CHAPTER IV
RESULTS AND DISCUSSION

4.1 Life Cycle Inventory of Rice Straw

The basis of any LCA study is the creation of an inventory, which contains the data of all inputs and outputs of processes that occur during the life cycle of a product. This includes the production phase, distribution, use and final disposal of the product.

4.1.1 The Inventory Data of Rice Straw Production

In this study, rice straw was considered in two cases: (1) as a waste and (2) as a by-product of rice (paddy) production

4.1.1.1 Case 1 : Rice Straw as a Waste Case

When rice straw was considered as a waste, rice cultivation was not included in the system boundary. Consequently, this case covered only on the rice straw harvesting. The rice straw collection data were collected at rice cultivation sites in Nakhon Rachasima province. The system boundary of rice straw production for rice straw as a waste case is shown in Figure 4.1.

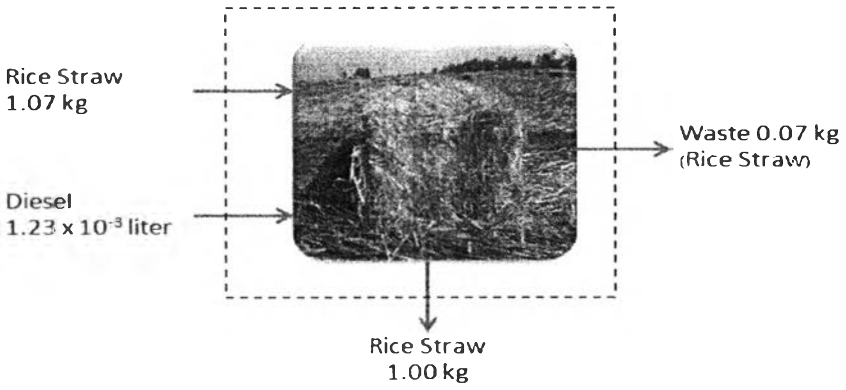


Figure 4.1 The system boundary of rice straw production for rice straw as a waste case.

The inventory data for production of one ton rice straw as a waste case are listed in Table 4.1.

Table 4.1 The inventory data for production of one ton rice straw as a waste case

Input inventory	Unit	Amount
Raw material:		
Rice straw	ton	1.07
Fuel/Energy:		
Diesel	liter	1.23
Output inventory	**Unit**	**Amount**
Product:		
Rice straw	ton	1.00
Waste:		
Rice straw	kg	70

4.1.1.2 Case 2 : Rice Straw as a By Product Case

In this case, the inventory data covered all agricultural field operations for rice production (soil preparation, rice production, paddy cultivation and harvesting). The inventory data for rice straw production in Thailand was collected from the environmental information databases by Suranaree Environmental Technology Research & Consulting Unit (SENTEC). The subsystem boundaries included the production of process materials such as fertilizers, pesticides and fuel for operating agricultural machinery production. The rice straw collection data used the same data as rice straw as a waste case. The system boundary of rice straw production as a by-product case is shown in Figure 4.2.

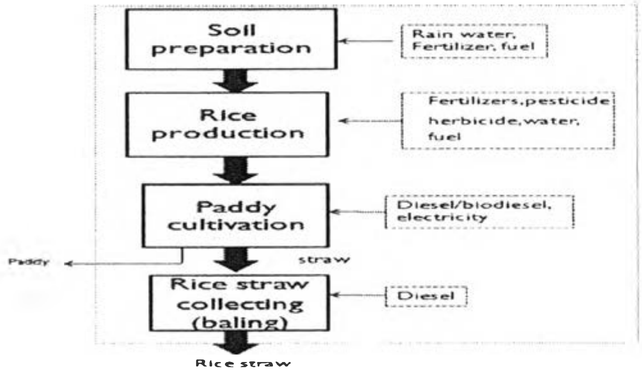


Figure 4.2 The system boundary of rice straw production as a by-product case.

Cost allocation is necessary for rice straw as a by-product case. The inventory data for production of one ton rice straw as a by-product case are listed in Table 4.2.

Table 4.2 The inventory data for production of one ton rice straw with cost allocation

Input inventory	Unit	with cost allocation Amount
Raw material:		
Rice seed	kg	0.27
Chemical:		
Glyphosate	kg	0.14
Paraquat	kg	0.13
Nitrogen	kg	0.38
Phosphorus	kg	014
Potassium	kg	0.07
Fuel/Energy:		
Diesel	liter	0.36
Output inventory	**Unit**	**Amount**
Product:		
Rice straw	ton	1.00
Emission to air:		
Carbon dioxide	kg	1.22E-6
Carbon monoxide	kg	8.54E-4
Nitrogen dioxide	kg	3.05E-6
Methane	kg	0.61E-4
Emission to water:		
Waste water	kg	0.63E-2

(Source: Adopted from SENTEC)

4.1.2 The Inventory Data of Rice Straw Transportation

The transportation distance of rice straw from rice straw production area to pyrolysis plant was calculated based on assumption. The location of pyrolysis plant and upgrading plant were created and compared in 2 cases. Case 1 design was simulated based on the different area of pyrolysis and upgrading plant while Case 2 design was simulated based on the same area of pyrolysis and upgrading plant. The descriptions of these two cases of rice straw transportation were mentioned in scope of research in Chapter III. Table 4.3a, 4.3b and Table 4.4 show the inventory data for transportation stage of rice straw for Case 1 and Case 2 (one way), respectively.

Table 4.3a The inventory data for transportation of one ton rice straw for Case 1

Input inventory	**Unit**	**Amount**
Raw material:		
rice straw	ton	1.39
Fuel:		
diesel	liter	1.89
Output inventory	**Unit**	**Amount**
Product:		
rice straw	ton	1
Emission:		
Carbon dioxide	kg	9.39
Carbon monoxide	kg	0.17
Nitrous dioxide	kg	0.97E-1
Particulate matter (PM)	kg	0.26E-1

Table 4.3b The inventory data for transportation of one ton raw bio-oil for Case 1

Input inventory	**Unit**	**Amount**
Raw material:		
raw bio-oil from pyrolysis	ton	1.75
Fuel:		
diesel	liter	6.4
Output inventory	**Unit**	**Amount**
Product:		
rice straw	ton	1
Emission:		
Carbon dioxide	kg	24.14
Carbon monoxide	kg	0.44
Nitrous dioxide	kg	0.25
Particulate matter (PM)	kg	0.67E-1

Table 4.4 The inventory data for transportation of one ton rice straw for Case 2

Input inventory	**Unit**	**Amount**
Raw material:		
rice straw	ton	1.39
Fuel:		
diesel	liter	1.89
Output inventory	**Unit**	**Amount**
Product:		
rice straw	ton	1
Emission:		
Carbon dioxide	kg	9.39
Carbon monoxide	kg	0.17
Nitrous dioxide	kg	0.97E-2
Particulate matter (PM)	kg	0.26E-1

4.2 Life Cycle Inventory of *Leucaena leucocephala*

4.2.1 The Inventory Data of *Leucaena leucocephala* Production

The *leucaena leucocephala* agricultural production model used test field data collected from PTT research and Technology Institute. The test field is operated in Pakchong district in Nakorn rachasima province in the land of 8 rai. In this part, the environmental and energy performance of fast growing tree production, considered for the whole biomass production system from soil preparation to the harvest of biomass. The *leucaena leucocephala* biomass crops are grown as a perennial with multiple harvest cycles (or rotations) occurring between successive plantings. The *leucaena leucocephala* can be harvested on every 1 year cycle. The two species of *leucaena leucocephala* which are cultivated in this area are Tarumba and Cunningham but this study focuses on Tarumba specie. There was no use of any fertilizer or pesticide in this site. The system boundary of *leucaena leucocephala* production is shown in Figure 4.3.

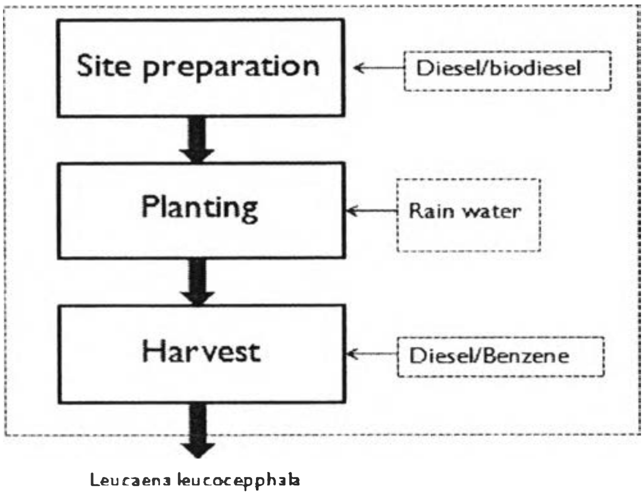


Figure 4.3 The system boundary of *leucaena leucocephala* production.

The input and output of *leucaena leucocephala* production are shown in Table 4.5.

Table 4.5 The input and output of 1 ton *leucaena leucocephala* production

Input inventory	Unit	Amount
Raw material:		
leucaena leucocephala	ton	1
Fuel/Energy:		
diesel	kg	0.77
benzene	kg	0.7
Output inventory	**Unit**	**Amount**
Product:		
leucaena leucocephala	ton	1

(Source: PTT research and Technology Institute)

4.2.2 *Leucaena leucocephala* Transportation

The transportation distance of *leucaena leucocephala* from the plantation area to pyrolysis plant was assumed to be within a 100 km radius of the pyrolysis plant. The pyrolysis and upgrading plant were assumed to locate in the same area (Case 2). The inventory data for *leucaena leucocephala* transportation (one way) are shown in Table 4.6.

Table 4.6 The inventory data for 1 ton *leucaena leucocephala* transportation

Input inventory	Unit	Amount
Raw material:		
leucaena leucocephala	ton	1.00
Fuel:		
diesel	liter	4.21
Output inventory	**Unit**	**Amount**
Product:		
leucaena leucocephala	ton	1.00
Emission:		
Carbon dioxide	kg	20.89
Carbon monoxide	kg	0.38
Nitrous dioxide	kg	0.22
Particulate matter (PM)	kg	0.57E-1

4.3 Life Cycle Inventory of Pyrolysis and Upgrading System

The pyrolysis stage has been separated into 2 steps: feed preparation and pyrolysis process. The feedstock preparation consists of feed drying and size reduction. The inventory data of feed preparation for *leucaena leucocephala* are shown in Table 4.7.

