CHAPTER IV

RESULTS AND DISCUSSION

4.1 Feedstocks and Composition

Main feedstocks used for ethanol production in Thailand are cassava and molasses. Total production of ethanol is approximately 3 Mliter/day. Table 4.1 below shows each ethanol plant and capacity in Thailand 2011.

Feedstocks used for generate bioethanol production are cassava rhizome, corn stover and sugarcane bagasse because they have high amount of lignocellulosic biomass to produce bioethanol and close to real plants that can be easily adapted for use it. Their agricultural residues in Thailand 2011 are shown in Table 4.2.

Table 4.1 Total ethanol plants in Thailand 2011 (http://www.dede.go.th)

No	Plant	Site	Capacity (l/d)	Feedstocks
1	Pawn Wi Lai Inter Group Trading	Ayuddhya	25,000	Molasses/Fresh Cassava Tubers
2	Thai Agro Energy	Suphanburi	150,000	Molasses
3	Thai Alcohol	NakornPathom	200,000	Molasses
4	Khon Kaen Alcohol	Khon Kaen	150,000	Molasses/(Starch liquid)
5	Thai Nguan Ethanol	Khon Kaen	130,000	Fresh Cassava Tubers/(Cassava Chips)
6	Thai Sugar Ethanol	Kanchanaburi	100,000	Molasses
7	KI Ethanol	Nakorn Ratchsima	100,000	Molasses
8	Petro Green (Kanlaseen)	Kanlaseen	230,000	Molasses/(sugarcane juice)
9	Petro Green (Chaiyapoom)	Chaiyapoom	230,000	Molasses/(sugarcane juice)
10	EkrathPattana	Nakorn Swan	230,000	Molasses

No	Plant	Site	Capacity (l/d)	Feedstocks
11	Thai Rung Rueng Energy	Saraburi	120,000	Molasses/(Baggase)
12	Ratchburi Ethanol	Ratchburi	150,000	Cassava Chips/Molasses
13	ES Power	Sakaew	150,000	Molasses/Cassava Chips
14	Maesawd Clean Energy	Tak	200,000	Sugarcane Juice
15	SupThip	Lopburi	200,000	Cassava Chips
16	TaiPing Ethanol	Sakaew	150,000	Fresh Cassava Tubers/Cassava Chips)
17	PSB Starch Production	Chonburi	150,000	Fresh Cassava Tubers/Cassava Chips)
18	Petro Green (DanChang)	Suphanburi	200,000	Molasses/(sugarcane juice)
19	Khon Kaen Alcohol (Boh Ploy)	Kanchanaburi	200,000	Molasses/(sugarcane juice)
	Total Production Capacity		**3,065,000**	

Table 4.2 Agricultural residues in Thailand 2011 (http://www.dede.go.th/)

Products	**Productions (Tons)**	**Residues**	**Available unused residues for energy (Tons)**	**Price of residues ($/kg)**
Cassava	21,912,400	Rhizome	1,335,999.02	0.0167[a]
Corn	4,816,650	Stover	2,878,622.71	0.0300[b]
Sugarcane	95,950,400	Bagasse	6,018,105.04	0.0100[c]

a: Jongpluenmpiti and Tangchaichit, 2012; b: http://www.dld.go.th/nspk_pkk/ac01.html; c: Pattaratierasakul 2010
1 dollar = 30 baht.

The chemical composition of their feedstocks based on dry basis (wt.%) from Thailand as shown in Table 4.3.

Table 4.3 Chemical composition of feedstocks in Thailand

Cassava rhizome (adapted from Pattiya *et al.*, 2010)

Composition	Content (wt.%)
Cellulose	29.93
Hemicellulose	42.73
Lignin	23.36
Ash	3.98

Corn stover (adapted from Chaiklangmuang *et al.*, 2011)

Composition	Content (wt.%)
Cellulose	48.93
Hemicellulose	20.46
Lignin	30.61

Sugarcane bagasse (adapted from Buaban *et al.*, 2010)

Composition	Content (wt.%)
Cellulose	45.86
Hemicellulose	28.84
Lignin	23.35
Ash	1.95

4.2 Process Design Description

The study of process design of bioethanol production from lignocellulosic biomass is based on National Renewable Energy Laboratory (NREL) in 2002 and 2011. (Aden *et al.*, 2002) studied bioethanol production of NREL 2002 process which consists of three main parts. The first part is pretreatment and hydrolysate conditioning. This part uses co-current dilute-acid (1.1% sulfuric acid) pretreatment to convert hemicellulose to soluble sugars which is mostly xylose. Glucan in the hemicellulose and a small portion of the cellulose are converted to glucose and some lignin is solubilized. Degradation products that occur in pretreatment reactions are furfural and hydroxymethyl furfural lead to decreasing performance in fermentation microorganisms. From reactor, streams are removed by flash drum after that they are sent to the solid-liquid separation separated liquid portion of the hydrolysate, containing sulfuric acid. This liquid is re-adjusted pH from 1 to 10 in overliming step using lime. The lime and sulfuric acid precipitated as gypsum. Overliming is a temperature and pH adjusting treatment designed to aid the conversion of hydrolysate to ethanol during fermentation not only limit the calcium concentration in solution to organism tolerant levels but also detoxify lignin-derived compounds. However, pH is still so high that the neutralization (reacidification) and precipitation of gypsum is needed in next processes and then the conditioned hydrolysate liquid is recombined with hydrolysate solids (cellulose) from solid-liquid separator and sent to saccharification and co-fermentation part.

The second part is saccharification and co-fermentation. It is the main part which enzymatic hydrolysis coupled with co-fermentation of the detoxified hydrolysate slurry is carried out in continuous hydrolysis tanks and anaerobic fermentation tanks in series. First saccharification is separated from the fermentation to raise temperature to help increase enzyme activity, reducing time and amount of enzyme loading. The enzyme used to saccharify the cellulose to glucose is cellulase enzyme that bought from enzyme manufacturer. Saccharified slurry is cooled to 41 °C and split 10% of it is fed to seed fermenters to produce inoculum and the other is sent to fermentation process.

For fermentation, the recombinant *Z.mobilis* bacterium is used as the biocatalyst, turn glucose and xylose from saccharified slurry to ethanol. The *Z.mobilis* is cultured in seed fermenters. Corn steep liquor (CSL) and diammonium phosphate (DAP) are both nitrogen sources required for *Z.mobilis* growth. The resulting beer is sent to product recovery.

The third part is product recovery. Distillation columns and molecular sieve are used to recover ethanol from raw fermenting beer and produce 99.5% pure ethanol for blending with gasoline. This process contains two distillation columns – the first one is a beer column, removing the dissolved CO_2 and most of the water, and the second one is rectification column that is used to rectify ethanol concentration to approach azeotropic composition. A mixture of nearly azeotropic water and ethanol is purified to 99.5% purity by using vapor-phase molecular sieve. Total chemical reactions and conversions of each part are given in the Appendix A.

(Humbird *et al.*, 2011) studied bioethanol production of NREL 2011 process. The main process is the same as (Aden *et al.*, 2002) but they change only overliming and conditioning section using ammonia conditioning instead of lime. So this work investigates both NREL 2002 and 2011 process to find high performance process design of bioethanol production.

4.3 Base Case Design of One Feedstock Case

4.3.1 <u>Process Specification of Base Case Design</u>

This work uses cassava rhizome and NREL 2002 process design to generate base case design. The target of ethanol production is 150,000 liter/day which is common plant's capacity in Thailand. The block flow diagram of ethanol production from cassava rhizome is shown in Figure 4.1 and the process design was generated by PROII 9.1 simulation program shown in Figure 4.2. In order to achieve the target of ethanol production, the amount of cassava rhizome should be used at least 467 tons/day, total fresh water consumption is 375 tons/day, gypsum waste produced from this process is about 23 tons/day, and the amount of sugar approximately 13% is lost to side reactions occurring at high pH or with the wet gypsum. The amount of solid waste, wastewater and waste gas from process is equal to 140, 440 and 234 tons/day respectively. The main process conditions are given in the Appendix B.

To satisfy the process, overall mass and energy balance for base case design are shown in Figure 4.3 and 4.4 respectively. All streams are used for calculation shown in Appendix D.

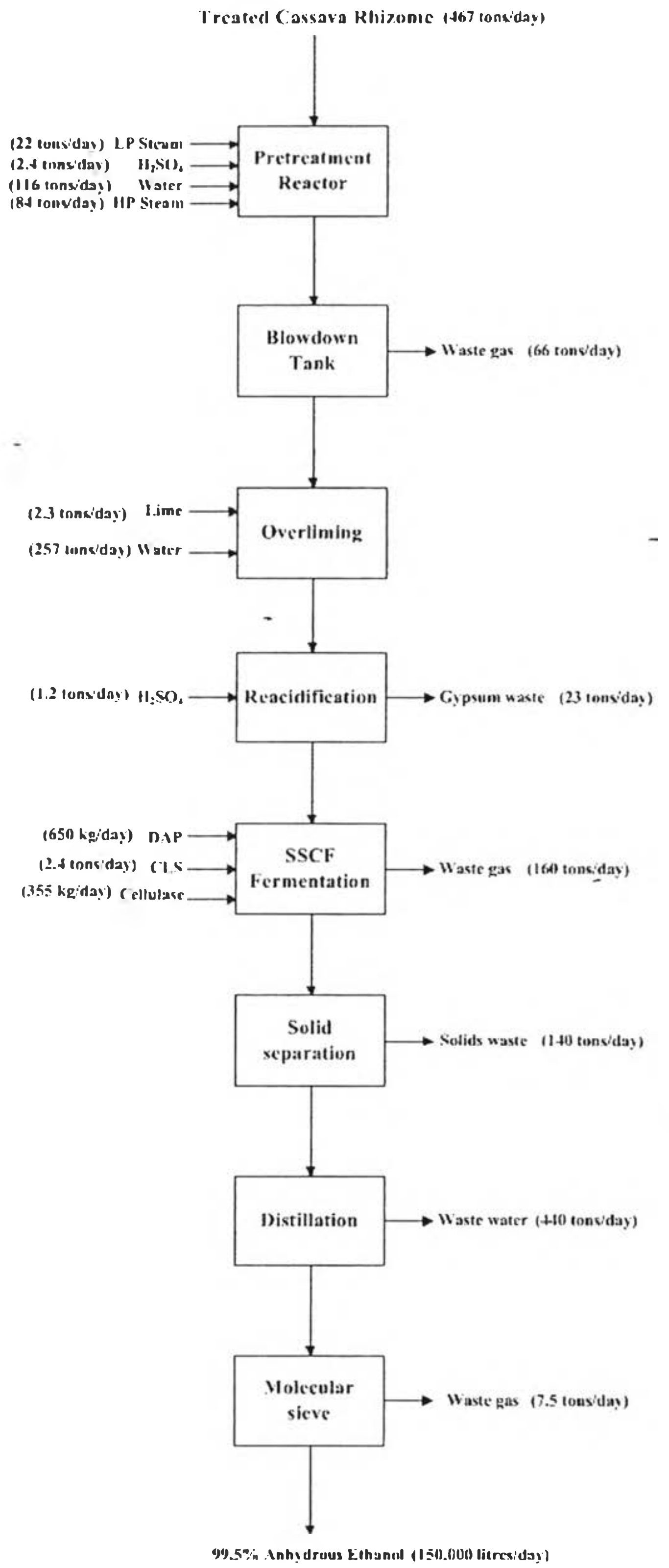

Figure 4.1 Block flow diagram of bioethanol production from cassava rhizome of base case.

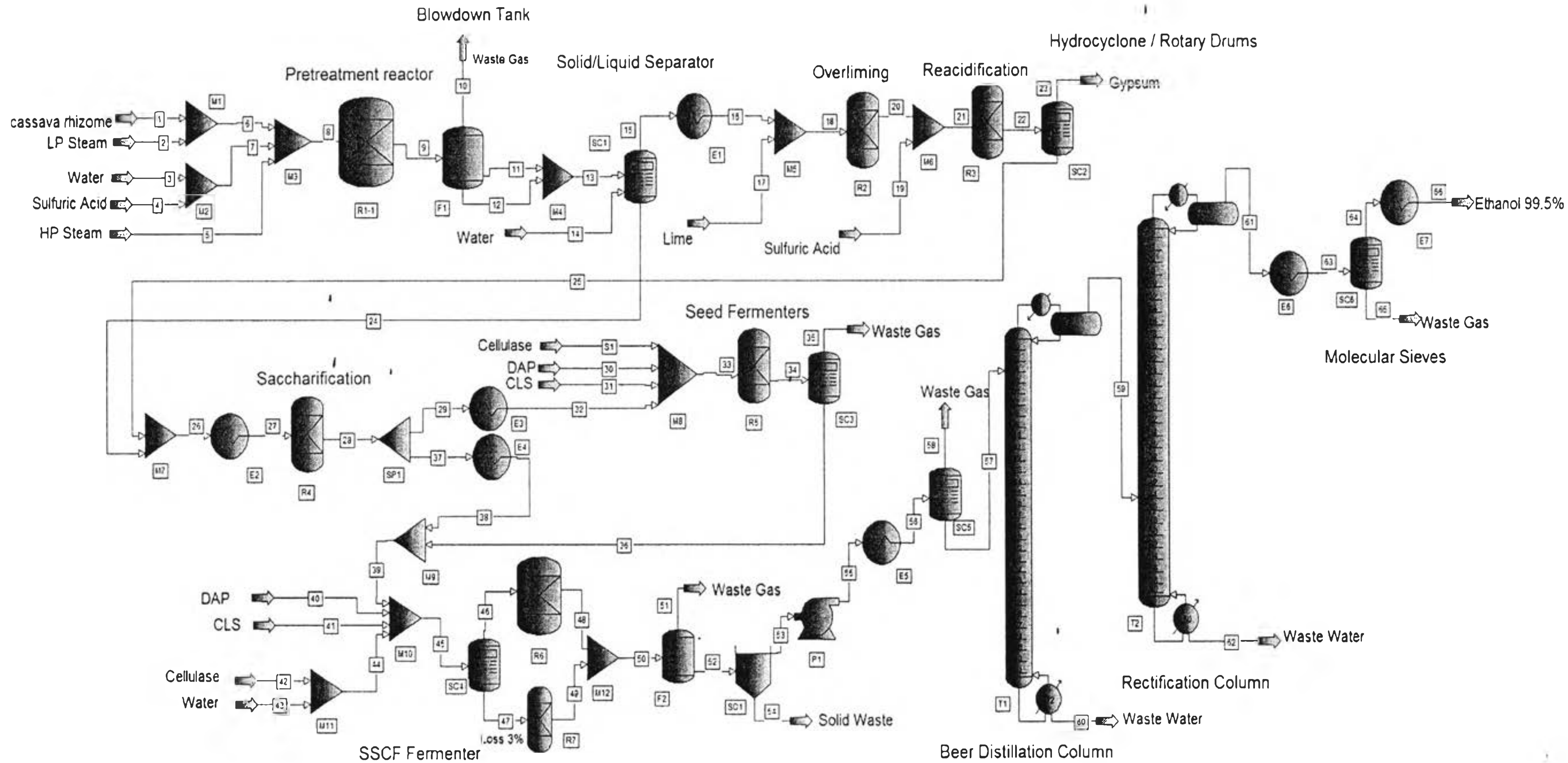

Figure 4.2 The process design of bioethanol production using cassava rhizome feedstock of base case design.

