP and energy resource impact lower than that in CSuE.

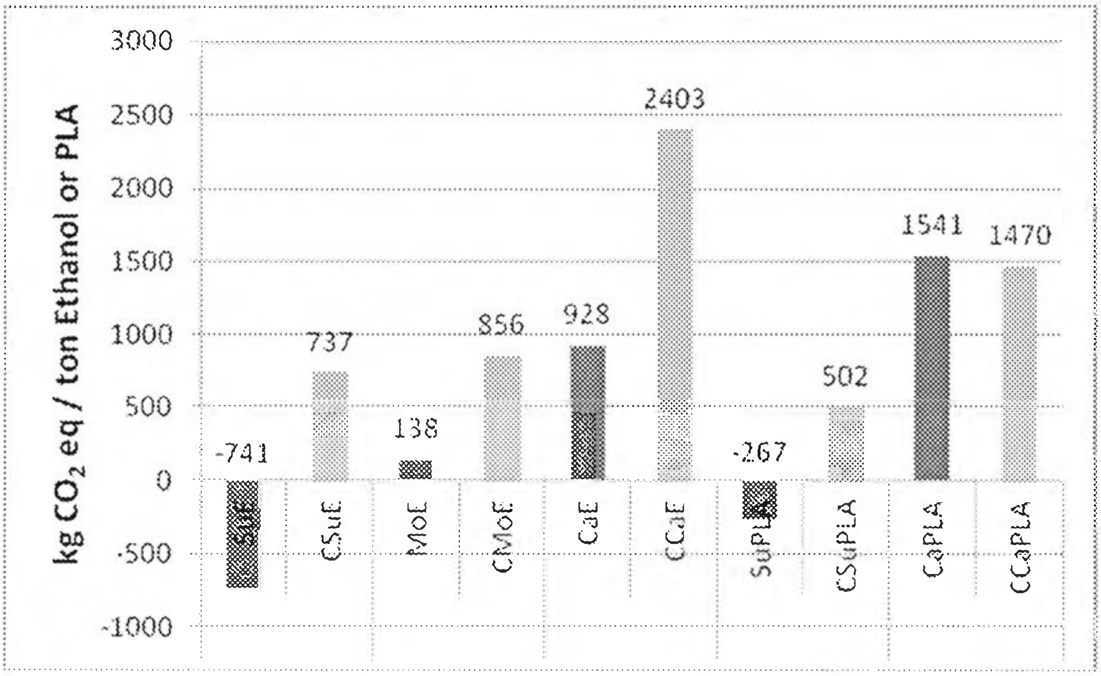


Figure 4.9 Comparison of GWP for each product between biorefinery process and conventional process.

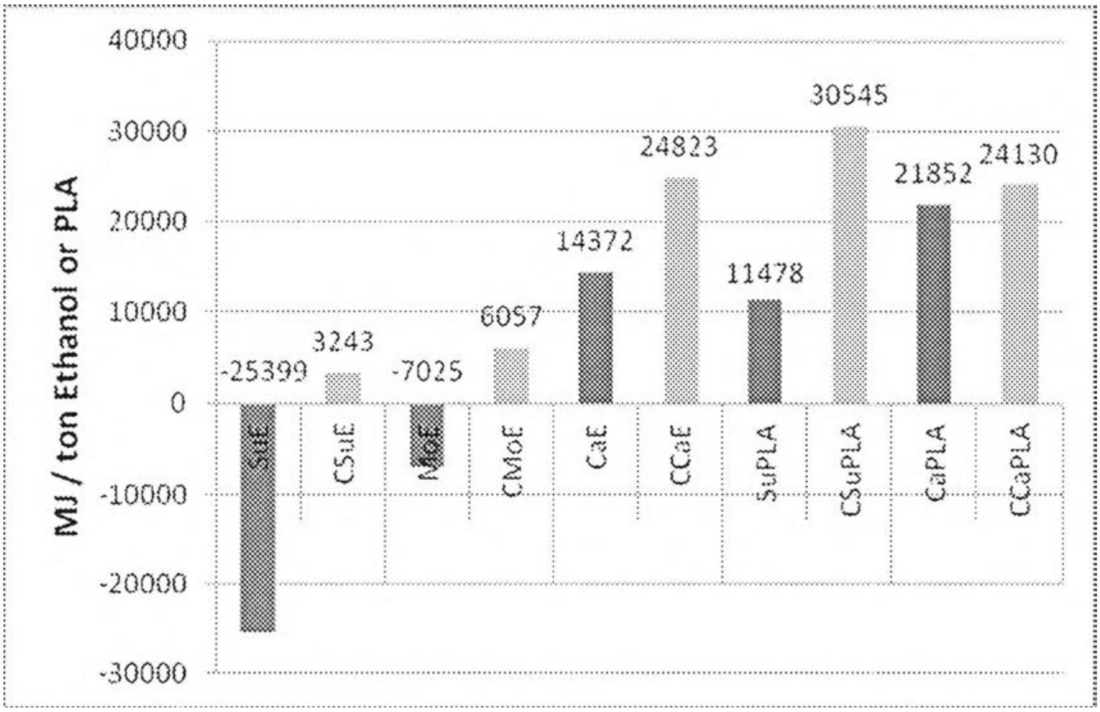


Figure 4.10 Comparison of energy consumption for each product between biorefinery process and conventional process.

4.6.2 Molasses based Ethanol

The conventional molasses based ethanol (CMoE) impacts data is acquired from Silalertruksa and Gheewala (2009). This impact data are average impacts of the three existing CMoE plants in Thailand. The difference between MoE and CMoE is the same as section 4.4.1. Thus, MoE has GWP and energy resource impact lower than that in CMoE.

4.6.3 Cassava based Ethanol

The conventional cassava based ethanol (CCaE) information is acquired from the same source as CMoE (Silalertruksa and Gheewala, 2009). The impacts of one existing CCaE plant in Thailand and designed operation plant are averaged. Due to CCaE plant use coal as fuel to generate electricity and steam, emissions from coal combustion lead to increase GWP impact. Moreover, the low efficiency of technology leads to the net energy loss. Thus, CCaE has GWP and energy resource impact higher than that in CaE.

4.6.4 Sugarcane based PLA resin

Currently, there has less information of conventional sugarcane based PLA resin (CSuPLA) production. The information from Groot and Borén (2010) is the single publication. Due to some different in assumptions and no steam credit in sugar mill process for CSuPLA, CSuPLA has higher GWP and energy consumption than SuPLA.

4.6.5 Cassava based PLA resin

Due to information used in this study was retrieve from the same source of the conventional cassava based PLA resin (CCaPLA) process (Petchprayul *et al.*, 2012), the diffence between CaPLA and CCaPLA is not much different.