Table 4.7 The inventory data of feed preparation for 1 ton *leucaena leucocephala*

Input inventory	Unit	Amount
Raw material:		
wet *leucaena leucocephala* chip	ton	1.30
Fuel/Energy:		
electricity for grinding^1	kWh	16
electricity for drying^2	kWh	127
Output inventory	**Unit**	**Amount**
Product:		
dry *leucaena leucocephala* chip	ton	1

(Source: 1 A plus power Co., Ltd., 2 calculation data)

For pyrolysis process, there are many kinds of biomass pyrolysis process, such as conventional, flash or fast which depend on operating conditions. This study focuses on fast pyrolysis process because it gives the highest yield when compared with other processes. Furthermore, the selection of the suitable process to recover the energy from a particular type biomass is the most important step towards a profitable investment. In this work, bubbling fluid bed technology is being considered. Data for fast pyrolysis were retrieved from Wellman Process Engineering Ltd. (WPEL).

In upgrading process, it is necessary to improve properties of raw bio-oil comes out from pyrolysis process due to its unfavorable nature i.e., highly oxygenated and low octane number making it undesirable as a ready alternative transportation fuel. To overcome these physicochemical issues, hydrodeoxygenation (HDO) reaction is a possible upgrading method by partial or total elimination of oxygen and hydrogenation of chemical structures. Since there is no commercial plant or any information of this part, process simulation is necessary to obtain relevant data such as energy consumption. Data for upgrading process simulation were extracted from those reported by Department of Chemical Engineering, University Technology PETRONAS.

4.3.1 Pyrolysis System

In this study, secondary data from Wellman Process Engineering Ltd. (WPEL) were used for the pyrolysis bio-oil production.

4.3.1.1 Background of Wellman Process

Wellman has a long history of thermal conversion of both coal and biomass. A novel oxygen donor biomass gasifier was constructed jointly with John Brown Engineers and Constructed in the mid 1980s and an updraft biomass gasifier with advanced tar cracking system are commercially available. At 250 kg/h of biomass fed, fast pyrolysis fluid bed pilot plant is currently under construction supported partly by the European Commission (Bridgwater and Peacocke, 2000).

4.3.1.2 Description of Technology

In this process, the reactor is a conventional bubbling fluid bed which is heated by combustion of by-product char in an annular fluid bed combustor with most heat requirements being met through the reactor wall. The product vapours are passed through two cyclones before being quenched with cooled recycle product oil. The vapours are finally passed through an electrostatic precipitator. The process conditions include very short residence time of < 2s and sand high heating rates of 500 °C (Peacocke *et al.*, 2006).

Process flowsheet for Wellman process is shown in Figure 4.4. At a capacity of 2 dry tons/h, all pumps and fans have a second identical unit included for redundancy. The Wellman process information and the yield of pyrolysis liquids from this process were assumed to be constant with scale as shown in Table 4.8 and Table 4.9, respectively.

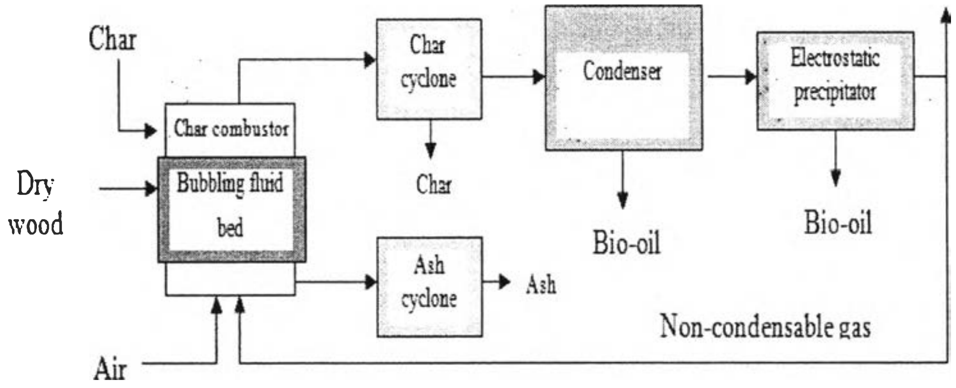


Figure 4.4 Wellman Process Engineering Ltd. Fast pyrolysis flowsheet (Adopted from Peacocke *et al.*, 2006).

Table 4.8 Wellman Process information (Extracted from Peacocke *et al.*, 2006)

Process information	
Feed	Dry wood chip
Scale	8 dry tons biomass/day
Particle size	0.5-4 mm
Bio-oil yield	79%
Type of reactor	Bubbling fluidize bed

Table 4.9 Pyrolysis liquids yield from Wellman process (Source: Peacocke *et al.*, 2006)

Process	**Wellman**
Yield, liters of oil per tonne of dry ash free wood	755
Yield, tonne oil of per dry ash free delivered tonne wood	0.89
Yield, tonnes oil per tonne wood fed to reactor	0.79

The inventory data of Wellman process for producing 1 kg of bio-oil are listed in Table 4.10.

Table 4.10 The inventory data of pyrolysis process

Input inventory	**Unit**	**Amount**
Raw material		
Dry wood chip	kg	1.27
Air	kg	2.23
Energy		
Electricity	kWh	0.15
Output inventory	**Unit**	**Amount**
Bio-oil	kg	1.00
Emission to air		
CO_2	kg	0.45
O_2	kg	0.46
N_2	kg	1.73
H_2O	kg	0.26

(Extracted data from Peacocke *et al.*, 2006)

4.3.2 Upgrading Process

In this stage, the primary data for upgrading process were created from simulation based on data extracted from PETRONAS.

4.3.2.1 Background of PETRONAS

To develop the bio-oil upgrading process flowsheet, the iCON (Virtual Materials Group Inc., 2009) process simulation package was employed. This commercial process simulator that developed by PETRONAS, Malaysia's national oil corporation, in collaboration with Virtual Materials Group (VMG) Inc., is based on Sim 42 and runs on VMGThermo as the plug-in thermodynamics property package database standard (Ahmad *et al.*, 2010).

4.3.2.2 Description of Technology

In this study, the bio-oil from the biomass fast pyrolysis is upgraded via HDO which consists of two stages. At the end of the second stage, the oxygen content in the bio-oil is expected to decrease significantly (Ahmad *et al.*, 2010). Figure 4.5 shows the overall process flow block diagram developed for the simulation to upgrade bio-oil via HDO. The feeds to this process consist of bio-oil and hydrogen.

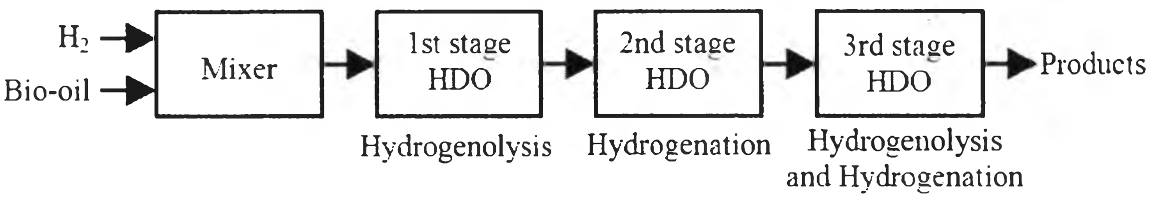


Figure 4.5: Overall process flow block diagram for upgrading process of bio-oil via HDO (Source: Ahmad *et al.*, 2010)

4.3.2.3 Three Alternative Designs

4.3.2.3.1 Process Simulation of Base Case Design

The process and simulation data extracted from PETRONS were used as a model for a base case design. Flowsheet of the base case design implemented in PRO/II for this study is shown in Figure A1 in Appendix A. In this part, steam used for heating was assumed to be generated from hardwood chips from forest (Simapro database). The inventory data of upgrading process are shown in Table 4.11 based on 1 toe of upgraded bio-oil.

Table 4.11 The inventory data of upgrading process (Base case design)

Input inventory	Unit	Amount
Raw material		
Raw bio-oil	ton	1.75
H_2	kg	21.36
Energy		
Electricity	kWh	379
Hot utility	MJ	22,820
Output inventory	**Unit**	**Amount**
Upgraded bio-oil	toe	1.0

(Source: Extracted data from PETRONAS)

4.3.2.3.2 Alternative-1: Heat Integration

The target of this alternative is to minimize energy consumption of the upgrading processes by calculating thermodynamically feasible energy targets (or minimum energy consumption) and achieving them by optimizing heat recovery systems. The energy targets can be achieved using heat exchangers to recover heat between hot and cold streams in two separate systems. The properties of hot and cold streams before and after making the heat integration (Alternative 1) are shown in Appendix B. After making the heat integration, the use of hot utility could be reduced to 6,970 MJ per toe.

4.3.2.3.3 Alternative-2: Heat Integration and 75% Heat Recovery

Heat recovery is an energy recovery by heat exchanger that recovers heat from a hot gas stream. It produces steam that can be used in a process. In the upgrading process, a large amount of heat is removed from the process. Therefore, heat recovery method has been applied in this alternative. In most cases the sensible heat recovery efficiency of reactor will be about 75% (McQuay International). Thus, we could bring 75% of the energy from heat removal in order to reduce over all quantity of hot utility.

4.4 Life Cycle Energy Analysis

A life cycle energy analysis (LCEA) is an approach in which all energy inputs of the entire production system of bio-oil conversion process are accounted. In this research, after performing the life cycle inventory analysis of the bio-oil conversion process, the life cycle energy efficiency was studied in term of Net Energy Ratio (NER) which refers to the ratio between total energy required completing the process life cycle and the amount of energy contained in the products.

In this study, the life cycle energy inputs in the product system were divided into four stages: energy used in rice straw and *leucaena leucocephala* cultivating and harvesting, energy used in transportation, energy used in pyrolysis, and lastly energy used in upgrading process.

4.4.1 Life Cycle Energy Consumption

4.1.1.1 Rice Straw as a Waste Case

For Case 1, pyrolysis and upgrading plants were located in Nakorn Sawan and Rayong province, respectively. The results of the life cycle energy analysis for the production of 1 toe bio-oil production are shown in Figure 4.6. The total energy consumption is shown to be 30.27 GJ per 1 toe bio-oil production and it is clear that the upgrading stage has the highest energy consumption, followed by the pyrolysis, and the transportation stage. The energy input in the rice straw cultivating and harvesting stage is lowest because in this case rice straw is considered as a waste. Therefore, all of energy usage in rice plantation phase was neglected.