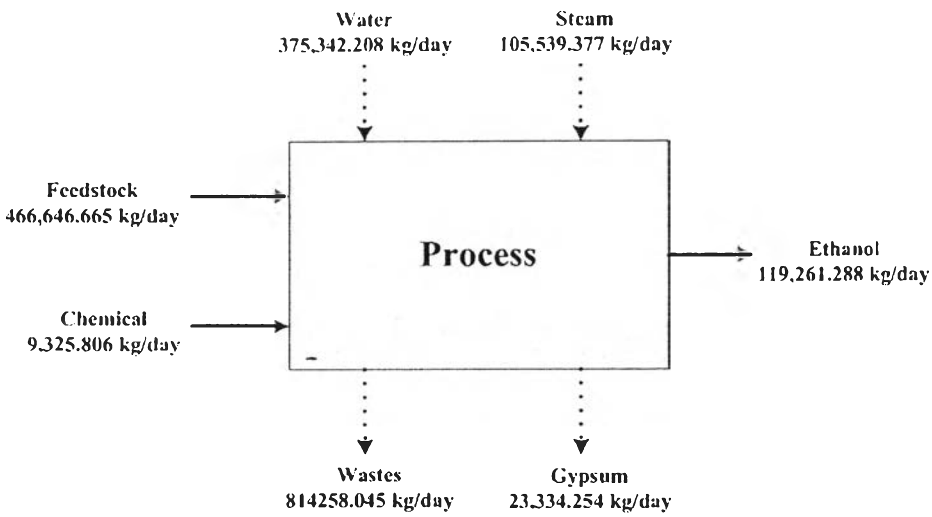

Figure 4.3 Overall mass balance of base case design.

Total mass flow entering the system is 956,854.055 kg/day and total mass flow leaving the system is 956,853.587 kg/day so the percent difference between input and output is 0.005%.

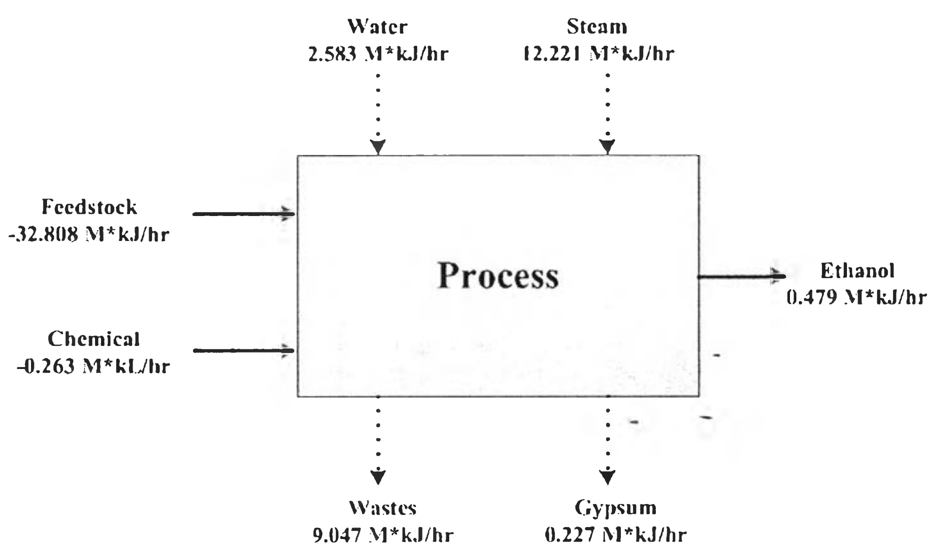

Figure 4.4 Overall energy balance of base case design.

Total energy flow entering the system is -18.267 M*kJ/hr and total energy flow leaving the system is 9.754 M*kJ/hr so the overall energy balance equals 28.021 M*kJ/hr.

4.3.2 Performance Criteria of Base Case Design

To investigate the bioethanol process in respect of investment, the economic evaluation by ECON software (Saengwirun, 2011) is used for analyzing total costs (raw materials cost, equipment cost, capital cost and operating cost) and profitability of process (rate of return, payback period and net present worth).

The information of raw materials, product and utility prices are given in the Appendix C. Total raw materials annual cost of base case design is about 4.97 M$/year, annual revenue of ethanol selling is about 39.22 M$/year for ethanol production 150,000 liter/day and total utility cost is about 6.11 M$/year. The sizing of equipment such as mixers, heat exchangers, reactors and distillation columns and purchase cost of equipment from ECON software are given in the Appendix C. Total equipment purchasing cost equals 24.72 M$.

4.3.2.1 Capital Cost of Base Case Design

Total capital investment cost of base case is 137.62 M$ that is divided into three main parts. The first part is direct cost including equipment purchasing cost, piping cost, electrical systems cost and etc. The second part is indirect cost including engineering and supervision cost, construction expenses and etc. The third part is working capital investment cost. All details are shown in Appendix C. The pie chart in Figure 4.5 shows breakdown of total capital investment cost and the highest cost is total direct cost section shared 71.15%. Total indirect cost and working capital cost section is 28.46% and 0.4% respectively.

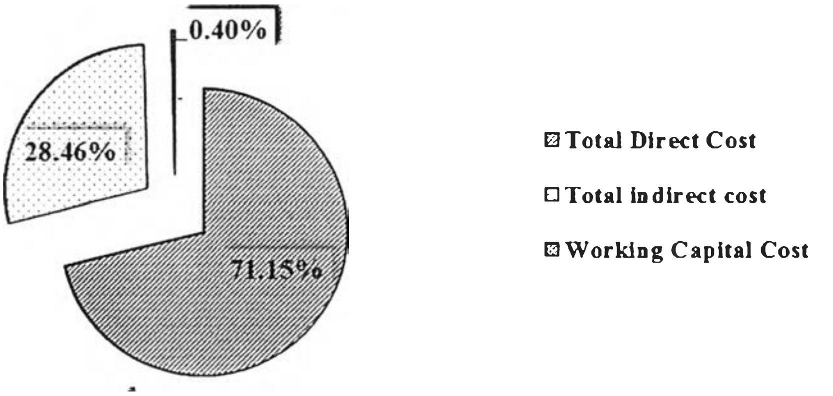

Figure 4.5 Breakdown of total capital investment cost of base case design.

From total direct cost section, this section is the highest cost that significant affected to investment cost of process. The direct costs are split into branch parts shown in Figure 4.6. So equipment costs, including purchase equipment delivered, is the largest portion that significant influence to process in term of high capital investment. Then equipment costs should be analysis that are divided into each main area to see further insight which area is high cost and it can reduce or not. The portion of equipment cost in main area in the process is shown in Figure 4.7.

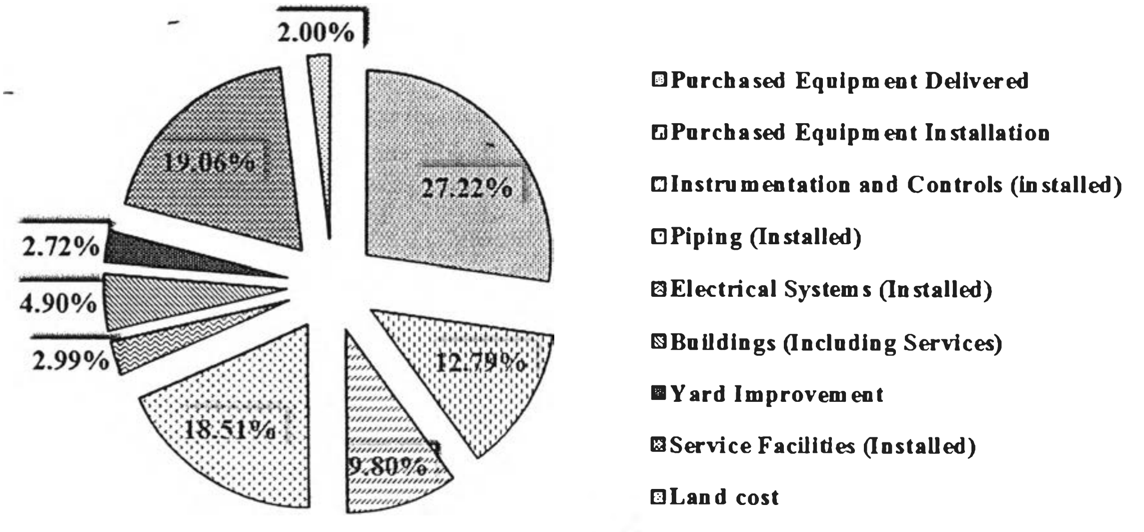

Figure 4.6 Breakdown of total direct cost section of base case design.

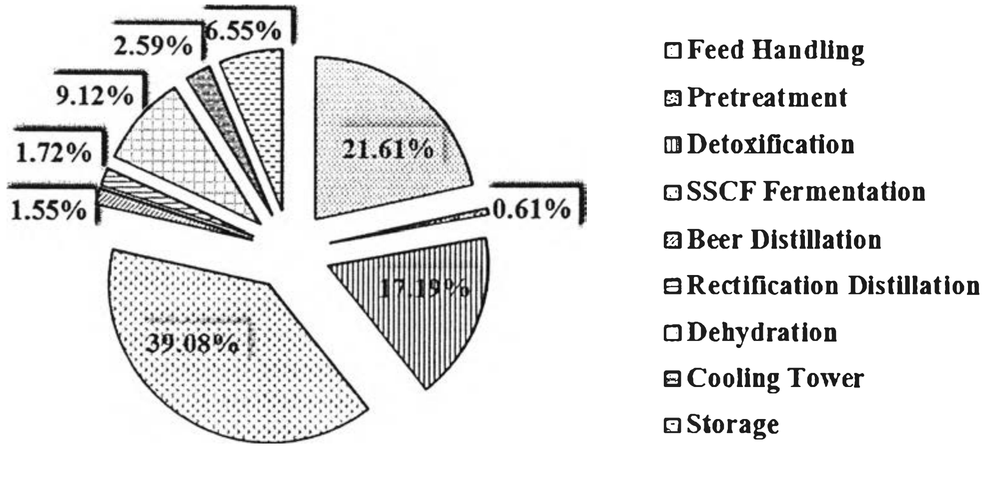

Figure 4.7 Equipment costs of each main area in the process of base case design.

From Figure 4.7, the highest portion is the SSCF fermentation part which part included three main units are saccharification, seed fermentation and fermentation unit and it is necessary to install into process because of ethanol production. The second high portion is feed handling part which cost used from NREL process. Focused on detoxification part, this part including overliming, reacidification and gypsum precipitation unit is third high portion section. It should be analysis in this part because not only high capital cost but this part used high amount of energy and water consumption and produced solid waste of gypsum.

4.3.2.2 Operating Cost of Base Case Design

Total operating cost of base case is 41.24 M$/year without depreciation factor that is divided into four main parts. The first part is variable costs including raw materials prices, utility costs, maintenance and repairs cost and etc. The second part is fixed charges including property taxes, insurance and so on. The third part is plant overhead cost including labor, supervision and maintenance cost. The fourth part is general expense including administration, distribution and selling, research and development cost. All details are shown in Appendix C. The pie chart in Figure 4.8 shows breakdown of total operating cost so the highest cost is variable cost section shared about 59.74%. The plant overhead, general expense, and fixed charges section are 16.66%, 13.55% and 10.04% respectively.

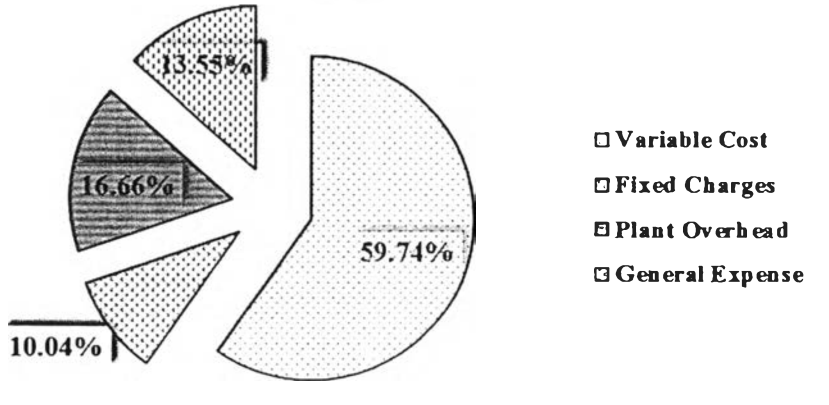

Figure 4.8 Breakdown of total operating cost of base case design.

According to variable cost section, this section is the highest cost that affected profitability of the process. The main variable costs are raw material prices and utility costs. They are split into small parts as shown in Figure 4.9 and 4.10 respectively.

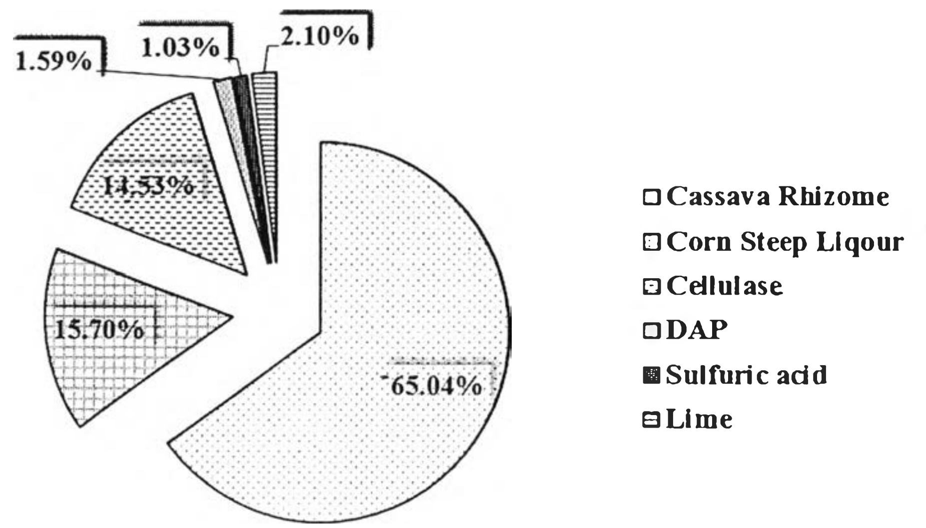

Figure 4.9 Breakdown of raw material prices of base case design.

From Figure 4.9, feedstock cost assumes more than half portion in raw material prices about 65.04%. Cassava rhizome feedstock is used for this process from agricultural waste of cassava production so the cost is very cheap but it is required a lot for ethanol production. Other high influence costs are corn steep liquor and cellulase shared about 15.70%, 14.53% respectively. Cellulase is enzyme used for convert cellulose to glucose and hemicellulose to xylose and corn steep liquor is nitrogen sources required for *Z.molibis* growth, all of these is necessary for the process; however, if the process performance is high enough, the required amount of raw materials will decrease; otherwise, cheaper raw materials is used instead.

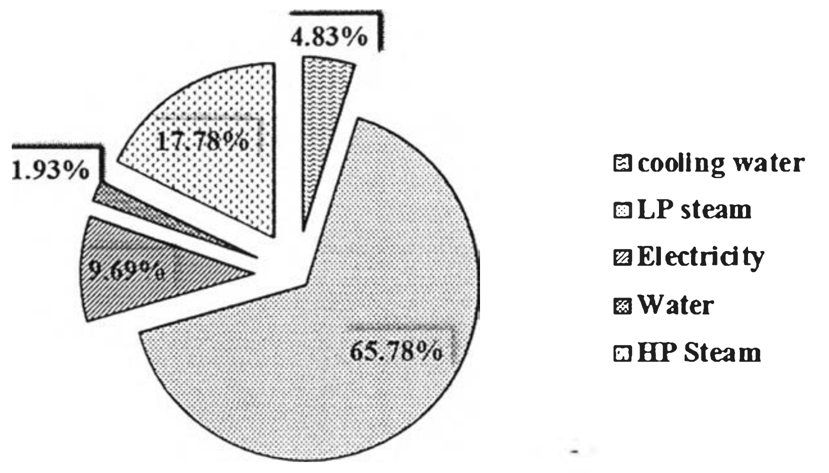

Figure 4.10 Breakdown of total utility costs of base case design.