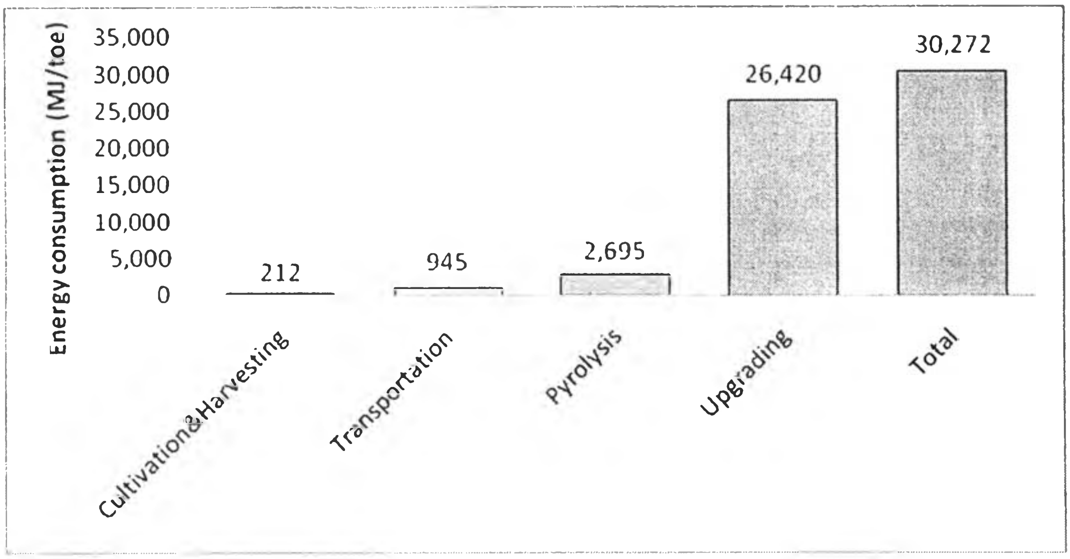


Figure 4.6 Life cycle energy consumption of 1 toe bio-oil production from rice straw as a waste case for Case 1.

The energy usage in the upgrading stage is highest (87.28% of total energy input) due to the intensive use of electricity and steam consumption. The energy usage in pyrolysis stage is the second, accounting for 8.90%, which mainly comes from the use of electricity. The transportation and cultivating/harvesting stage are shown to consume relatively low energy portion in the life cycle, 3.12% and 0.70%, respectively.

For Case 2, pyrolysis and upgrading plants were located in the same area in Rayong province. The results of the life cycle energy analysis for the production of 1 toe bio-oil production are shown in Figure 4.7. The total energy consumption is shown to be 29.70 GJ per 1 toe bio-oil production. The reduction of energy consumption in Case 2 compared to Case 1 is due to the shorter distance of transportation.

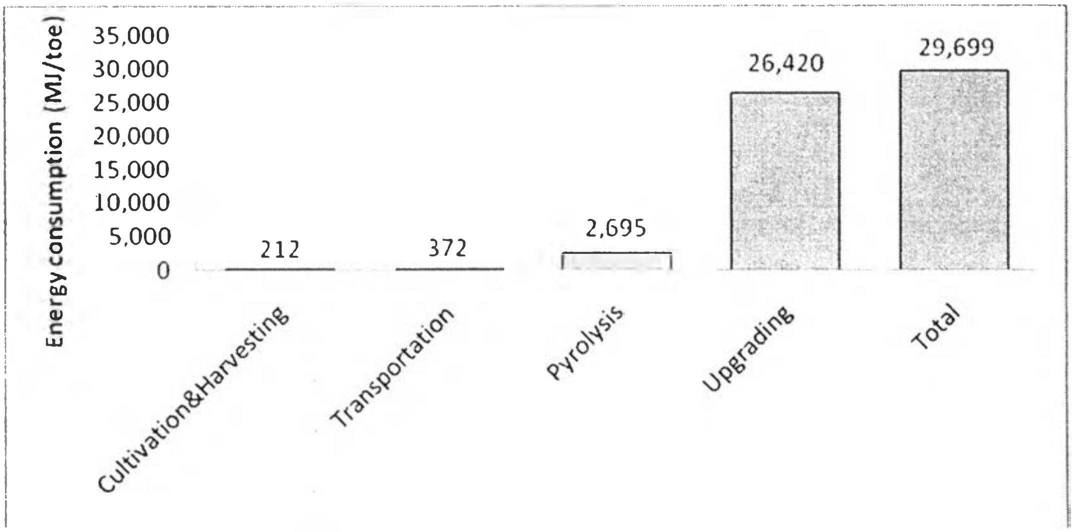


Figure 4.7 Life cycle energy consumption of 1 toe bio-oil production from rice straw as a waste case for Case 2.

4.4.1.2 Rice Straw as a By-product Case

The economic allocation was used in this part of study based on price from Thai Center Market as of 25 March 2011. The results of the life cycle energy analysis for the production of 1 toe bio-oil are shown in Figure 4.8.

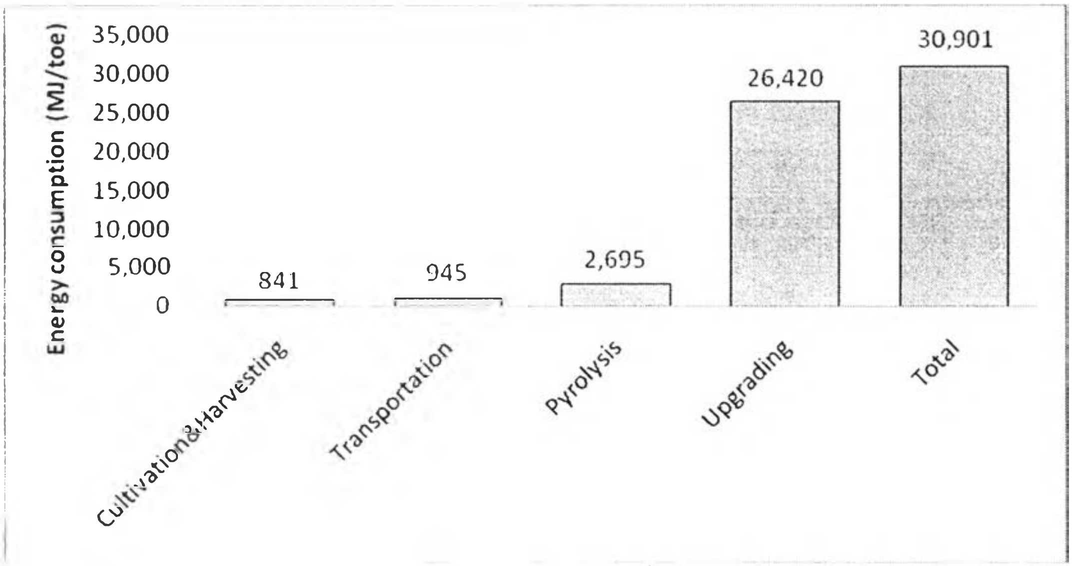


Figure 4.8 Life cycle energy consumption of 1 toe bio-oil production from rice straw as a by-product case for Case 1.

The results show that the production of bio-oil required the total energy input of 30.90 GJ/toe bio-oil. The energy usage (electricity and hot steam from burning hard wood) in the upgrading stage is highest which account for 85.50% of total energy input. The energy usage in pyrolysis stage is the second, accounting for 8.72%, followed by the transportation stage (3.06%). Cultivation and harvesting stage is shown to consume the lowest energy in the life cycle, accounting for only 2.72% because the very small share of agricultural energy consumption allocated to rice straw. If larger bio-oil markets can be established with higher price of rice straw as a feedstock, values assessed using economic allocation will shift upward.

For Case 2 where pyrolysis and upgrading plants are assumed to be located at the same area in Rayong province, the results of the life cycle energy analysis for the production of 1 toe bio-oil production are shown in Figure 4.19. The total energy consumption was found to be 30.33 GJ per 1 toe bio-oil production. The reduction of energy consumption in Case 2 compared to Case 1 is due to the shorter distance of transportation.

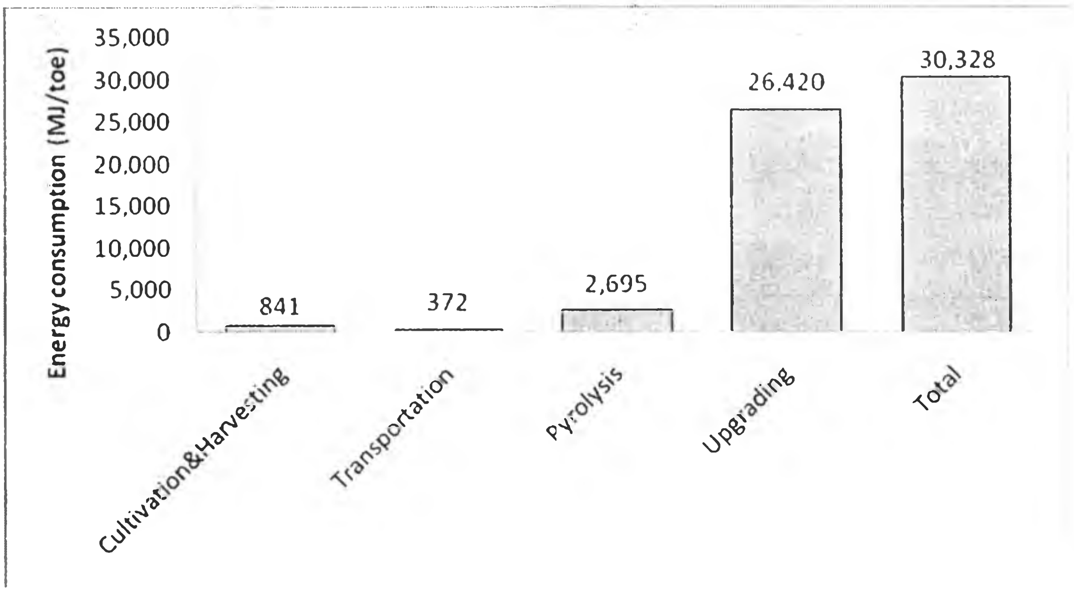


Figure 4.9 Life cycle energy consumption of 1 toe bio-oil production from rice straw as a by-product case for Case 2.

4.4.1.3 Leucaena leucocephala

The results of the life cycle energy analysis for the production of 1 toe bio-oil production from *leucaena leucocephala* are shown in Figure 4.10.

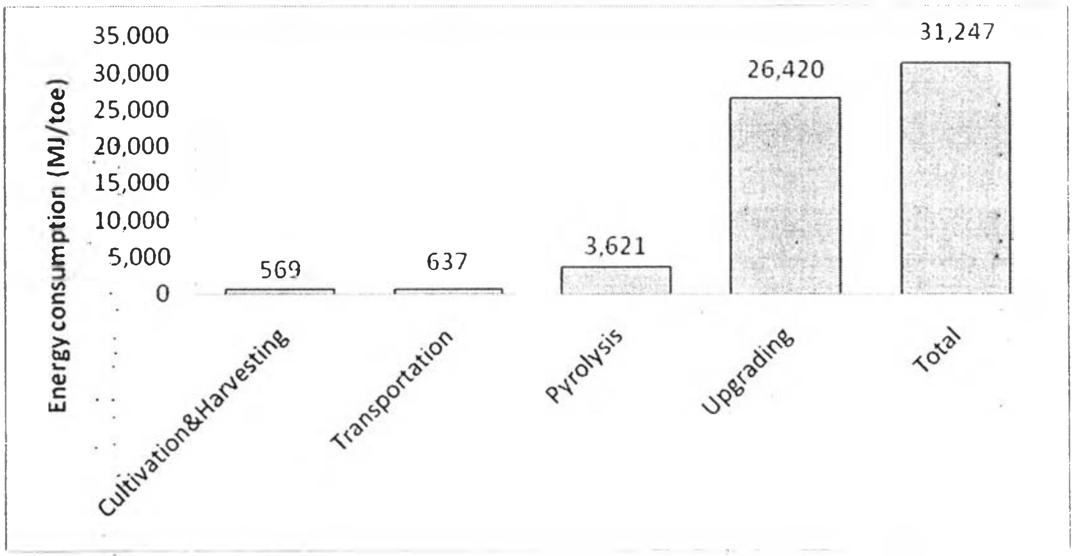


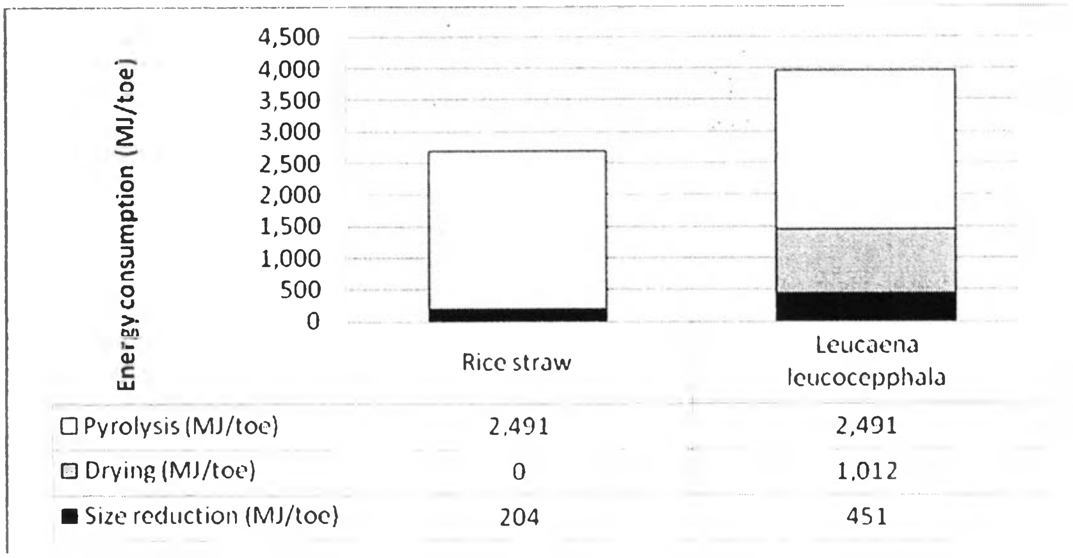
Figure 4.10 Life cycle energy consumption of 1 toe bio-oil production from *leucaena leucocepphala.*

The result show that the production of 1 toe of bio-oil from *leucaena leucocepphala* required the total energy input of 31.25 GJ per 1 toe bio-oil production. The energy usage in the upgrading stage is highest which accounts for 84.55% of total energy input. The energy usage in pyrolysis stage is the second, accounting for 11.59%, which mainly came from the use of electricity. The transportation and cultivating/harvesting stages are shown to consume relatively low energy in the life cycle, 2.04% and 1.82%, respectively for *leucaena leucocepphala.*

The results from Figure 4.7 - 4.11 also show that the transportation of rice straw for Case 1 shows the highest energy consumption in transportation stage because of the long distance of transportation. Moreover, when comparing the same distance of transportation but different in feedstock. The results show that transport of *leucaena leucocepphala* consumes higher energy consumption than rice straw based on the same distance (Case 2) due to the lower load during transportation.

4.4.2 Net Energy Ration (NER)

Figure 4.12 represents the comparison between the total energy output and energy input for various cases of feedstocks. For rice straw as a waste case (W), the NER of 1.39 and 1.42 are achieved for Case 1 (C1) and Case 2 (C2), respectively. For rice straw as a by-product case (BP), the NER of 1.36 and 1.39 are achieved for Case 1 (C1) and Case 2 (C2), respectively. For *leucaena leucocepphala*, NER of 1.35 can be achieved indicating a net energy gain for both feedstocks. The result from energy analysis also shows the NER of bio-oil production from *leucaena leucocepphala* has the lowest energy efficiency. This is explained by the fact that a large amount of energy was required for *leucaena leucocepphala* drying prior to pyrolysis while for rice straw drying, there was no additional energy required because the rice straw was dried by sun light. The energy consumption results are shown in Figure 4.11.



	Rice straw	Leucaena leucocepphala
☐ Pyrolysis (MJ/toe)	2,491	2,491
▨ Drying (MJ/toe)	0	1,012
■ Size reduction (MJ/toe)	204	451

Figure 4.11 Comparison of energy consumption (MJ/toe bio-oil) in pyrolysis stage.

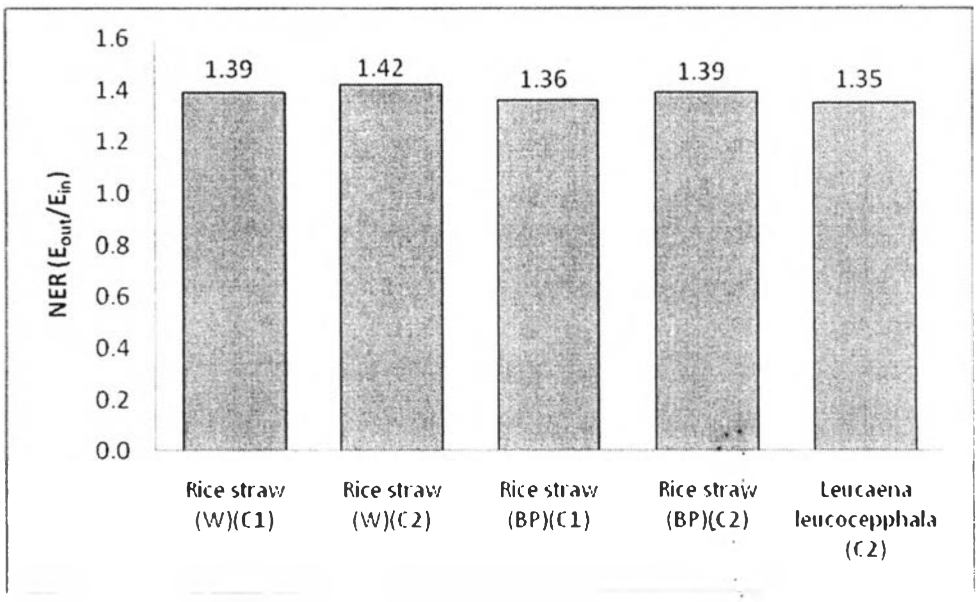


Figure 4.12 The comparison of NER based on 1 toe bio-oil production for various assumptions of the base case.

However, the results from the section 4.4.1 indicate that large amount of energy consumption is spent in the upgrading process. The energy usage in this stage came from electricity (25%) and steam from burning hard wood (85%). The energy efficiency ratio (NER) would be higher by improving energy usage in this stage. Thus, two new alternatives were created and evaluated in order to examine the possible effects on the NER. The comparison of energy consumption in upgrading process between the base case and two new design alternatives is shown in Figure 4.13 and the comparison of life cycle energy efficiency in term of NER is shown in Figure 4.14.

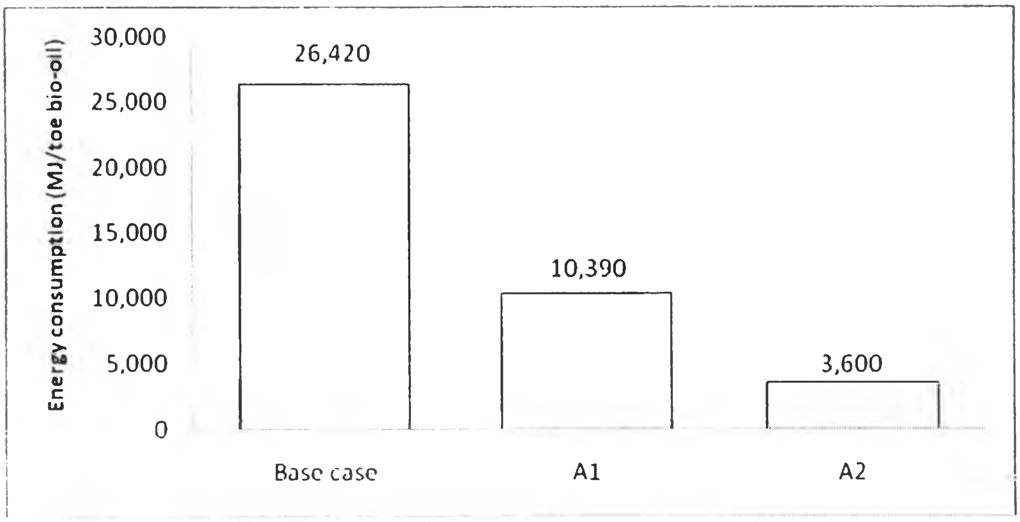


Figure 4.13 Comparison of energy consumption (MJ/toe bio-oil) in upgrading process between the Base case and Alternatives based on 1 toe of bio-oil production (A1: Alternative-1, A2: Alternative-2).