From Figure 4.10, the main utility cost comes from low pressure steam about 65.78%. It is mainly used for pre-heat in reboiler of distillation columns. Other costs are high pressure stem used only for pre-heat of feedstock, cost of electricity mainly from cooling tower, feed handling and detoxification section including overliming and reacidification step (solid-liquid separator and hydrocyclone) and finally cost of cooling water used to cool stream in most of heat exchangers.

To reduce utility costs, the first option focused on steam (low and high pressure steam). It should be diminished someway such as heat integration or steam generation. The second one is electricity that should be lowered by lignin combustion process using solid waste to produce electricity and steam. The last one is water consumption that should be reduced by water recycle. These criteria should be analysis in new case design for process improvement.

4.3.2.3 Economic Analysis of Base Case Design

For this work, the project life time is 20 years. The Minimum Acceptable Rate of Return (MARR) for this project is assumed to 15%. The depreciation rate for the process is estimated to be 20 years by MACRS method. The income tax rate paid to the government is assumed to be 30%. According to the ethanol price trend, the price will sharply increase in near future, the inflation rate is assumed to 2% of construction, 10% of product price and 10% of total production cost. The chemical engineering plant cost index (CEPI) is set to 584.6 which is annual index in 2012. So the total results of base case design from simulation and ECON software program in terms of process specification, performance and economic criteria, these values are concluded in Table 4.4.

Table 4.4 The sustainability metrics of base case design

Variables	**Base case**
Process specification	
Feedstock type	Cassava rhizome
Feedstock usage (kg/day)	466,646.6650
Chemical usage (kg/day)	9,325.8060
Ethanol production (liters/day)	150,000.68
Net fresh water added to the system (kg/day)	375,342.2080
Performance criteria	
Raw material usage (kg RM/kg EtOH produced)	3.9910
Net fresh water usage (kg/kg EtOH produced)	3.1472
Total energy usage (GJ/kg EtOH produced)	0.02112
Total wastes production (kg/kg of EtOH produced)	12.6866
Hazardous raw material (kg/kg EtOH produced)	0.0300
Economic criteria	
Revenue ethanol selling without cost ($x10^6$\$/year)	39.222
Total utility cost ($x10^6$\$/year)	6.1145
Total capital investment ($x10^6$\$)	137.6176
Capital cost per year ($x10^6$\$/year)	6.8809
Total operating cost ($x10^6$\$/year)	41.2361
Minimum ethanol selling price ($/kg EtOH produced)	1.0478
Net Revenue per year ($x10^6$\$/year)	**-8.8946**

From Table 4.4, net revenue per year is negative value, -8.8946 M$/year, which means base case design cannot make a profit. So this process has many points that decreased performance of the process such as high consumption of raw materials (feedstock, water and chemical), high energy usage and more wastes production. The important point that impact to this process is overliming and conditioning step because this part has not only high water and energy consumption but high solid waste (gypsum waste) production which the significant amount of sugar losses as much as 13% with gypsum wastes. The high sugar losses the more raw_materials needs; furthermore; gypsum disposal cost is so high about 0.021 $/kg (Aden *et al.,* 2002) that decreases profitability of process.

According to the information of material and energy consumption, overliming process play a crucial role in process cost. That gypsum waste is high produced results in high glucose losses. Finally, raw material prices unnecessarily increases.

To improve this part, the base case design should be improved by reducing parameters that affected to performance of process which is feedstock and utility consumption, sugar losses and else.

However, in case this process is possible, all costs should be reconsidered; for examples, costs of raw materials such as cassava rhizome price and ethanol selling price to make this process become economically feasible. But this work did not focus on cost analysis because it adjusts only costs of raw materials and product to get profitability.

4.4 New Cases Design of One Feedstock Cases

4.4.1 Alternative A Case Design

This alternative case still uses cassava rhizome as feedstock from base case but the process will be changed from base case deign used NREL 2011 process. For many reasons as mentioned in previous case, overlimng and conditioning step is replaced by ammonia conditioning process in this case. The ammonia conditioning can adjust pH slurry from 1 to 5 whereas overliming step needs more one step (neutralization) for re-adjusting pH to 5 because of over-conditioning. Block flow diagram of new process using ammonia conditioning is shown in Figure 4.11. The high miscibility of ammonia also permits conditioning of the whole hydrolysate slurry and eliminates the solid-liquid separation step which reduces the capital cost investment (NREL, 2011). While ammonia is considerably more expensive than lime which ammonia price is 700$/ton, the economic benefits of reducing sugar losses and reducing capital cost will make ammonia more economical which will be investigated in economic evaluation part. The new process design from simulation program is shown in Figure 4.12.

The next analysis is economic evaluation which investigate variable as same as base case design. The result of economic evaluation form alternative A case by ECON software is shown in Table 4.5 and it is compared with base case design.

The result from Table 4.5 alternative A case is more economic feasibility than base case design which net revenue is 2.98 M$/year, rate of return is 16% and payback period is 4.7 year. Then it should be investigated with base case design in details which factors are better than in base case design including process specification, performance and environmental impacted assessment.

The first consideration is focusing on equipment costs as shown in Figure 4.13 compared with base case design. The total capital cost of alternative A case design is 102.81 M$ less than base case design, 137.62 M$, because detoxification part was changed to ammonia conditioning process reduced cost by 6 M$. The second is considering in operating cost of raw material prices and utility cost. Alternative A case use less raw materials compared with base case design because of no sugar losses as base case in detoxification resulting in additional feed is not required. Figure 4.14 is shown breakdown of raw materials of alternative A case and compare with base case design.

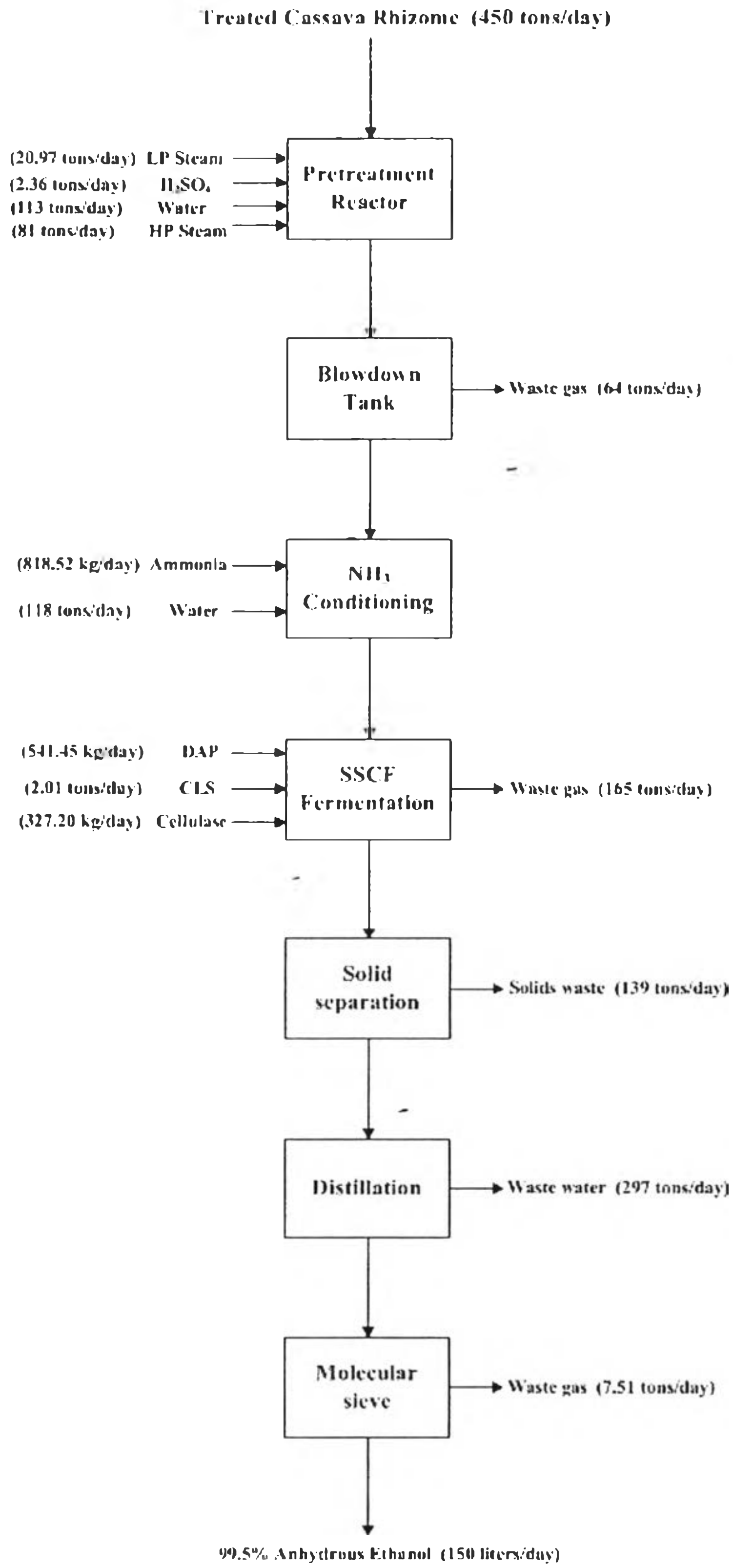

Figure 4.11 Block flow diagram of bioethanol production from cassava rhizome of alternative A case.

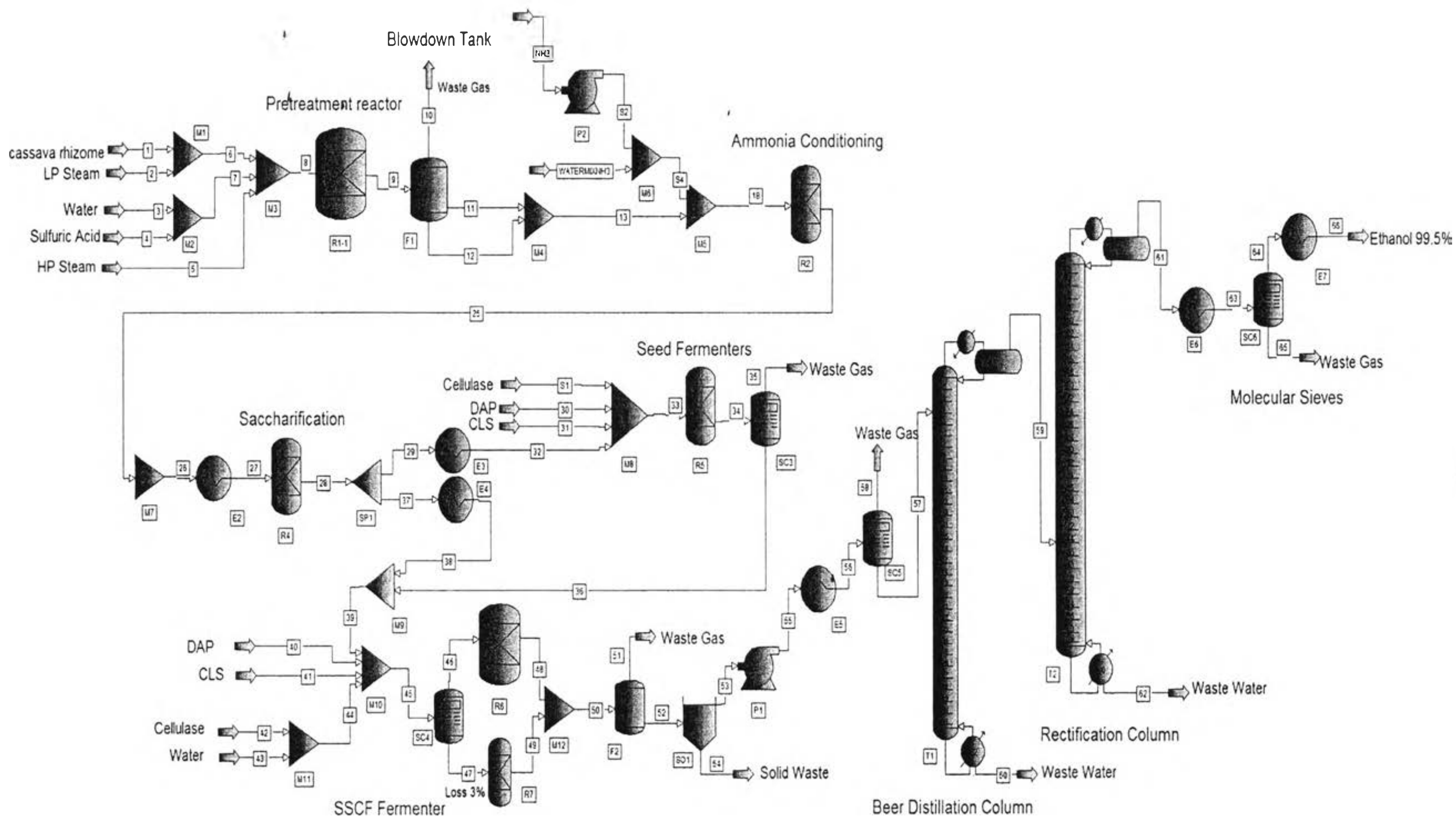

Figure 4.12 The process design of bioethanol production using cassava rhizome feedstock of alternative A case design.

Table 4.5 The sustainability metrics of alternative A case design compared with base case design

Variables	Base case	Alternative A
Process specification		
Feedstock type	Cassava rhizome	Cassava rhizome
Feedstock usage (kg/day)	466,646.6650	450,270.202
Chemical usage (kg/day)	9,325.8060	6,049.838
Ethanol production (liters/day)	150,000.68	150,000.87
Net fresh water added to the system (kg/day)	375,342.2080	233,011.8340
Performance criteria		
Raw material usage (kg RM/kg EtOH produced)	3.9910	3.8263
Net fresh water usage (kg/kg EtOH produced)	3.1472	- 1.9538
Total energy usage (GJ/kg EtOH produced)	0.02112	0.02047
Total wastes generation (kg/kg EtOH produced)	12.6866	7.5896
Hazardous raw material (kg/kg EtOH produced)	0.0300	0.02
Economic criteria		
Revenue Ethanol selling without cost ($\times 10^6$\$/year)	39.222	39.222
Total utility cost ($\times 10^6$\$/year)	6.1145	5.7243
Total capital investment ($\times 10^6$\$)	137.6176	102.8112
Capital cost per year ($\times 10^6$\$/year)	6.8809	5.1406
Total operating cost ($\times 10^6$\$/year)	41.2361	31.1039
Minimum ethanol selling price (\$/kg EtOH produced)	1.0478	0.7903
Net Revenue per year ($\times 10^6$\$/year)	-8.8946	2.9770
Project life time (years)	-	20.00
Rate of return (%)	-	16.00
Pay Back period (years)	-	4.70
Net Present Worth ($\times 10^6$\$)	-	18.63

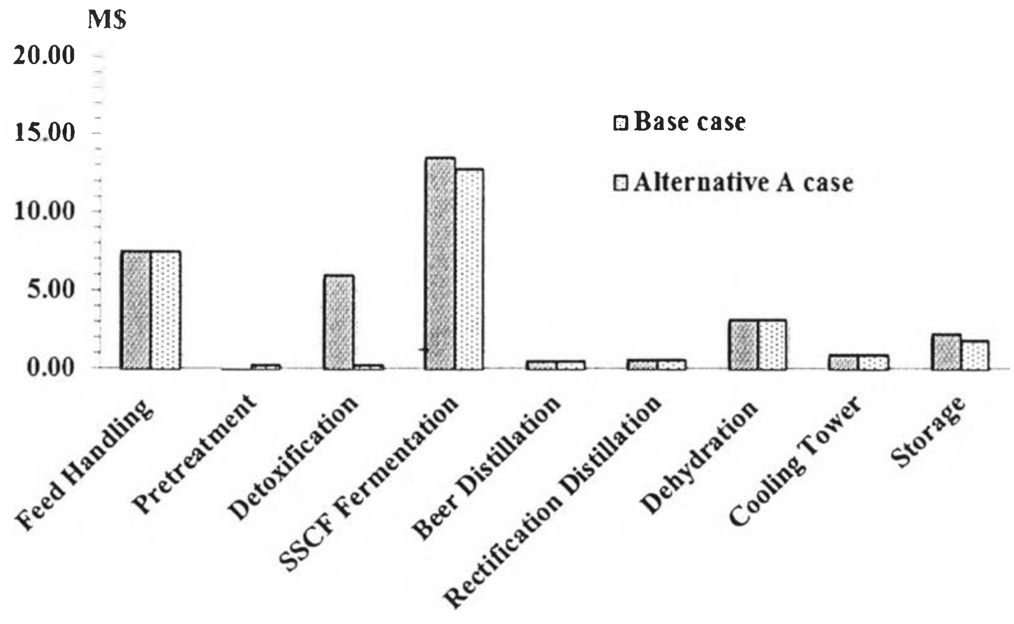

Figure 4.13 Equipment costs of alternative A case compared with base case design.

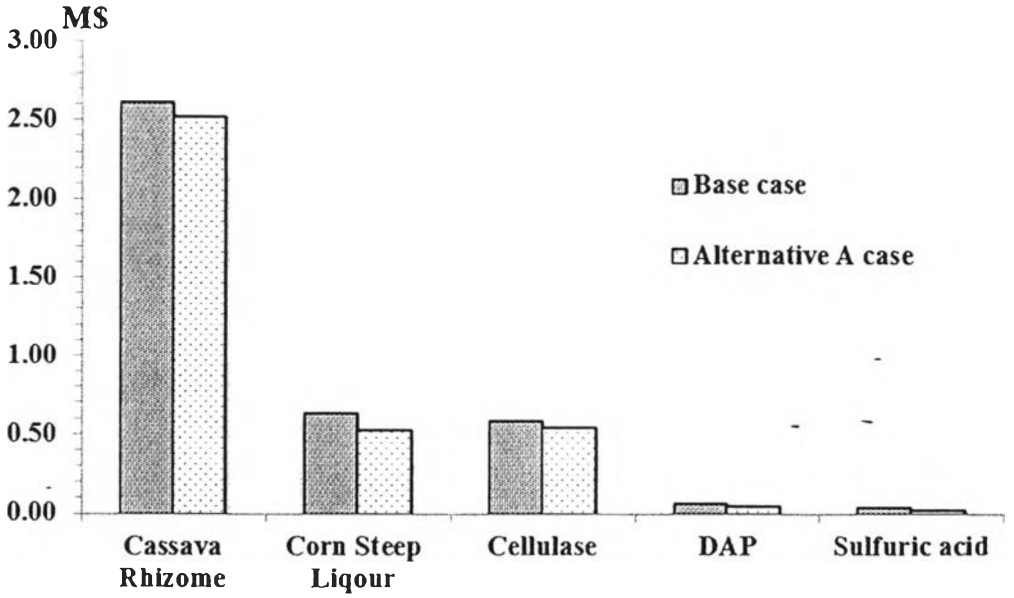

Figure 4.14 Breakdown of raw material prices of alternative A case compared with base case design.

Continued on utility cost of alternative A case, this process has less utility consumption, espescially water, than base case design due to the same way of decreased raw materials usage leads to reduced utility usage. So utility cost of alternative A case is shown in Figure 14.15 compared with base case design.

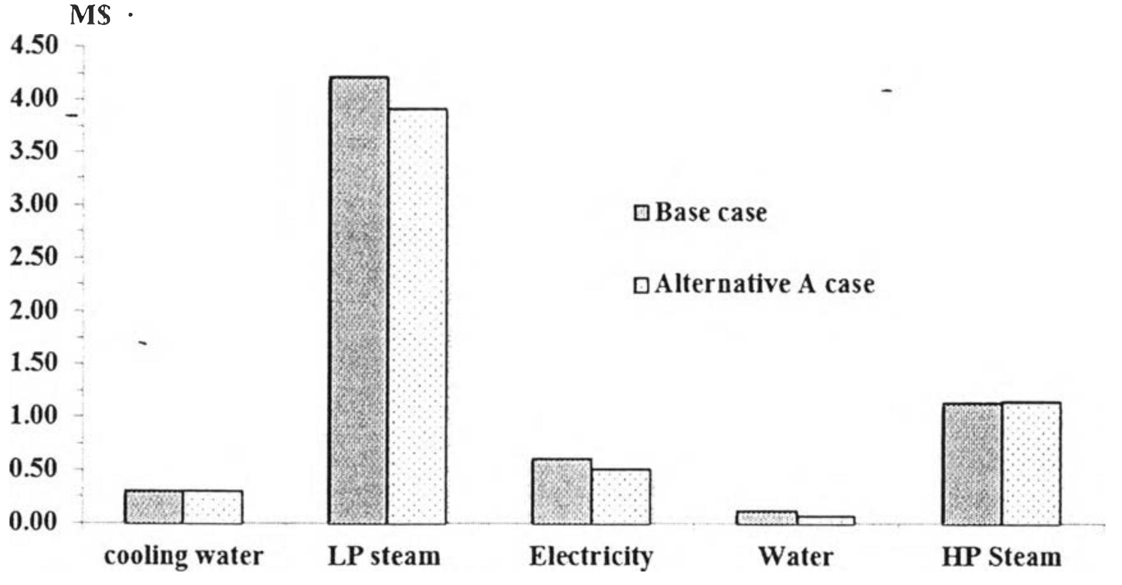

Figure 4.15 Breakdown of utility costs of alternative A case design compared with base case design.

Moreover, total wastes generation in of alternative A case is less than base case design. Total wastes generation of A case and base case is about 7.59 and 12.69 kg/kg EtOH produced respectively which means this process is more eco-friendly than base case design. So the process that suitable for bioethanol production is NREL 2011 process. Then this process is used for bioethanol production in next cases design.

4.4.2 Alternative B Case Design

This alternative used corn stover as feedstock instead of cassava rhizome in base case and alternative A case since, the first reason, chemical composition of corn stover is different from cassava rhizome composed of cellulose 49.93%, hemicellulose 20.46%, lignin 30.61% and free-ash basis. The second, the amount of corn stover is two times higher than cassava rhizome in Thailand implying that corn stover is better option for long-term compared with cassava rhizome. The last, corn stover is agricultural residues after corn is harvested. In common practice, it is open burnt to atmosphere or used for landfill in local area. In addition, it help reduce CO_2 emission and greenhouse gases by not burning it. For all of these reasons corn stover seems to be superior to cassava rhizome.

The analysis of bioethanol production is the same as alternative A case and block flow diagram of corn stover is shown in Figure 4.16. By PROII simulation program and ECON software in the same conditions, MARR is 15%, project life time is 20 years.

The result from simulation program and economic evaluation is shown in Table 4.6 and compared with previous cases. So net fresh water consumption about 196.91 tons/day is better than previous cases; nevertheless, the net revenue of alternative B case is 0.975 M$/year, rate of return is 11%, and payback period is 6.26 years which these values are less than alternative A case design. The only disadvantage of corn stover is feedstock cost because it is three times expensive than cassava rhizome.

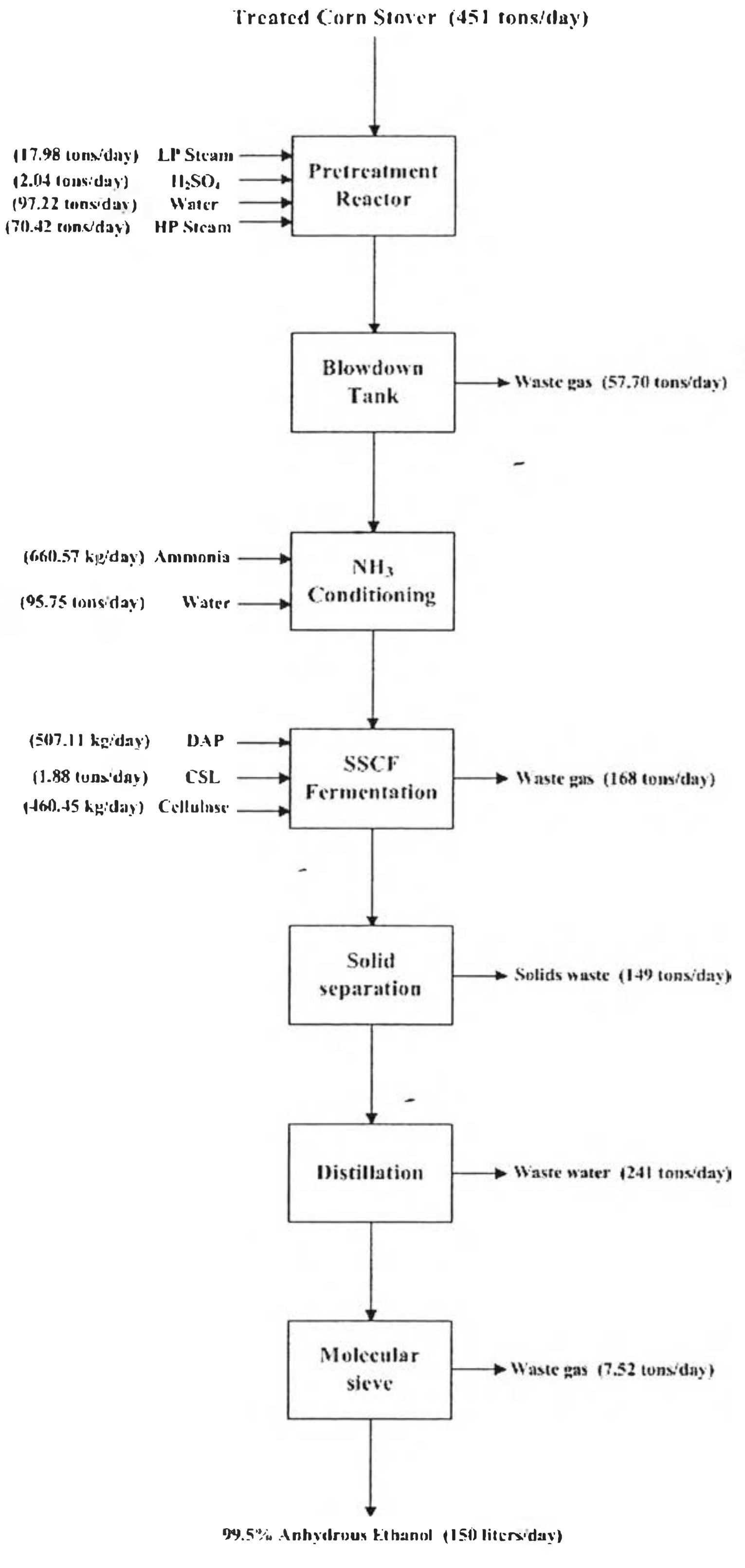

Figure 4.16 Block flow diagram of bioethanol production from corn stover of alternative B case.

Table 4.6 The sustainability metrics of alternative B case design compared with previous cases design

Variables	Base case	Alternative A	Alternative B
Process specification			
Feedstock type	Cassava rhizome	Cassava rhizome	Corn stover
Feedstock usage (kg/day)	466,646.6650	450,270.202	451,372.639
Chemical usage (kg/day)	9,325.8060	6,049.838	5,546.771
Ethanol production (liters/day)	150,000.68	150,000.87	150,000.82
Net fresh water added to the system (kg/day)	375,342.2080	233,011.8340	196,911.9100
Performance criteria			
Raw material usage (kg RM/kg EtOH produced)	3.9910	3.8263	3.8312
Net fresh water usage (kg/kg EtOH produced)	3.1472	1.9538	1.6511
Total energy usage (GJ/kg EtOH produced)	0.02112	0.02047	0.02021
Total wastes generation (kg/kg EtOH produced)	12.6866	7.5896	6.8750
Hazardous raw material (kg/kg EtOH produced)	0.0300	0.02	0.0171
Economic criteria			
Revenue Ethanol selling without cost ($\times 10^6$\$/year)	39.222	39.222	39.222
Total utility cost ($\times 10^6$\$/year)	6.1145	5.7243	5.6275
Total capital investment ($\times 10^6$\$)	137.6176	102.8112	102.9743
Capital cost per year ($\times 10^6$\$/year)	6.8809	5.1406	5.1487
Total operating cost ($\times 10^6$\$/year)	41.2361	31.1039	33.0986
Minimum ethanol selling price (\$/kg EtOH produced)	1.0478	0.7903	0.8410
Net Revenue per year ($\times 10^6$\$/year)	-8.8946	2.9770	0.9753
Project life time (years)	-	20.00	20.00
Rate of return (%)	-	16.00	11.00
Pay Back period (years)	-	4.70	6.26
Net Present Worth ($\times 10^6$\$)	-	18.63	6.11
Ranking	**Base case**	**1**	**2**

Total capital investment cost quite equals alternative A case design about 102.97 M\$. In term of total operating cost, the cost is higher than alternative A case about 2 M\$/year. Raw material prices are compared with previous case as shown in Figure 4.17.

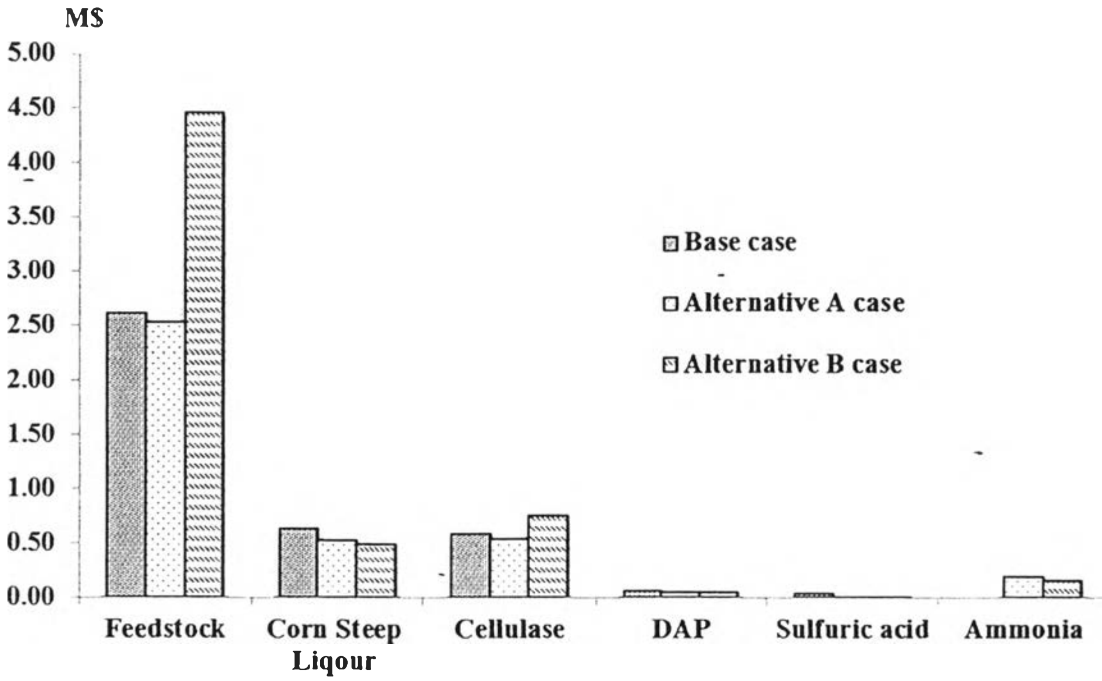

Figure 4.17 Breakdown of raw material prices of alternative B case compared with previous cases.

For alternative B case, feedstock and cellulase prices are higher than two prvious cases about 2 and 0.2 M\$/year respectively.