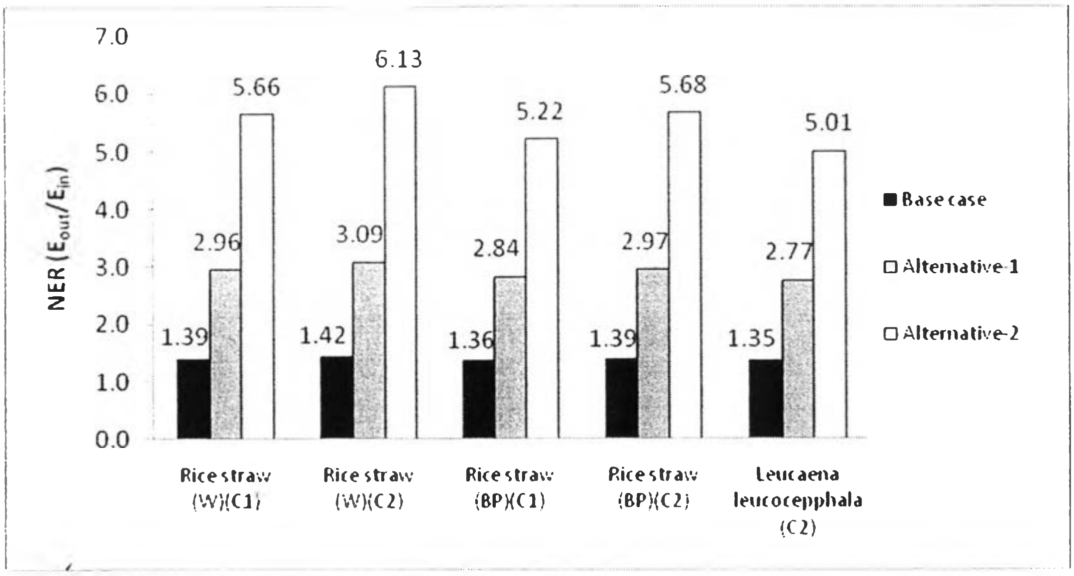
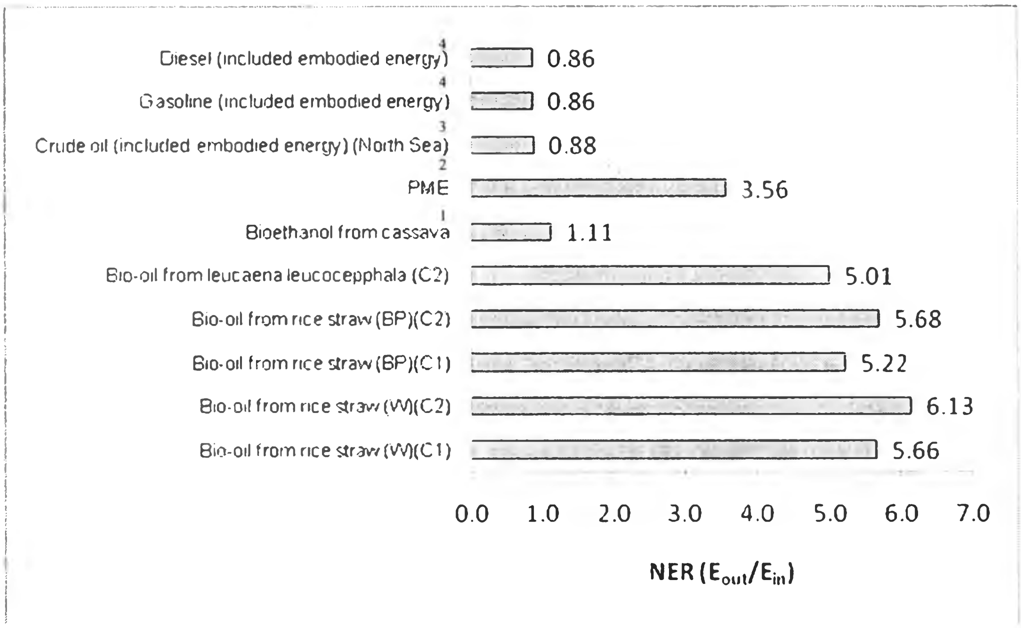


Figure 4.14 Comparison of net energy ratio from bio-oil conversion process between the Base case and Alternatives based on 1 toe of bio-oil production.

The results shown in Figure 4.13 indicate that if the heat integration and heat recovery of the upgrading process are applied, the total energy consumption would reduce by seven times from the base case design. This reflects 60.67% and

86.37% reduction from the base case design for A1 and A2, respectively. Figure 4.14 clearly shows that the new design alternatives are more energy effective than the base case. Alternative-2 is the most energy effective design with an increase in the value of NER of 307% and 332% for rice straw as a waste case for Case 1 and Case 2, respectively, and 284% and 309% for rice straw as a by product case for Case 1 and Case 2, respectively, and 270% higher than the base case design for *leucaena leucocepphala*. The comparison of NER of conventional fuels and biofuels are compared with Alternative-2 of this study based on 1 toe of fuels production as shown in Figure 4.15. The NER is approximately fourth times when comparing with the Base case design in all case of feedstocks.



1.Papong and Malakul, 2010 2. Papong *et al.*, 2010, 3. Simapro data base, 4. PTTRIT

Figure 4.15 Comparison of NER between bio-oil production from Alternative-2 and conventional fuels and biofuels based on 1 toe of fuels.

When comparing the NER of the bio-oil (Alternative-2) with other fuels, the results show that, the bio-oil is more energy efficient than petroleum-based fuels such as crude oil from North Sea, gasoline and diesel. A recent study conducted by Papong and Malakul (2010) on the energy analysis of bioethanol production from cassava with the utilization of co-products in Thailand obtained the NER of 1.11, which is much less than that of bio-oil in our study. The NER of bioethanol is quite small due to the use of coal for power and steam production in the bioethanol plants. When comparing with the palm methyl ester (PME) in Papong *et al.* (2010), the bio-oil productions are more energy effective with the higher NER than the PME because PME consumed a lot of energy which mainly came from the use of methanol in conversion stage and also N-fertilizer usage in palm oil plantation stage.

4.5 Overall Life Cycle Impact Assessment

A life cycle impact assessment (LCIA) is used to evaluate the environmental impact in various categories. After performing the life cycle inventory analysis (LCI) of the base case design of bio-oil production from rice straw and *leucaena leucocephala* using SimaPro 7.0, CML 2 baseline 2000 method was then utilized to evaluate the environmental impacts.

4.5.1 LCIA Results of the Base Case Design

The results of the base case analysis are shown in Tables 4.12 □ 4.16.The life-cycle environmental impact assessment covering cultivation and harvesting, transportation pyrolysis bio-oil and upgrading system from two feedstocks of this study shows that the bio-oil upgrading stage has the highest environmental impact in almost all impact categories such as global warming or greenhouse gas (GHG), acidification, eutrophication, and human toxicity categories, except bio-oil production from *leucaena leucocephala.* The highest GHG emissions come from pyrolysis stage.

Table 4.12 Average percent contribution to environmental impacts in 1 toe bio-oil production from rice straw as a waste case for Case 1

(Unit: %)

Process	GWP	AP	EP	HTP
Cultivation & Harvest	0.33	0.35	0.25	0.80
Transportation	21.10	3.18	1.26	5.62
Pyrolysis	27.77	14.40	7.05	0.21
Upgrading	**50.80**	**82.07**	**91.44**	**93.37**

Table 4.13 Average percent contribution to environmental impacts in 1 toe bio-oil production from rice straw as a waste case for Case 2

(Unit: %)

Process	GWP	AP	EP	HTP
Cultivation & Harvest	0.39	0.32	0.03	0.85
Transportation	5.82	0.64	0.25	1.16
Pyrolysis	33.32	14.78	7.38	0.22
Upgrading	**60.47**	**84.26**	**92.34**	**97.77**

Table 4.14 Average percent contribution to environmental impacts in 1 toe bio-oil production from rice straw as a by product case for Case 1

(Unit: %)

Process	GWP	AP	EP	HTP
Cultivation & Harvest	3.06	3.07	1.49	1.35
Transportation	20.52	3.09	1.25	5.59
Pyrolysis	27.15	14.01	6.97	0.20
Upgrading	**49.27**	**79.83**	**90.29**	**92.86**

Table 4.15 Average percent contribution to environmental impacts in 1 toe bio-oil production from rice straw as a by product case for Case 2

(Unit: %)

Process	GWP	AP	EP	HTP
Cultivation & Harvest	3.36	3.03	1.52	1.41
Transportation	5.63	0.63	0.25	1.15
Pyrolysis	32.23	14.36	6.34	0.22
Upgrading	**58.51**	**81.98**	**91.89**	**97.22**

Table 4.16 Average percent contribution to environmental impacts in 1 toe bio-oil production from *leucaena leucocepphala* for Case 2

(Unit: %)

Process	GWP	AP	EP	HTP
Cultivation & Harvest	0.76	1.39	0.45	1.66
Transportation	7.58	1.09	0.49	2.50
Pyrolysis	**56.18**	32.74	17.86	0.61
Upgrading	35.48	**64.78**	**81.20**	**95.23**

According to the study on various impacts (global warming, eutrophication, acidification and human toxicity) resulting from the production of bio-oil from rice straw, it is found that the process of upgrading has the most influence upon the environment for all four cases. For bio-oil production from *leucaena leucocepphala*, the highest GWP is come from pyrolysis stage due to the electricity consumption of oven, which used for *leucaena leucocepphala* drying. The results of all four impact categories are summarized as shown in Figure 4.16 □ 4.19.