The analyis of utility cost is shown in Figure 4.18 compared with two previous cases. High pressure steam and water pirce is less than two previous cases about 0.15 and 0.02 M\$/year respectivety because its composition does not have ash content; other costs is relatively the same.

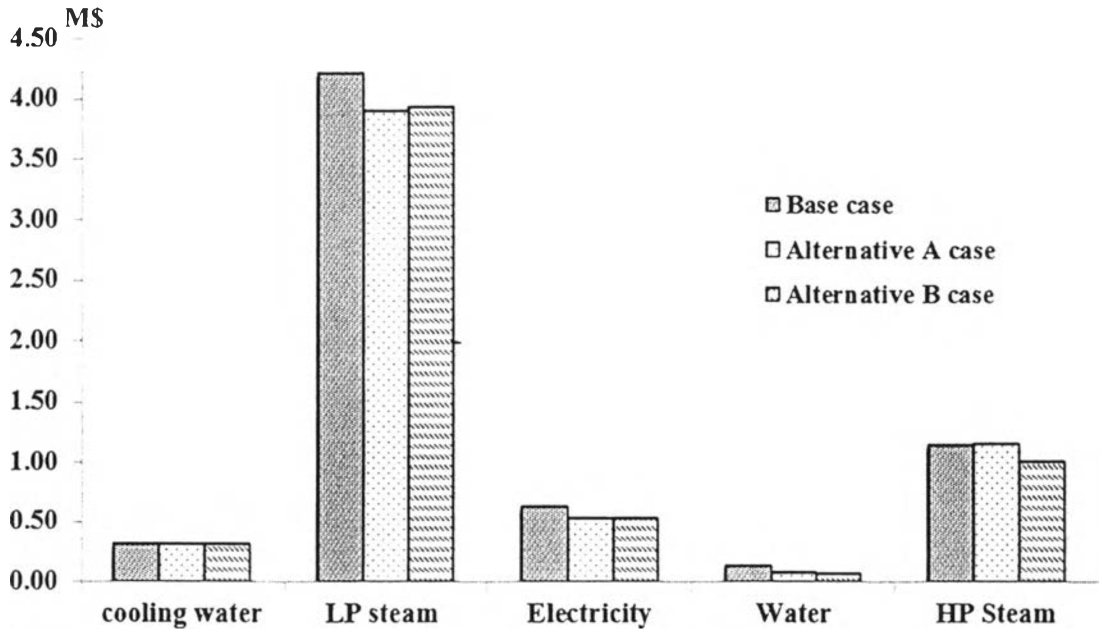

Figure 4.18 Breakdown of utility costs of alternative B case compared with previous cases.

An alternative B case design makes lower profit than alternative A case but higher than base case design. Rate of return of this process design is 10% which less than minimum accepted rate of return (15%). It is not attractive to invest in this process in term of economic; however, it can reduce environmental impact such as CO_2, and greenhouse gases emission.

The next cases of study are concerned about chemical composition, price of feedstock and other factors that affected the performance of the process in term of sustainability.

4.4.3 Alternative C Case Design

This case is sugarcane bagasse as feedstock when compared with previous cases in Thailand, chemical composition of sugarcane bagasse composes of 45.86% cellulose, 28.84% hemicellulose, 23.35% lignin and 1.95% ash so it is different with cassava rhizome composition but it is relatively the same as corn stover composition - cassava rhizome has little bit lower cellulose and lignin contents and higher hemicellulose and ash contents. The amount of sugarcane bagasse is the highest about 6 tons per year compared with previous lignocellulosic biomass cases, 6 times than cassava rhizome and 3 times than corn stover. So it is quite proper in long-term to produce biofuels; nevertheless, sugarcane bagasse is used generally for produce electricity and steam production and animal feeds that means price is rather competitive when used for produce ethanol fuel.

In Thailand, price of sugarcane bagasse has the lowest price about 0.01 $/kg. Block flow diagram of alternative C case for bioethanol production is shown in Figure 4.19 and the process used for bioethanol production is still the same. The result of alternative C case form simulation program and ECON software is given in Table 4.7 compared with previous cases.

The net revenue of alternative C case is 5.05 M$/year, Rate of return is 22%, and payback period is 3.69 years. These values are more than all previous cases design that means this process can make the highest profit and should be selected. Then raw material prices and utility costs are examined and shown in Figure 4.20 and 4.21, respectively.

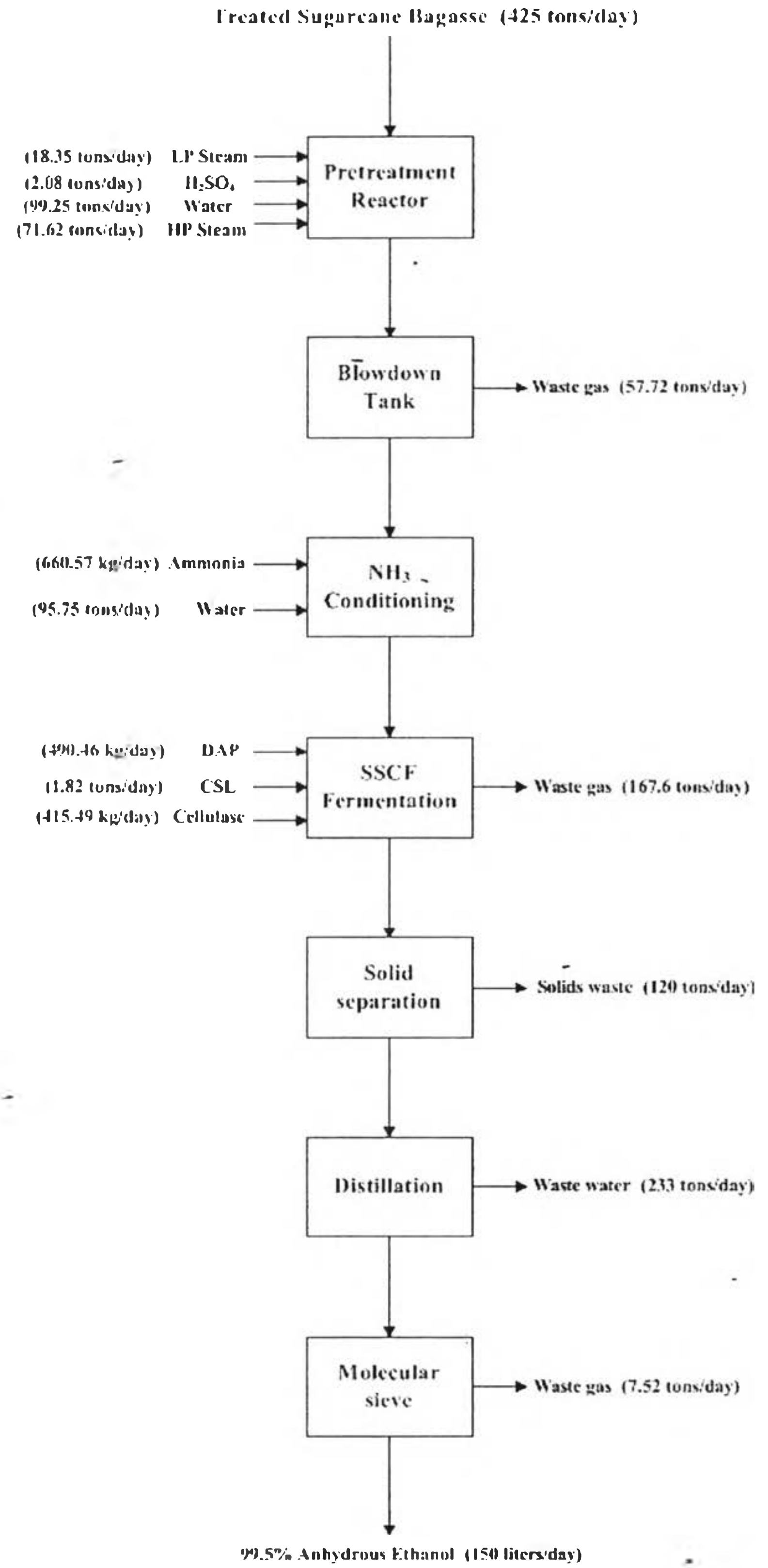

Figure 4.19 Block flow diagram of bioethanol production from sugarcane bagasse of alternative C case.

Table 4.7 The sustainability metrics of alternative C case design compared with previous cases design

Variables	Base case	Alternative A	Alternative B	Alternative C
Process specification				
Feedstock type	Cassava rhizome	Cassava rhizome	Corn stover	Sugarcane Bagasse
Feedstock usage (kg/day)	466,646.6650	450,270.202	451,372.639	425,630.293
Chemical usage (kg/day)	9,325.8060	6,049.838	5,546.771	5,467.284
Ethanol production (liters/day)	150,000.68	150,000.87	150,000.82	150,000.78
Net fresh water added to the system (kg/day)	375,342.2080	233,011.8340	196,911.9100	198,485.3990
Performance criteria				
Raw material usage (kg RM/kg EtOH produced)	3.9910	3.8263	3.8312	3.6147
Net fresh water usage (kg/kg EtOH produced)	3.1472	1.9538	1.6511	1.6643
Total energy usage (GJ/kg EtOH produced)	0.02112	0.02047	0.02021	0.02020
Total wastes generation (kg/kg EtOH produced)	12.6866	7.5896	6.8750	6.6982
Hazardous raw material (kg/kg EtOH produced)	0.030	0.02	0.017	0.017
Economic criteria				
Revenue Ethanol selling without cost ($x10^6$\$/year)	39.222	39.222	39.222	39.222
Total utility cost ($x10^6$\$/year)	6.1145	5.7243	5.6275	5.6154
Total capital investment ($x10^6$\$)	137.6176	102.8112	102.9743	99.8931
Capital cost per year ($x10^6$\$/year)	6.8809	5.1406	5.1487	4.9947
Total operating cost ($x10^6$\$/year)	41.2361	31.1039	33.0986	29.1777
Minimum ethanol selling price (\$/kg EtOH produced)	1.0478	0.7903	0.8410	0.7414
Net Revenue per year ($x10^6$\$/year)	-8.8946	2.9770	0.9753	5.0503
Project life time (years)	-	20.00	20.00	20.00
Rate of return (%)	-	16.00	11.00	22.00
Pay Back period (years)	-	4.70	6.26	3.69
Net Present Worth ($x10^6$\$)	-	18.63	6.11	31.6112
Ranking	**Base case**	**2**	**3**	**1**

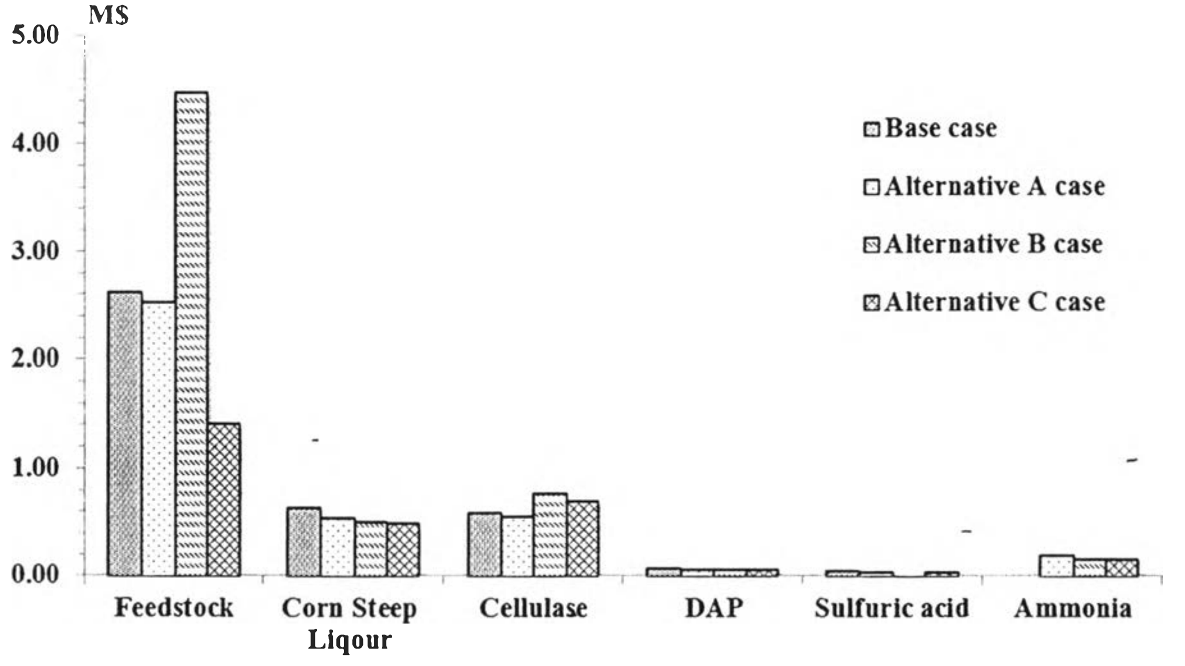

Figure 4.20 Breakdown of raw material prices of alternative C case compared with previous cases.

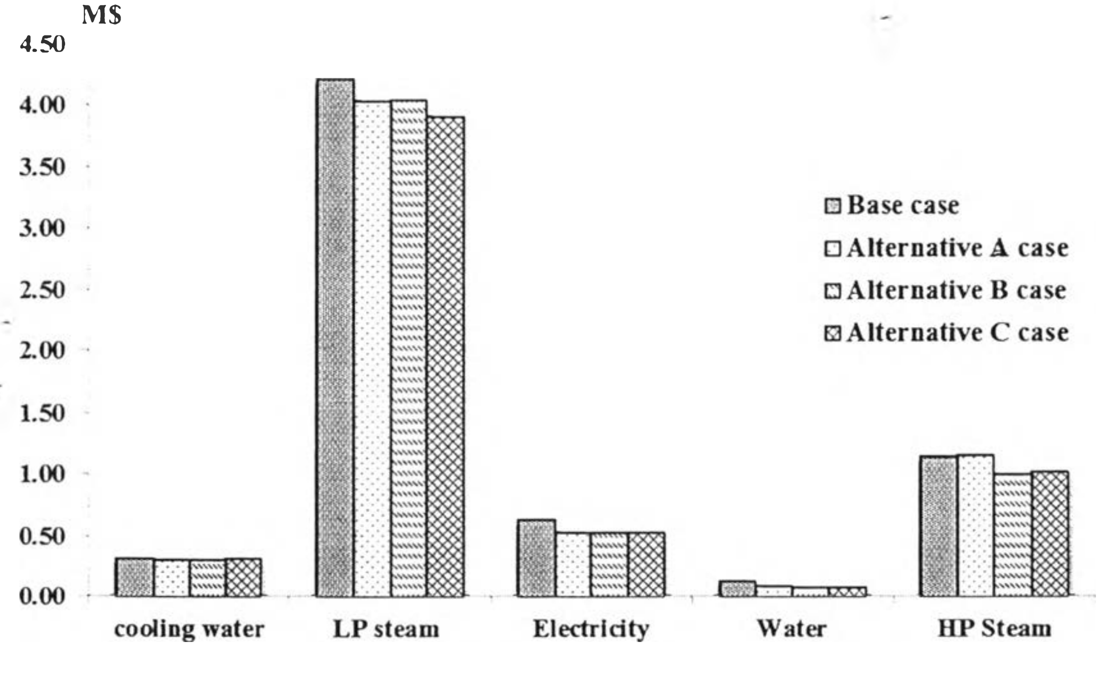

Figure 4.21 Breakdown of utility costs of alternative C case compared with previous cases.

From Figure 4.20, the adventage of alternative C case is feedstock cost. Its cost is less than half of cost per year compared with other cases. other raw material prices relatively the same as expected. Cellulase cost is a bit higher than base case and alternative A case becaue of high cellulose content.