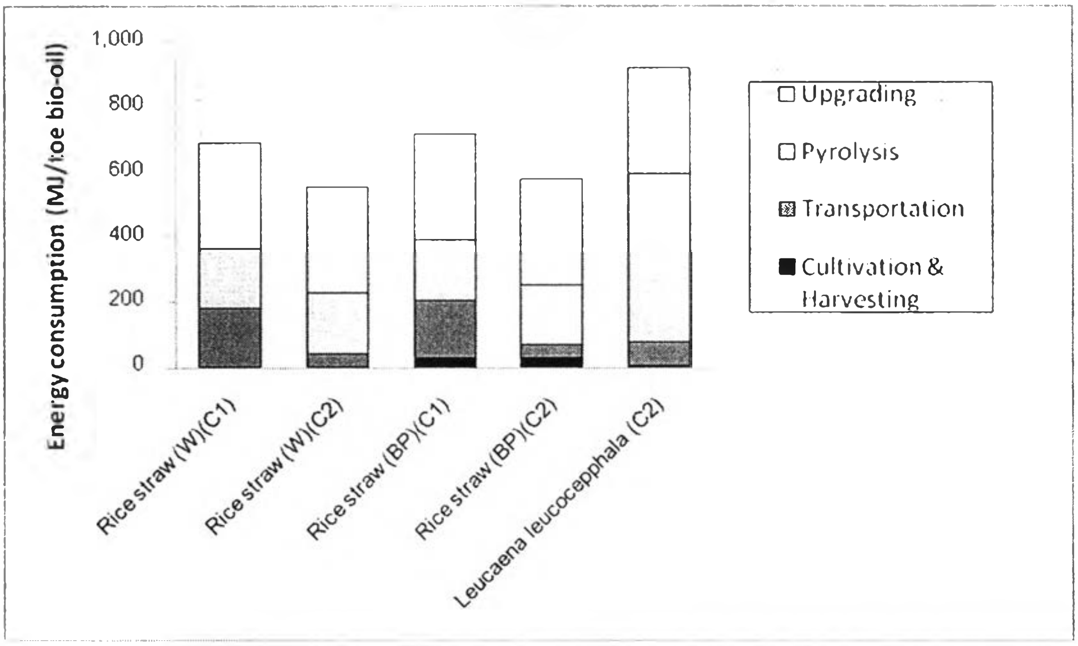


Figure 4.16 Distribution of GWP based on 1 toe bio-oil production for various cases of feedstocks.

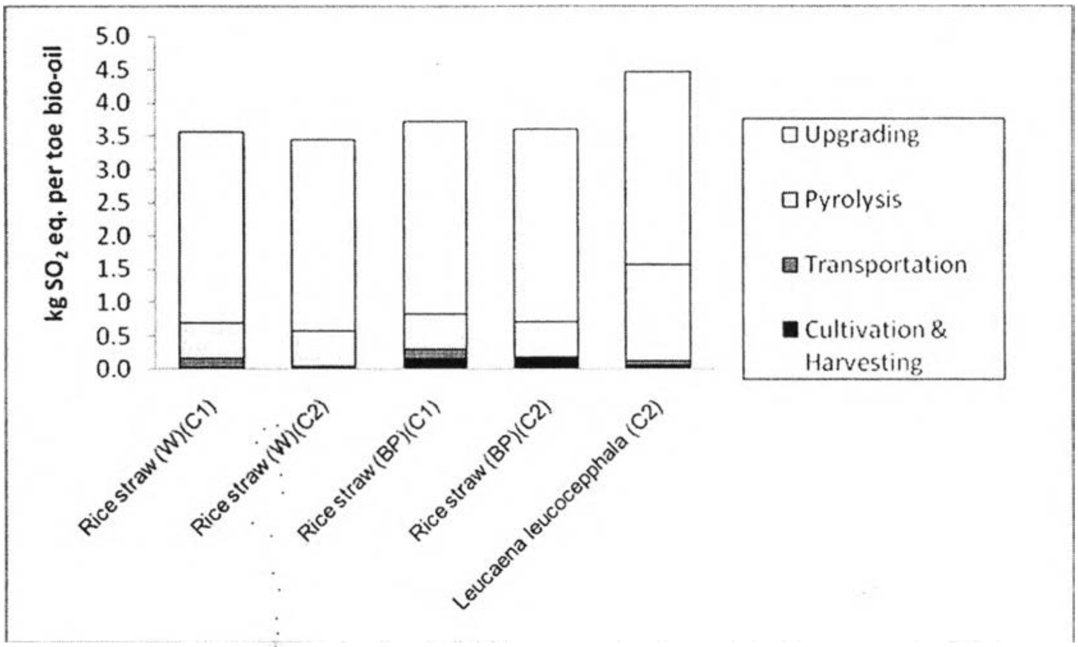


Figure 4.17 Distribution of AP based on 1 toe bio-oil production for various cases of feedstocks.

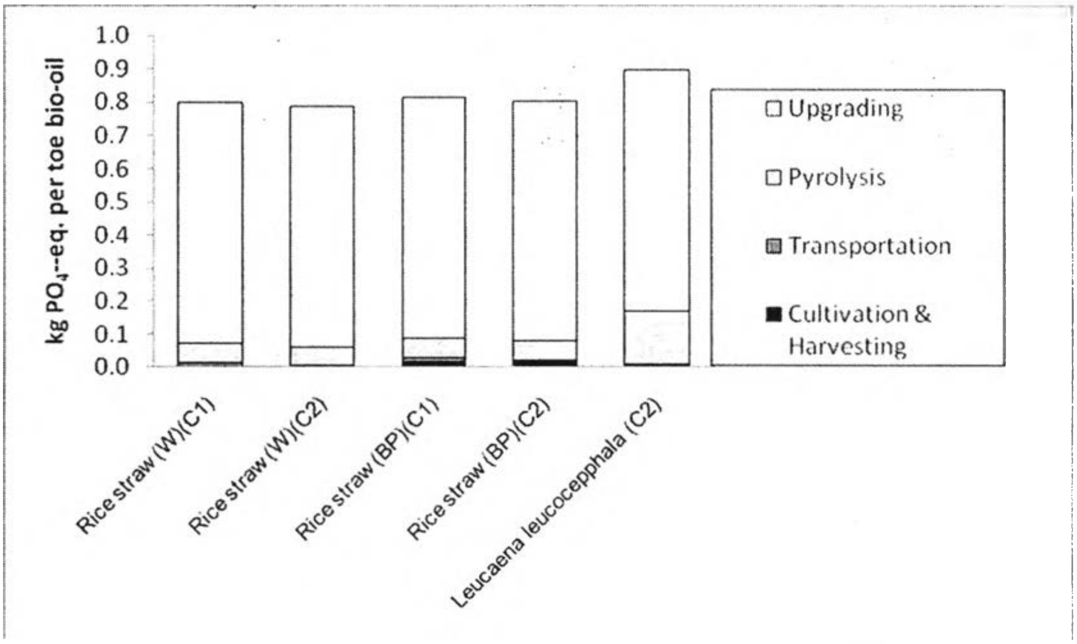


Figure 4.18 Distribution of EP based on 1 toe bio-oil production for various cases of feedstocks.

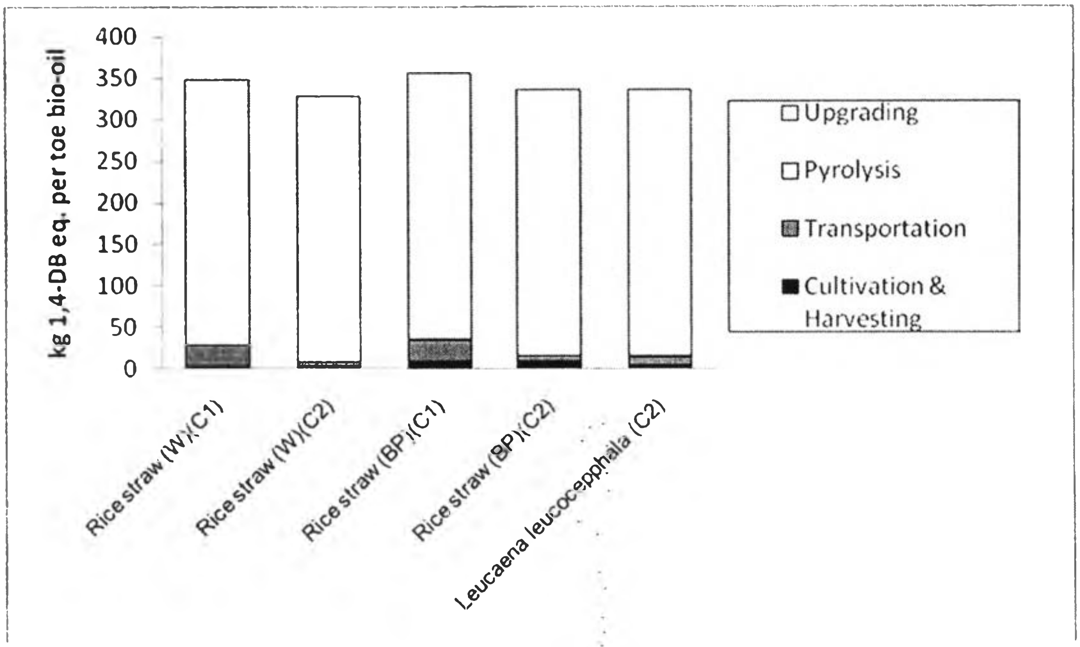
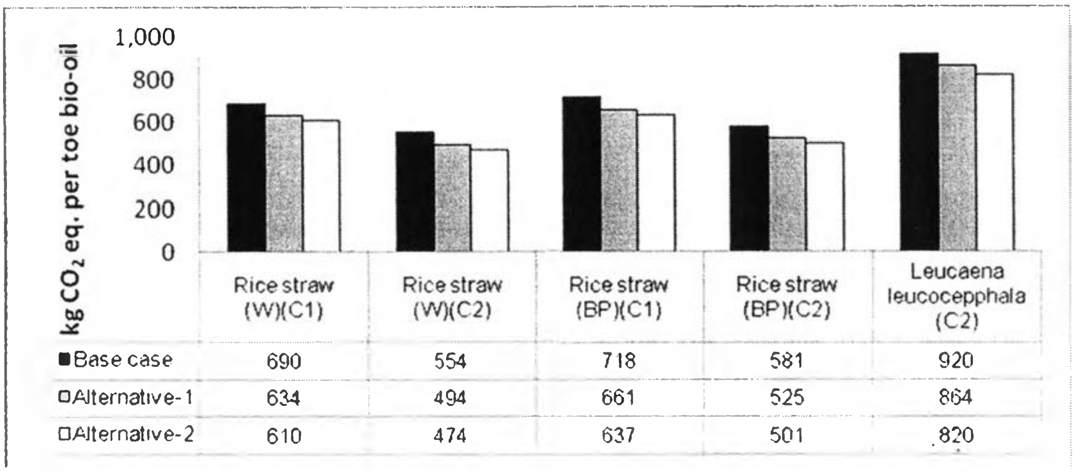


Figure 4.19 Distribution of HTP based on 1 toe bio-oil production for various cases of feedstocks.