Most of utility costs of alternative C case is less than previous cases whereas water and high pressure steam are slightly more than alternative B case design as shown in Figure 4.21; however, the value of total utility cost is the lowest as shown in Table 4.7. The reason of higher use of water and high pressure steam consumption than alternative B case is sugarcane bagasse consists of ash content contribute to using more water and steam to pre-heat feedstock before feeding to pretreatment reactor.

Focused on total wastes generation in Table 4.7, it is the lowest wastes production compared with all cases that is better for environment in term of reduced waste disposal and pollutions kinds of water and air pollution and else.

Finally, The conclusion of all cases design is compared with all crucial factors, process specification, performance and economic criteria as shown in Table 4.7. The alternative C case design is the best sustainable of one feedstock case for bioethanol production and other are cassava rhizome and corn stover, respectively.

4.5 New Cases Design of Multi-Feedstocks Cases

Multi-feedstocks are of interest because they enhance long-term security of feedstocks supply for sustainable bio-ethanol production which is becoming one of the critical factors for sustainability of biofuels. They are increasing flexibility of using feedstocks for bioethanol production. Thailand has a variety of agricultural residues which are currently abundant, preventing uncertainty situations, reducing energy consumption based on fossil fuels and finally reducing greenhouse gases emission; for examples,

Discontinuity of supply: the amount of biomass depends on agricultural yield. During harvest season, the quantity is high enough for ethanol production. In contrast the supply during off season so low that the price fluctuates all the time. This cycle happens every year. Moreover unexpected situations may be involved for example flooding, drought and insect

Difficulty to predict the amount and price in long term: the amount of biomass relies on several factors such as trend of framing caused by market price of agricultural product, government policy, environmental condition and else.

No purchasing credit: to purchase various kinds of feedstocks, only cash is admitted, not like other industrial product such as oil and gas that can be paid by credit at 5-6 months.

Competition against other industries: there are many kinds of industries also need the biomass for their process. For example, power plant use cassava rhizome and sugarcane bagasse to produce electricity, sugar mills use bagasse as fuel for production of thermal energy for the distillation process and a few corn stover are as for animal feed. Price of biomass will certainly rise.

Burning Biomass: In Thailand, open burning of agricultural residues is generally a common practice because it is the most convenient and it is an easy way to eliminate residues in the land preparation for next harvest. The major economic crops which are frequently subjected to open burning in the field are corn, sugarcane, and especially rice paddy. Not only burning of crop residues is a major source of greenhouse gases emission, such as carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), volatile organice compounds (VOCs), and nitrogen oxide (NO_x) but also it can affect inspiration system of human.

For all of reasons, this work assumes one feedstock cases are not flexible in term of feedstock supply that are not suitable for sustainability. New cases design of multi-feedstocks are improved to get the best sustainable process design in term of process specification, performance criteria and environmental impacted assessment criteria.

4.5.1 Alternative D Case Design

4.5.1.1 Multi-feedstocks of Alternative D Case Design

This alternative case combines feedstocks of each previous alternative case (cassava rhizome, corn stover and sugarcane bagasse) feeding to the process and this case is assumed a base case of multi-feedstocks case design. Block flow diagram of alternative D case is shown in Figure 4.22. The amount of feedstocks of each type used for process is calculated to find optimal feedstocks ratio.

The optimal feedstocks ratio is calculated by minimize feedstocks cost basis. The objective function of calculation and constraint is given in equation 4.1.

$$F_{obj} = \sum_{i=1}^{n} c_i f_i x_i \qquad ; \quad 0.05 \leq f_i \leq 0.5 \qquad (4.1)$$

i = type of feedstock

c = cost of each feedstock i, \$/kg

f = fraction of each feedstock i

x = amount of feedstock i, kg/day

From equation 4.1, the fraction of each feedstock equals 0.45 of cassava rhizome, 0.05 of corn stover and 0.50 of sugarcane bagasse to get the minimum feedstock cost. The process design from simulation program is shown in Figure 4.23.

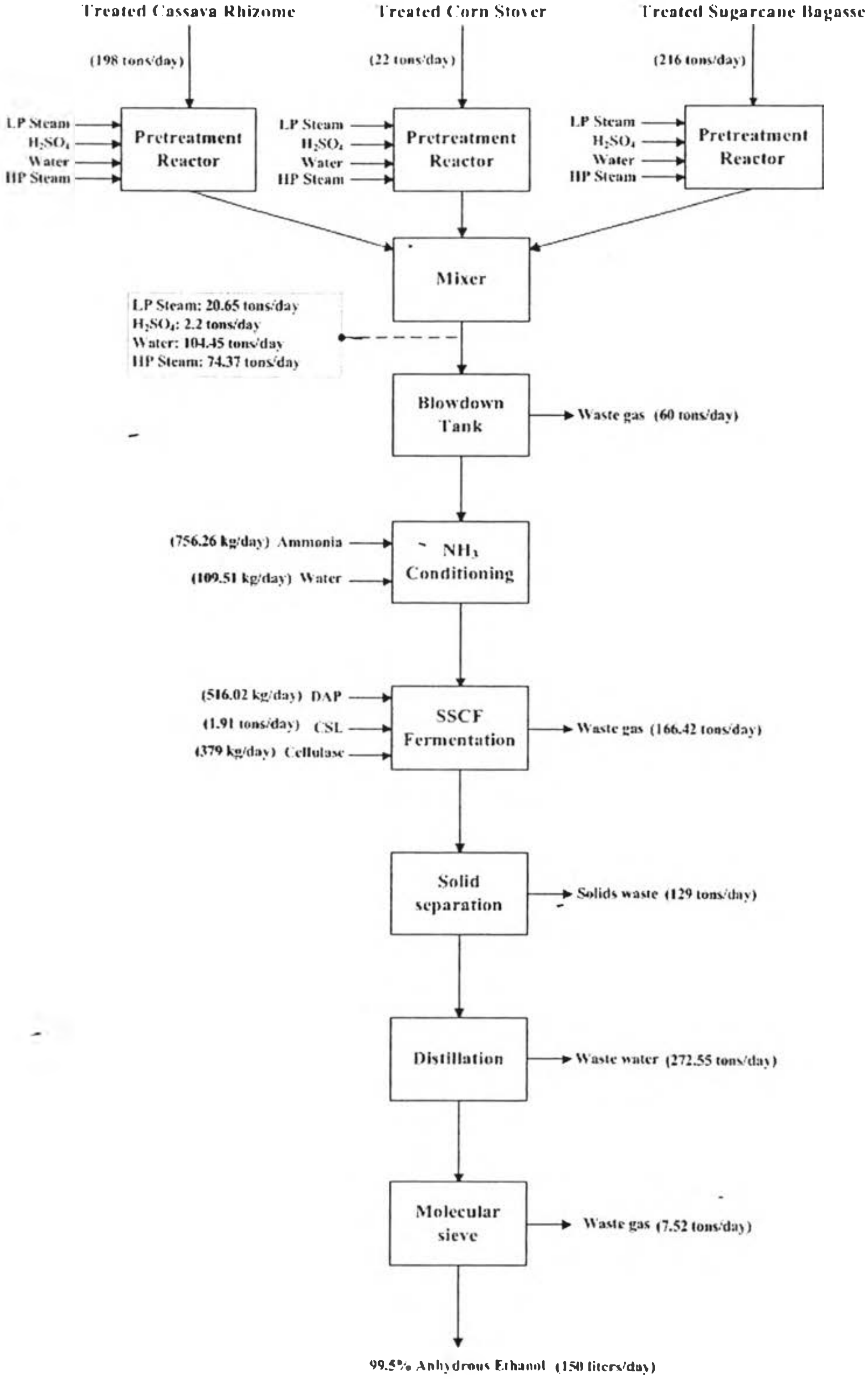

Figure 4.22 Block flow diagram of bioethanol production from combined feedstocks of alternative D case.

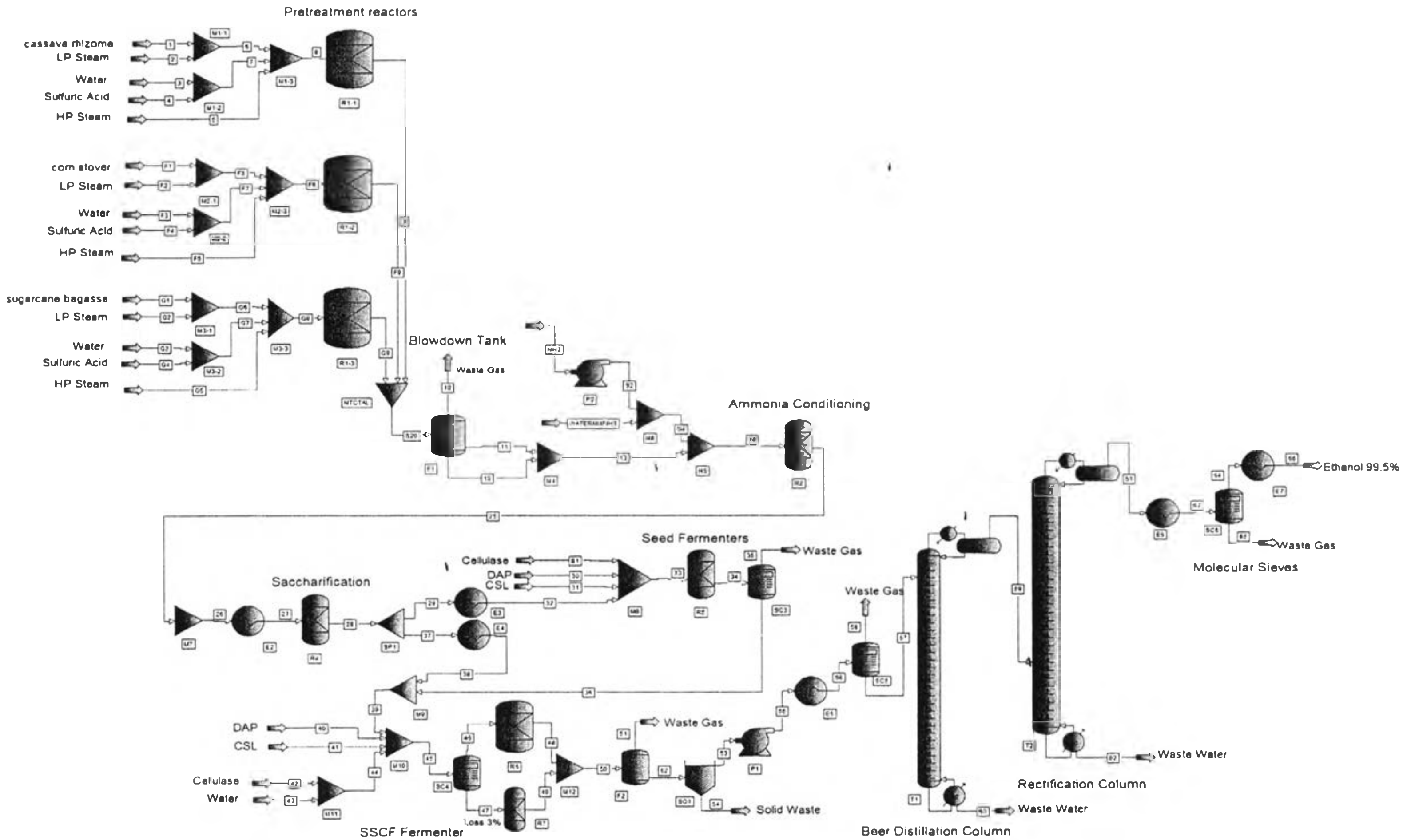

Figure 4.23 The process design of bioethanol production using combined feedstocks of alternative D case design.

Results of sustainability in terms of process specification, performance and economic criteria are shown in Table 4.8.

Table 4.8 The sustainability metrics of alternative D case compared with the best of separated case design

Variables	**Alternative D**
Process specification	
Feedstock type	Combined
Feedstock usage (kg/day)	437,468.049
Chemical usage (kg/day)	5,757.871
Ethanol production (liters/day)	150,000.528
Net fresh water added to the system (kg/day)	216,918.9790
Performance criteria	
Raw material usage (kg RM/kg EtOH produced)	3.7164
Net fresh water usage (kg/kg EtOH produced)	1.8188
Total energy usage (GJ/kg EtOH produced)	0.02027
Total wastes generation (kg/kg EtOH produced)	7.1519
Hazardous raw material (kg/kg EtOH produced)	0.0184
Economic criteria	
Revenue Ethanol selling without cost (x10^6\$/year)	39.222
Annual feedstock cost/ kg of product (\$/kg EtOH produced)	0.0515
Total utility cost (x10^6\$/year)	5.6495
Total capital investment (x10^6\$)	103.6372
Capital cost per year (x10^6\$/year)	5.1819
Total operating cost (x10^6\$/year)	30.6425
Minimum ethanol selling price (\$/kg EtOH produced)	0.7786
Net Revenue per year (x10^6\$/year)	3.4043
Project life time (years)	20.00
Rate of return (%)	17.00
Pay Back period (years)	4.48
Net Present Worth (x10^6\$)	21.3089
Ranking	**Base case**

Focused on economic criteria in Table 4.8, the net revenue of alternative D case is 3.40 M$/year, rate of return is 17% and payback period is 4.48 years. More clearly, raw material prices and utility costs of alternative D case are analyzed in Figure 4.24 and 4.25 respectively.

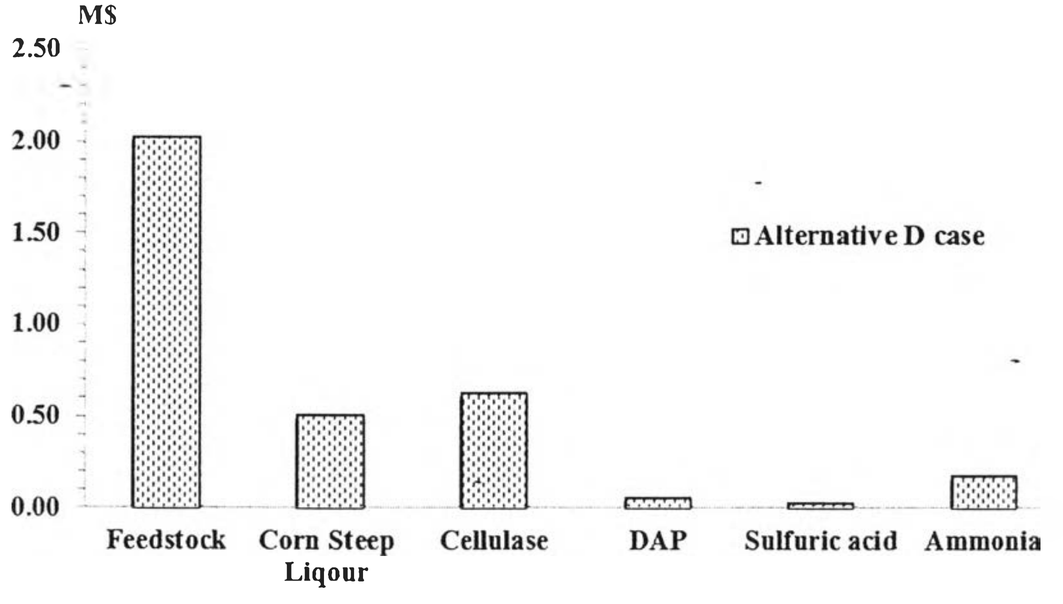

Figure 4.24 Breakdown of raw material prices of alternative D case.