In concluding, the process of upgrading has had the most influence on the environmental impacts, except the greenhouse gas emission from bio-oil production from *leucaena leucocephala*. It is interesting to note here that the energy consumption is higher in upgrading stage than in pyrolysis stage and the highest greenhouse gas emissions are from electricity (85% of energy usage in upgrading stage come from hot steam from burning hard wood). The before one should pay more attention to the use of electricity together with the steam in bio-oil production. In this aspect, the present study suggests two alternative designs that can reduce the impact in bio-oil production.

4.5.2 LCIA Result of Design Alternatives

With regard to global warming potential (GWP as CO_2-equivalent), Alternative-1 (A1) and Alternative-2 (A2) have shown to reduce the greenhouse gas (GHG) emission in both of feedstocks as shown in Figures 4.20.



	Rice straw (W)(C1)	Rice straw (W)(C2)	Rice straw (BP)(C1)	Rice straw (BP)(C2)	Leucaena leucocepphala (C2)
■ Base case	690	554	718	581	920
▨ Alternative-1	634	494	661	525	864
□ Alternative-2	610	474	637	501	820

Figure 4.20 Comparison of the GWP (kgCO_2-equivalent) generated from bio-oil conversion process between the base case and alternatives per 1 toe of bio-oil.

From Figure 4.20, it can be seen that bio-oil produced from *leucaena leucocephala* has shown to have the highest GHG emissions in this study. The high contribution comes from the intense use of electricity for *leucaena leucocephala* drying in pyrolysis stage. The comparison of bio-oil produced from rice straw between Case 1 and Case 2 shows that Case 2 has less GHG emission than Case 1 due to the shorter distance for transportation which uses less diesel consumption. When focusing on bio-oil production as a waste case (Case 1) and by-product case (Case 1), the result illustrates that by-product case has higher GHG emission than the waste case which comes from diesel and fertilizer used in cultivation stage.

Among various design alternative, Alternative-2 has been shown to reduce GHG emission (kg CO_2 equivalent/kg bio-oil) for both of rice straw and *leucaena leucocephala*. It reflects 11.59% and 14.44% reduction from the Base case design for rice straw as a waste case for Case 1 and Case 2, respectively, and 11.28% and 13.77% for rice straw as a by-product case for Case 1 and Case 2, respectively. The 10.87% reduction is obtained for bio-oil production from *leucaena leucocephala*. The reduction of greenhouse gas emission comes from less energy consumption compared with the Base case design. This is attributed to the lower steam consumption in the upgrading stage, where the heat duty is decreased.

For other impact categories such as acidification, eutrophication, and human toxicity, the impacts observed in Alternative-1 and Alternative-2 are also lower than Base case design as shown in Figures 4.21, 4.22 and 4.23.

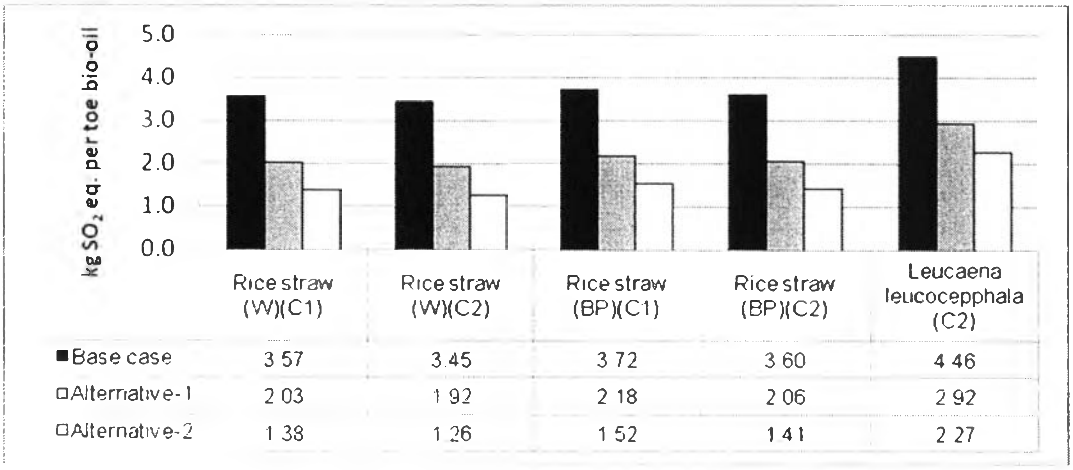


Figure 4.21 Comparison of the AP (kgSO$_2$-equivalent) generated from bio-oil conversion process between the Base case and alternatives per 1 toe of bio-oil.

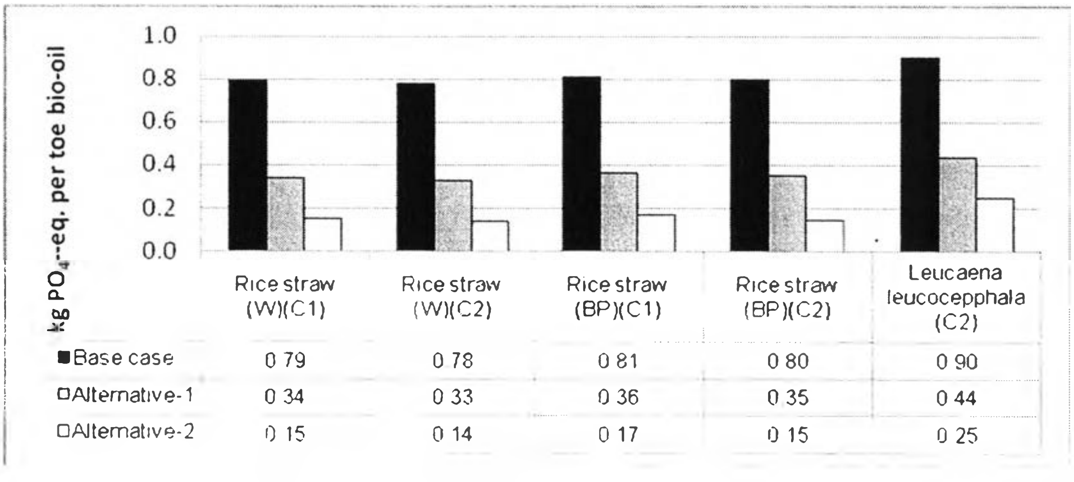


Figure 4.22 Comparison of the eutrophication (kgPO$_4$--equivalent) generated from bio-oil conversion process between the Base case and Alternatives per 1 toe of bio-oil.

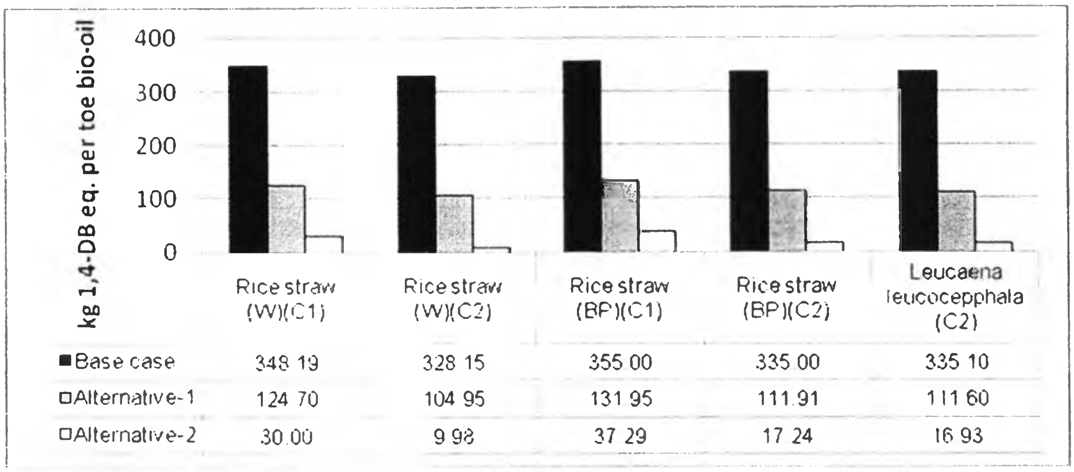


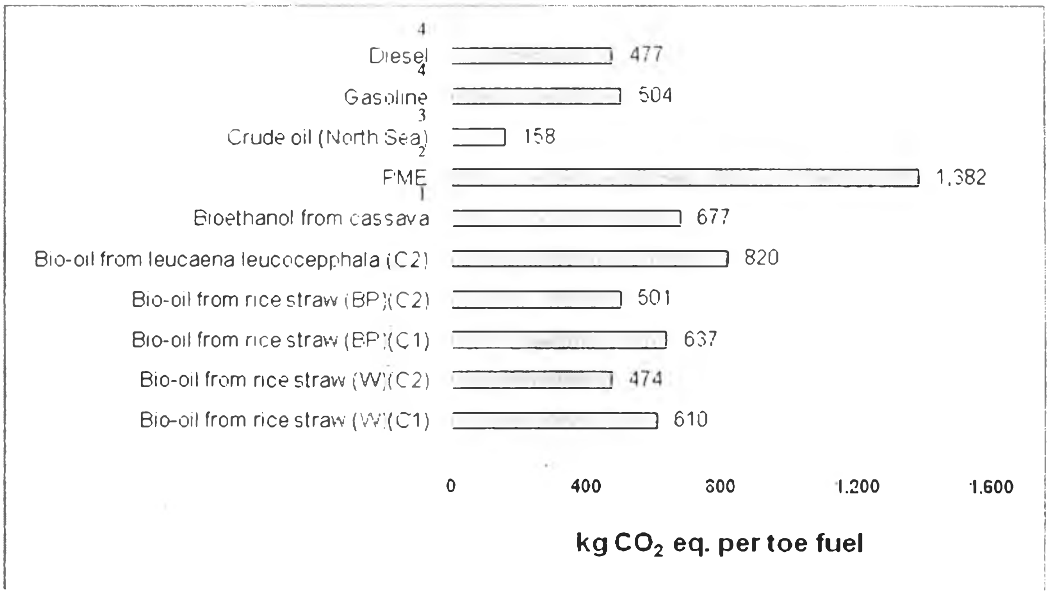
Figure 4.23 Comparison of the human toxicity (kg 1,4-DB equivalent) generated from bio-oil conversion process between the Base case and Alternatives per 1 toe of bio-oil.