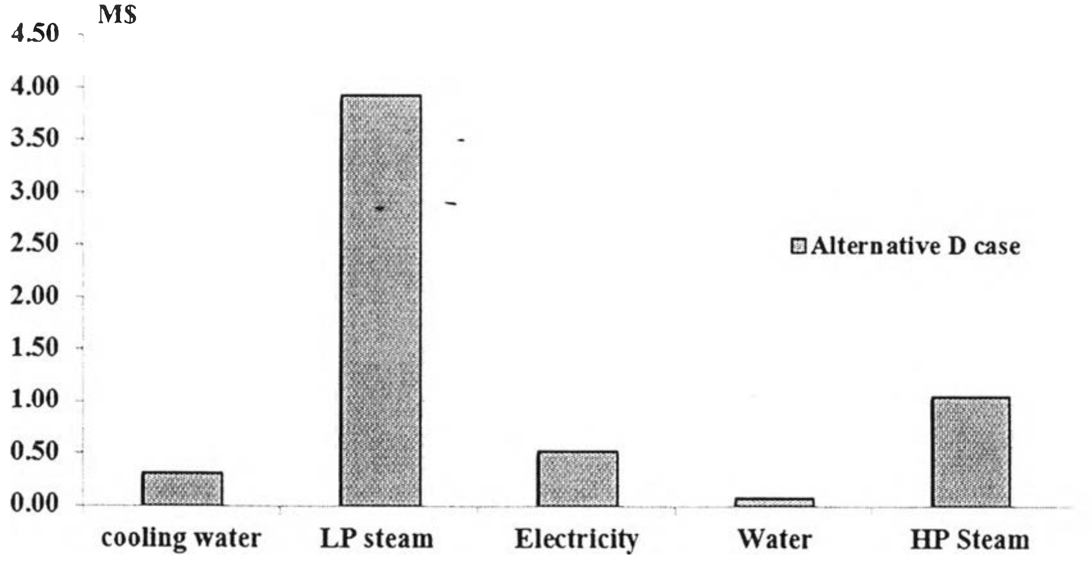

Figure 4.25 Breakdown of utility costs of alternative D case.

4.5.1.2 Sustainability Analysis of Alternative D Case

SustainPro software was used for analysis sustainable process design. It performs decomposition of process in term of process pathways (close path and open path) of each compound. This software classifies the sustainability results into three groups: energy, raw material and water usage. The main indicators used to investigate in software are 3 indicators;

Material Value Added (MVA) indicator indicates value added of the compound between the first and the end point of the specified pathway (only open path). If this value is negative that means compound in a specified pathway was losing its values along the process, theoretically, MVA should be equal to zero.

Energy and waste cost (EWC) indicator indicates the amount of energy in term of stream and units (heat exchangers) that can be saved in each pathway in the process. If this value is positive that means the specified pathway lost energy out of process. EWC can be decreased by reuse energy that losses from process by heat integration.

Total Value Added (TVA) indicator indicates the economic influence of a compound in a specified path. It is calculated by MVA subtracted with EWC. If this value is negative that means a compound in specified path was losing value along the process in term of mass and energy. This work used this indicator for analysis in term of sustainability because it includes with MVA and EWC criteria.

Results of sustainability analysis from SustainPro software are shown in Appendix E that summarize total open path, flow-rate, MVA and EWC of each open path in the process. Table 4.9 presents the sensitivity analysis of sustainability of alternative D case shown only open paths are high bottlenecks in process in term of MVA, EWC and TVA.

Table 4.9 Sensitivity analysis results of high bottlenecks of alternative D case

Path	MVA	EWC	TVA	Probability
OP 177	-27.39036	973.28873	-1000.6791	High
OP 356	-454.75406	0.01482	-454.7688	High
OP 351	-397.48919	16.77849	-414.26768	High
OP 33	-255.55569	70.72156	-326.27726	High
OP 176	-1.12861	319.05145	-320.18006	High
OP 263	-7.897462	293.56217	-301.45963	High

Path	MVA	EWC	TVA	Probability
OP 29	-234.27523	64.26179	-298.53702	High
OP 135	-7.57396	281.40983	-288.98379	High
OP 281	-5.53624	205.79196	-211.32820	High
OP 153	-5.47540	203.43814	-208.91354	High
OP 368	-181.33841	0.67500	-182.01341	Low
OP 357	-170.56374	0.01103	-170.57477	High
OP 17	0	153.03881	-153.03881	Low
OP 21	0	132.69867	-132.69867	Low
OP 170	-3.04185	109.39207	-112.43392	High
OP 359	-39.91504	59.97138	-99.88642	Low
OP 27	0	98.754098	-98.75409	Low
OP 262	-0.32541	92.52496	-92.85037	High
OP 5	0	90.66765	-90.66765	Low
OP 134	-0.31208	88.72967	-89.04175	High
OP 345	-82.53781	3.52841	-86.06622	High
OP 67	0	80.25553	-80.25553	Low
OP 280	-0.22811	64.86154	-65.08965	High
OP 152	-0.22561	64.14488	-64.37049	High
OP 245	-1.65544	61.53565	-63.19109	High
OP 81	0	59.62587	-59.62587	Low
OP 117	-1.41726	52.65825	-54.07552	High
OP 361	-21.34191	32.35121	-53.69312	Low
OP 365	-46.01517	0.02291	-46.03809	Low
OP 31	-34.10942	10.03507	-44.14449	High
OP 334	0	36.52012	-36.52012	Low
OP 32	-28.39507	8.07519	-36.47027	High
OP 169	-0.12533	35.48612	-35.61146	High
OP 66	0	34.04469	-34.04469	Low
OP 256	-0.87705	32.97738	-33.85444	High
OP 28	-26.03058	7.33935	-33.36993	High
OP 128	-0.84113	31.61241	-32.45354	High
OP 162	-0.90335	30.50541	-31.40877	High

From Table 4.9, High probability means that specified pathway has high chances to improve the process sustainability. Open paths which has high probability are shown below the path-flow details of each compound and its score of probability to improve it in Table 4.10.

Table 4.10 Path-flow details of each compound and its score of probability

Path	Compound	Stream	Path-flow details	Score
OP 280	H_2O	G5 – 62	P1-E2-E4-E5-R1-3-R2-R4-R6-CondT1-RebT2	38
OP 281	H_2O	G5 – 60	P1-E2-E4-E5-R1-3-R2-R4-R6-RebT1	37
OP 262	H_2O	G3 – 62	P1-E2-E4-E5-R1-3-R2-R4-R6-CondT1-RebT2	35

Path	Compound	Stream	Path-flow details	Score
OP 256	H_2O	G3 – 60	P1-E2-E3-E5-R1-3-R2-R4-R5-R6-RebT1	35
OP 152	H_2O	5 – 62	P1-E2-E4-E5-R1-1-R2-R4-R6-CondT1-RebT2	35
OP 134	H_2O	3 – 62	P1-E2-E4-E5-R1-1-R2-R4-R6-CondT1-RebT2	35
OP 128	H_2O	3 – 60	P1-E2-E3-E5-R1-1-R2-R4-R5-R6-RebT1	35
OP 135	H_2O	3 – 60	P1-E2-E4-E5-R1-1-R2-R4-R6-RebT1	34
OP 263	H_2O	G3 – 60	P1-E2-E4-E5-R1-3-R2-R4-R6-RebT1	34
OP 245	H_2O	G2 – 60	P1-E2-E4-E5-R1-3-R2-R4-R6-RebT1	33
OP 153	H_2O	5 – 60	P1-E2-E4-E5-R1-1-R2-R4-R6-RebT1	33
OP 117	H_2O	2 – 60	P1-E2-E4-E5-R1-1-R2-R4-R6-RebT1	33
OP 177	H_2O	WATERMIXNH3- 60	P1-E2-E4-E5-R2-R4-R6-RebT1	31
OP 169	H_2O	WATERMIXNH3- 62	P1-E2-E3-E5-R2-R4-R5-R6-CondT1-RebT2	31
OP 176	H_2O	WATERMIXNH3 - 62	P1-E2-E4-E5-R2-R4-R6-CondT1-RebT2	30
OP 170	H_2O	WATERMIXNH3- 60	P1-E2-E3-E5-R2-R4-R5-R6-RebT1	29
OP 162	H_2O	43 – 60	P1-E5-R6-RebT1	16
OP 32	Lignin	G1 – 54	E2-E3-R1-3-R2-R4-R5-R6	23
OP 28	Lignin	1 – 54	E2-E3-R1-1-R2-R4-R5-R6	23
OP 29	Lignin	2 – 54	E2-E4-R1-1-R2-R4-R6	22
OP 33	Lignin	G1 – 54	E2-E4-R1-3-R2-R4-R6	22
OP 31	Lignin	F1 – 54	E2-E4-R1-2-R2-R4-R6	21
OP 351	CSL	41 – 60	P1-E5-R6-RebT1	18
OP 345	CSL	31 – 60	P1-E5-R5-R6-RebT1	18
OP 357	Cellulase	S1 – 54	R5-R6	7
OP 356	Cellulase	42 – 54	R6	7

As seen in Table 4.10, the highest chances to de-bottleneck is water paths giving the highest score and number of paths in the process including water from mixed with feedstocks and ammonia conditioning. Water paths can be improved by water-recycle and heat integration to reduced TVA. The second is lignin paths. Instead of discard, it can be improved by use as solid wastes for combustion to produces energy, electricity and steam for process. The third is CSL paths because of expensive price it can be reduced by finding cheaper prices and use for combustion the same as lignin. The last is cellulase paths and it can be improved in the same way as CSL paths. The conclusion of methods to process improvement is shown in Table 4.11.

Table 4.11 The conclusion of methods to process improvement

Compound	Methods
Water	Water-recycle and Heat integration
Lignin	Solid combustion
CSL	Solid combustion, other purchase prices
Cellulase	Solid combustion, other purchase prices

4.5.1.3 Life Cycle Assessment of Alternative D Case

The basis of this work is to produce one kilogram of 99.5% bioethanol production from cellulosic multi-feedstocks. The system boundary of alternative D case design is shown in Figure 4.26 that includes cultivation and transportation of feedstocks to the process.

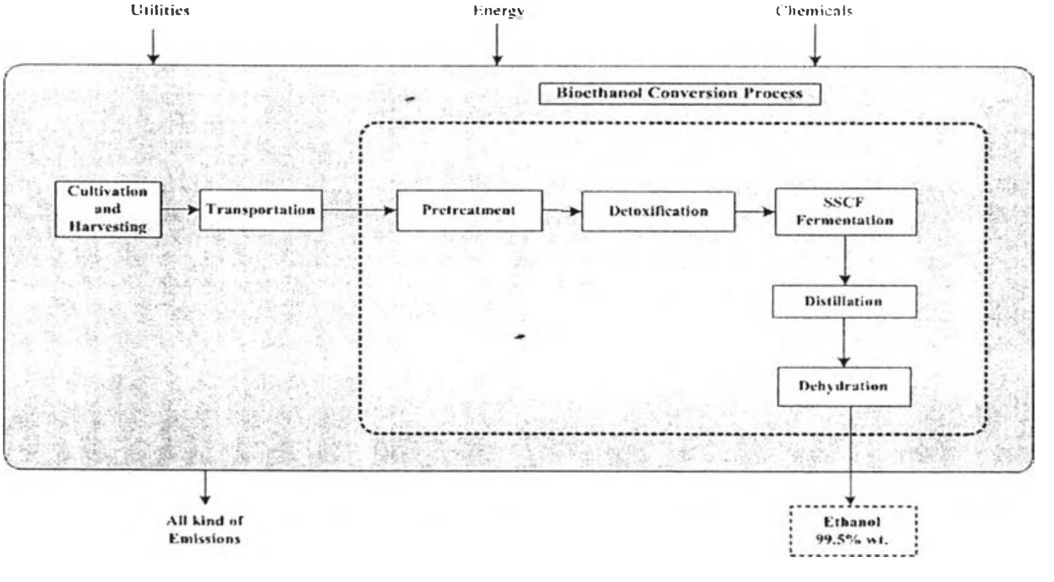

Figure 4.26 System boundary of alternative D case design.

In the bioethanol conversion process, it is divided into five stages: pretreatment, detoxification, SSCF fermentation, distillation and dehydration as shown in Appendix F.

Main input and output data of life cycle inventory got from literatures such as cassava cultivation from (Khongsiri, 2009), sugarcane cultivation and transportation from (MTEC, 2012) otherwise from databases and results of program such as corn plantation from (Schaer, 1993) of SimaPro7.1 due to it does not have data in Thailand, input and output data of bioethanol conversion process (five stages) from PROII9.1 program. All details of inventory data, cradle-to-gate, for the process are presented in Appendix F. The life cycle inventory analysis was performed on the raw material inputs, electricity, heat, air emission, water emission and emission to soil involved in the life cycle assessment of bioethanol production by cellulosic multi-feedstocks based on one kilogram of 99.5% bioethanol.

The inventory data in each stage (Appendix F) was analyzed by SimaPro7.1 program to evaluate life cycle impacts of bioethanol production using CML 2 baseline 2000 method in terms of abiotic depletion (ADP), global warming (GWP100), ozone layer depletion (ODP), human toxicity (HT), fresh water aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity, photochemical oxidation (PCO), acidification (AD) and eutrophication (EU). Results of life cycle impact assessment are shown in Table 4.12 that used mass allocation method and excluded emission from equipment.

Table 4.12 Results from life cycle impact assessment of bioethanol production of alternative D case design

Life Cycle Impact Assessment	Unit	Total
abiotic depletion	kg Sb eq	1.07E-02
global warming (GWP100)	kg CO_2 eq	2.66E+00
ozone layer depletion (ODP)	kg CFC-11 eq	1.65E-07
human toxicity	kg 1,4-DB eq	3.23E-01
fresh water aquatic ecotox.	kg 1,4-DB eq	2.99E-02
marine aquatic ecotoxicity	kg 1,4-DB eq	2.43E+02
terrestrial ecotoxicity	kg 1,4-DB eq	6.46E-03
photochemical oxidation	kg C_2H_4	4.59E-02
acidification	kg SO_2 eq	4.92E-03
eutrophication	kg PO_4 eq	1.06E-02

4.5.2 Alternative E Case Design

From the bottleneck of the previous case (alternative D case), this case focuses on reducing energy usage by means of heat integration. It uses alternative D case as the base case to improve process design. Heat integration uses pinch analysis method to generate heat exchanger networks.

4.5.2.1 Heat Exchanger Networks by Pinch Analysis

In the process, it has nine heat exchangers to pre-heat or cool down streams that compose of three cold streams and seven hot streams. Total cold and hot streams in the process are used to do heat exchanger networks described in Table 4.13.

Table 4.13 Cold and hot streams in the process in each heat exchanger

Cold streams				
Unit	Supply (˚C)	Target (˚C)	Enthalpy (MJ/hr)	FC_p (MJ/hr-˚C)
E5	41.31	100	3,482.00	59.33
E6	78.17	100	156.20	7.16
E-SACC	26.906	65	2,449.00	64.29
Hot streams				
Unit	Supply (˚C)	Target (˚C)	Enthalpy (MJ/hr)	FC_p (MJ/hr-˚C)
E2	82.647	65	1,205.30	68.30
E3	65	41	153.50	6.40
E4	65	41	1,414.90	58.95
E7	100	40	4,879.40	81.32
E-AM	85.89	82.647	223.50	68.92
E-SEED	75.228	41	974.50	28.47
E-FER	74.22	41	9,666.00	290.97

The minimum temperature approach (ΔT_{min}), heat recovery approximation temperature, is assumed to equals 10 °C. The pinch point is 100 °C for hot streams and 90 °C for cold streams calculated by pinch analysis method. The composite curve is shown in Figure 4.27.