From the four impact categories above, it could be summarized that the new design alternatives are more environmental friendly than the base case, Alternative-2 has been shown to be the most environmental friendly with the highest reduction of all impact categories. The reduction is mainly through the lower energy consumption in the upgrading stage.

4.5.3 Environmental Comparison with Other Fuels

The assessments of four impacts categories are made to compare the impact of bio-oil production in this study and other fuels. The results of global warming potential (GWP), acidification, eutrophication and human toxicity potential are displayed in Figure 4.24–4.27, respectively.

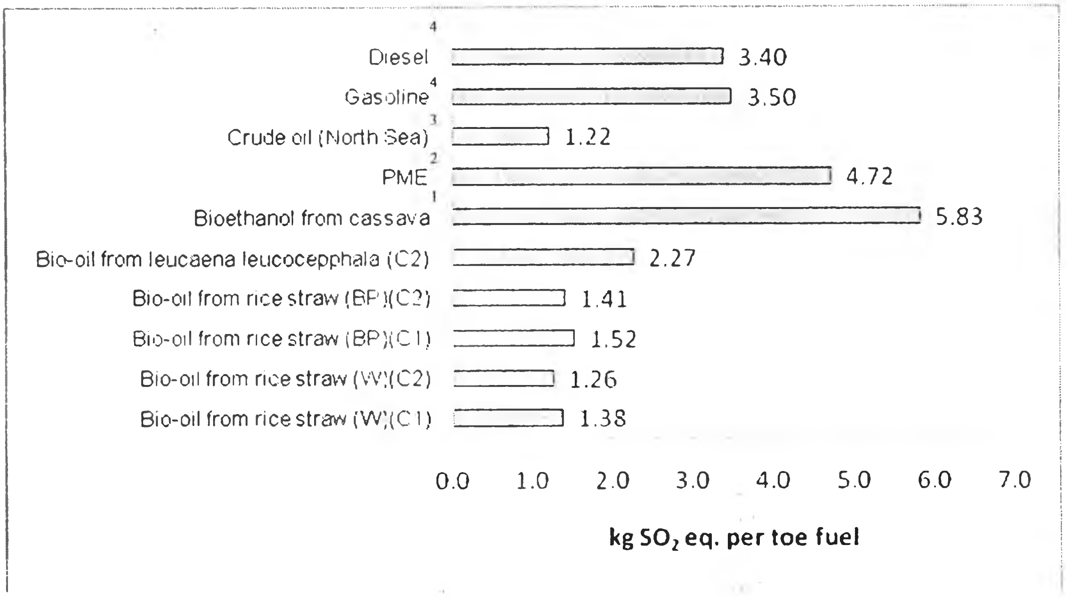
Considering the contributions to greenhouse gases (GHG), the use of bio-oil can reduce greenhouse gas emissions when compared to PME. The large CO_2 emission of PME comes from steam and power utilization. The GHG emission of PME is approximately 2.6 times higher than that of bio-oil in the fuel production phase. The bioethanol from cassava produces higher GWP than the bio-oil, except bio-oil production from *leucaena leucocephala*. When comparing with petroleum fuels, the result shows that GHG emissions in the fuel production phase of bio-oil for Case 1 are shown to be slightly higher.



1. Papong and Malakul, 2010 2. Papong *et al.*, 2010. 3. Simapro data base, 4. PTTRIT

Figure 4.24 Comparison of GWP from bio-oil conversion process (Alternative 2) between conventional fuels and biofuels based on 1 toe of fuels production.

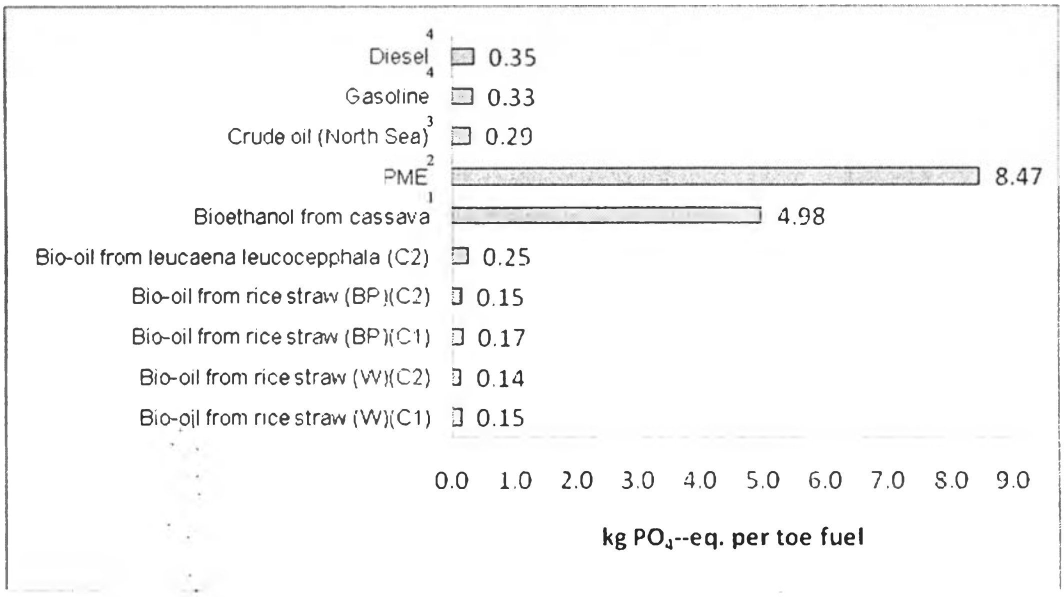
Regarding acidification results shown in Figure 4.25, bioethanol from cassava shows the highest impact which this is due to burning coal in the bioethanol conversion stage. Bio-oil has lower impact than PME because the less use of N-fertilizer and the allocation in rice cultivation stage resulting in lower ammonium emission than palm oil plantation. When comparing to petroleum fuels, the contributions from bio-oil are lower than diesel and gasoline but still higher than raw crude oil.



1. Papong and Malakul, 2010 2. Papong *et al.*, 2010, 3. Simapro data base, 4. PTTRIT

Figure 4.25 Comparison of AP from bio-oil conversion process (Alternative-2) between conventional fuels and biofuels based on 1 toe of fuels production.

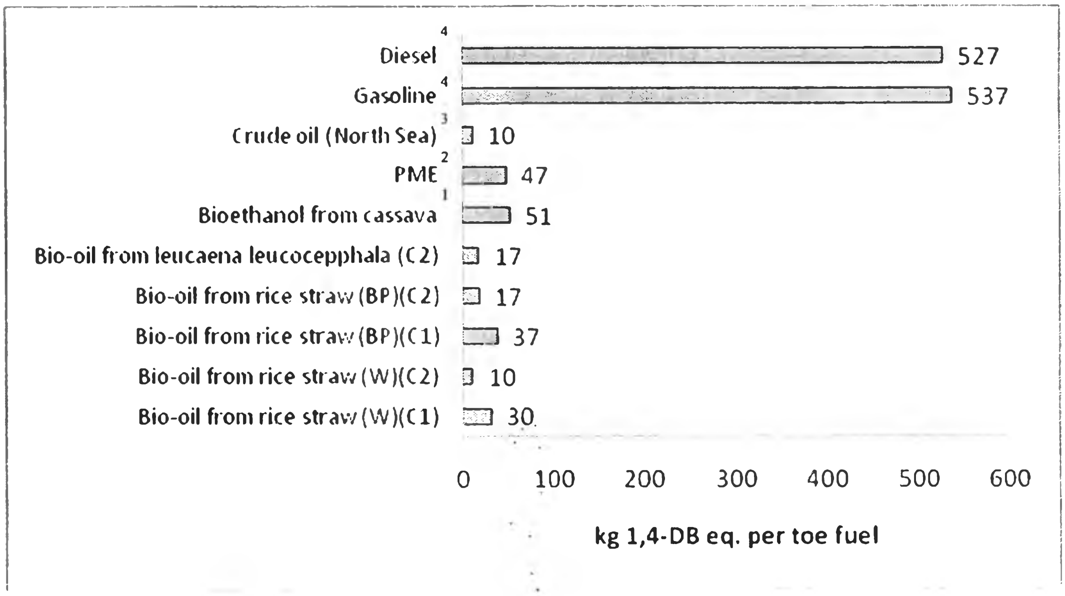
The comparison of eutrophication potential is described in Figure 4.26. In most cases, the impact of eutrophication emissions can be attributed directly to the agricultural production process. Therefore, the production of raw materials such as palm oil for PME and cassava for bioethanol could contribute to this issue. According to our results, there is almost no contribution from agricultural activities, because there was no agricultural waste or emission produced from rice straw for waste case and *leucaena leucocepphala* plantation. For rice straw as a by-product case, the result shows slightly higher impact but still lower than petroleum fuels.



1. Papong and Malakul, 2010 2. Papong *et al.*, 2010, 3. Simapro data base, 4. PTTRIT

Figure 4.26 Comparison of EP from bio-oil conversion process (Alternative-2) between conventional fuels and biofuels based on 1 toe of fuels production.

From to Figure 4.27, it can be seen that almost all human toxicity impact in our study comes from steam combustion in the upgrading stage. In this category, the result does show environmental benefits when compares with PME and bioethanol, however, it presents a large advantage when compares with diesel and gasoline.



1. Papong and Malakul, 2010 2. Papong *et al.*, 2010, 3. Simapro data base, 4. PTTRIT

Figure 4.27 Comparison of HTP from bio-oil conversion process (Alternative-2) between conventional fuels and biofuels based on 1 toe of fuels production.