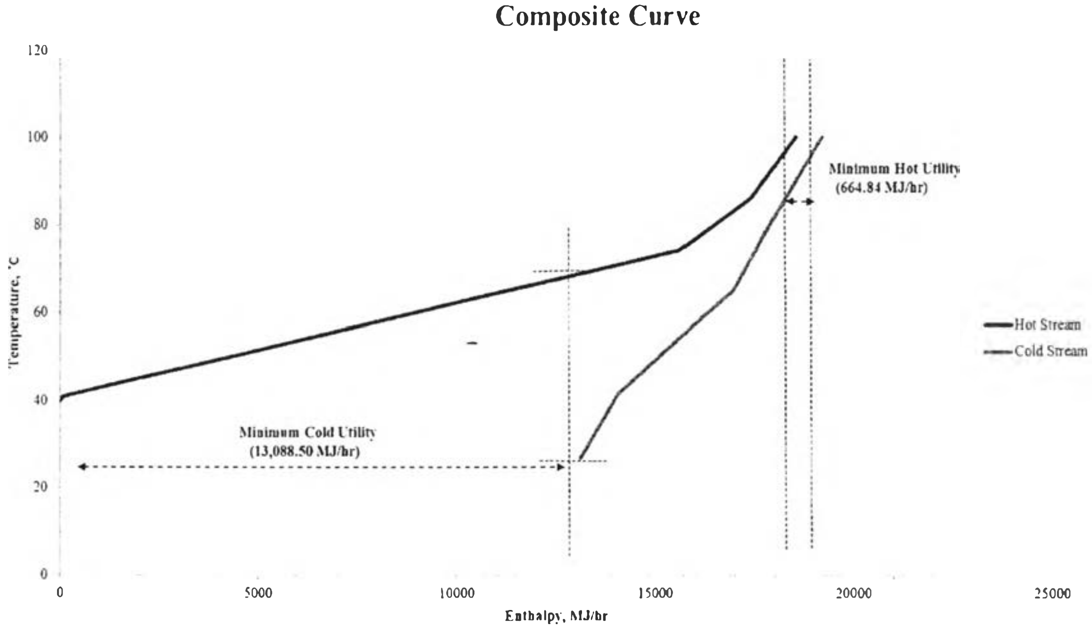

Figure 4.27 Composite curve of alternative E case design.

As seen Figure 4.27, the minimum cold and hot utility required for the process equals 13,088.50 and 664.84 MJ/hr respectively. The heat exchanger network in this process is shown in Figure 4.28. There are three stream pairs that can exchange energy in the process, between streams of E7 and E5 (2888.7 MJ/hr), E-AM and E6 (55.28 MJ/hr) and finally E-FER and E-SACC (2448.81 MJ/hr). Seven coolers and two heaters are required for the process. The next progress was generating process design with heat exchanger network in PROII 9.1 simulation program as shown in Figure 4.29.

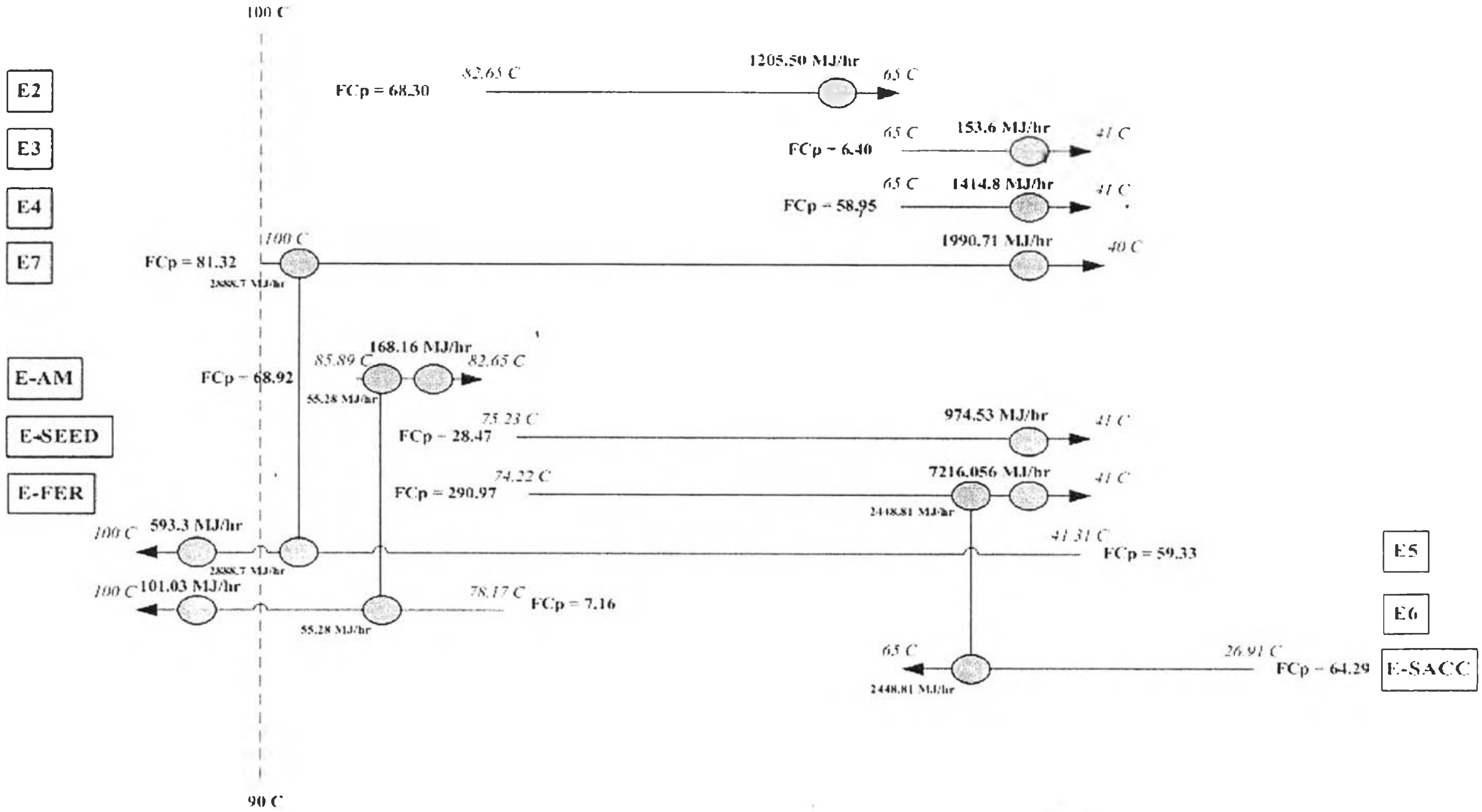

Figure 4.28 Heat exchanger networks of alternative E case design.

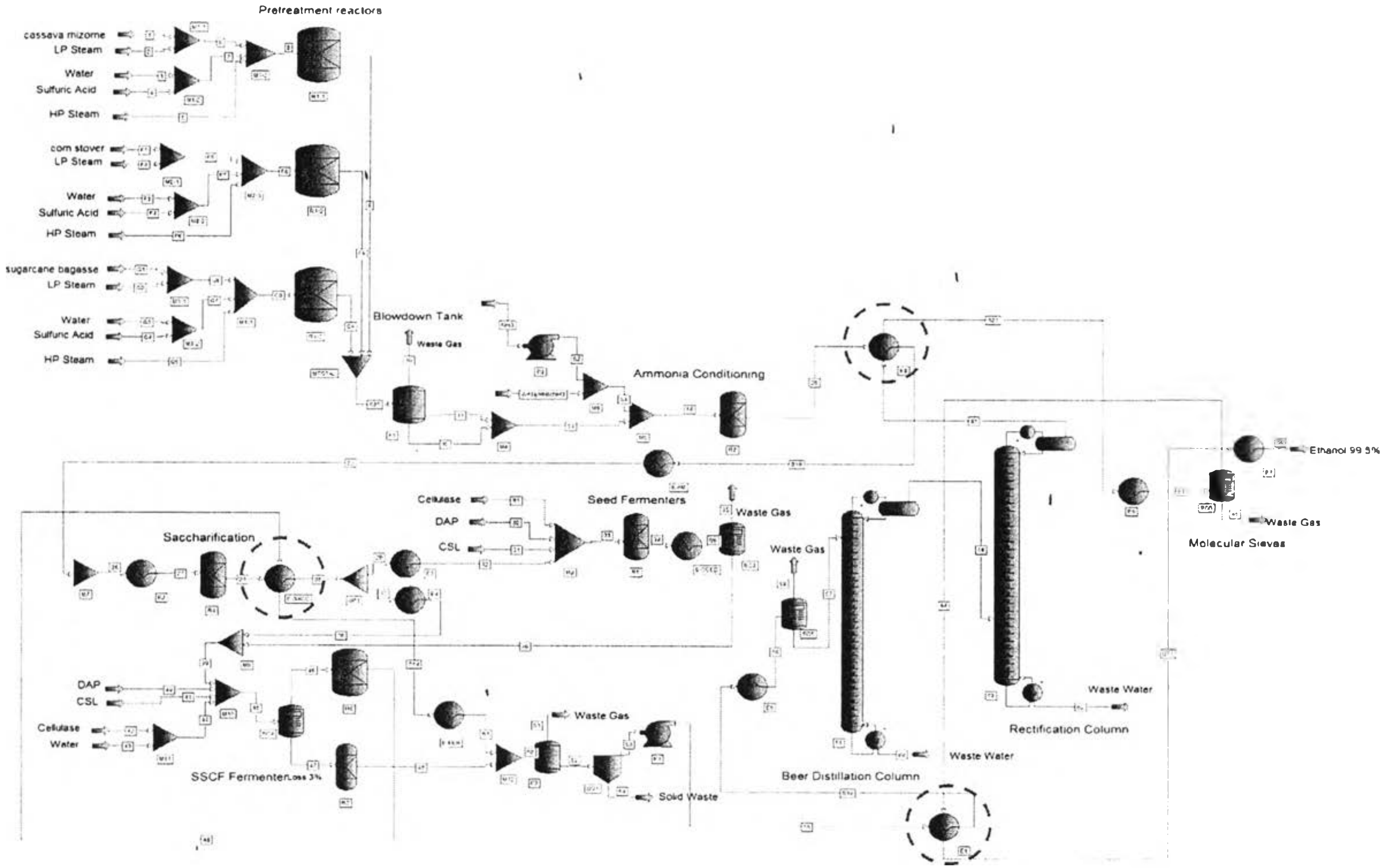

Figure 4.29 The process design of bioethanol production of alternative E case design with heat exchanger networks.

4.5.2.2 Sustainability Analysis of Alternative E Case

Firstly, alternative E case design was analyzed by SustainPro software. Results of sustainability analysis from software are shown in Appendix E. The de-bottlenecks of alternative E case in term of energy usage that SustainPro indicates by EWC indicator. Compared with EWC, the previous case design (alternative D case) that has high bottleneck in the process is used to compare with alternative E case (after heat integration) as shown in Table 4.14.

Table 4.14 The de-bottlenecks of alternative E case compared with alternative D case

Path	EWC (Alternative D case)	EWC (Alternative E case)	TVA (Alternative D case)	TVA (Alternative E case)
OP 177	973.28873	506.7959	-1000.6791	-533.9176
OP 356	0.01482	0.0135	-454.7688	-454.6733
OP 351	16.77849	9.2130	-414.26768	-406.7869
OP 33	70.72156	62.4166	-326.27726	-317.8860
OP 176	319.05145	245.4135	-320.18006	-247.0509
OP 263	293.56217	157.4837	-301.45963	-165.2400
OP 29	64.26179	57.3312	-298.53702	-291.6065
OP 135	281.40983	151.0763	-288.98379	-158.5160
OP 281	205.79196	108.9241	-211.32820	-114.2888
OP 153	203.43814	109.2169	-208.91354	-114.5951
OP 368	0.67500	0.1680	-182.01341	-181.5137
OP 357	0.01103	0.0117	-170.57477	-170.7792
OP 17	153.03881	138.1808	-153.03881	-138.1808
OP 21	132.69867	132.6986	-132.69867	-132.6987
OP 170	109.39207	57.8600	-112.43392	-60.8721
OP 359	59.97138	53.5978	-99.88642	-93.5127
OP 27	98.754098	97.5425	-98.75409	-97.5425
OP 262	92.52496	70.9407	-92.85037	-71.4089
OP 5	90.66765	82.8041	-90.66765	-82.8042
OP 134	88.72967	68.0464	-89.04175	-68.4956
OP 345	3.52841	1.9672	-86.06622	-84.5278
OP 67	80.25553	68.0240	-80.25553	-68.0240
OP 280	64.86154	49.0663	-65.08965	-49.3902
OP 152	64.14488	49.1924	-64.37049	-49.5172
OP 245	61.53565	34.4908	-63.19109	-36.1895
OP 81	59.62587	50.0034	-59.62587	-50.0034
OP 117	52.65825	28.2698	-54.07552	-29.6619
OP 361	32.35121	28.6017	-53.69312	-49.9364
OP 365	0.02291	0.0209	-46.03809	-46.0931
OP 31	10.03507	9.0236	-44.14449	-43.1331
OP 334	36.52012	19.9059	-36.52012	-19.9059

Path	EWC (Alternative D case)	EWC (Alternative E case)	TVA (Alternative D case)	TVA (Alternative E case)
OP 32	8.07519	7.2007	-36.47027	-35.5862
OP 169	35.48612	27.3497	-35.61146	-27.5316
OP 66	34.04469	22.6237	-34.04469	-22.6238
OP 256	32.97738	17.9405	-33.85444	-18.8020
OP 28	7.33935	6.6136	-33.36993	-32.6442
OP 128	31.61241	17.2105	-32.45354	-18.0368
OP 162	30.50541	16.4408	-31.40877	-17.3277

As seen above values in Table 4.14, EWC of alternative E case are less than alternative D case. It can conclude that heat integration can reduce EWC compared with the previous case. For example, OP177 which the highest bottleneck of EWC can be reduced about 2 times that means the process has higher efficiency in term of energy usage and TVA of alternative E case can be reduced because of decreased EWC.

Secondly, alternative E case design is calculated in term of economic evaluation as same as previous conditions by ECON software. The net revenue of alternative E case is 5.0154 M$/year, rate of return is 21% and payback period is 3.80 years. The sustainability metrics of alternative E case is shown in Table 4.15 compared with a previous case.

Table 4.15 The sustainability metrics of alternative E case compared with previous cases

Variables	Alternative D	Alternative E
Process specification		
Feedstock type	Combined	Combined
Feedstock usage (kg/day)	437,468.049	437,303.217
Chemical usage (kg/day)	5,757.871	5,767.114
Ethanol production (liters/day)	150,000.528	150,000.0930
Net fresh water added to the system (kg/day)	216,918.9790	217,895.1460
Performance criteria		
Raw material usage (kg RM/kg EtOH produced)	3.7164	3.715
Net fresh water added to the system/kg of product (kg/kg EtOH produced)	1.8188	1.8215
Total energy usage (GJ/kg EtOH produced)	0.02027	0.01275

Total wastes generation (kg/kg EtOH produced)	7.1519	7.1425
Hazardous raw material/kg of product (kg/kg EtOH produced)	0.0184	0.0184
Economic criteria		
Revenue Ethanol selling without cost ($x10^6$\$/year)	39.222	39.222
Total utility cost ($x10^6$\$/year)	5.6495	3.7970
Total capital investment ($x10^6$\$)	103.6372	105.0243
Capital cost per year ($x10^6$\$/year)	5.1819	5.2512
Total operating cost ($x10^6$\$/year)	30.6425	28.9622
Minimum ethanol selling price (\$/kg EtOH produced)	0.7786	0.7337
Net Revenue per year ($x10^6$\$/year)	3.4043	5.0154
Project life time (years)	20.00	20.00
Rate of return (%)	17.00	21.00
Pay Back period (years)	4.48	3.7961
Net Present Worth ($x10^6$\$)	21.3089	31.3930
Ranking	**Base case**	**1**

From Table 4.15, alternative E case can make more profit because of reducing energy usage resulting in total utility cost is decreased about 2 M\$/year from the previous case. Raw materials usages are quite the same as alternative D case. When focused on total utility cost of alternative E case, it is compared with the previous case in Figure 4.30. Cooling water and LP steam cost of alternative E case are two times less than the previous case and other are not different.

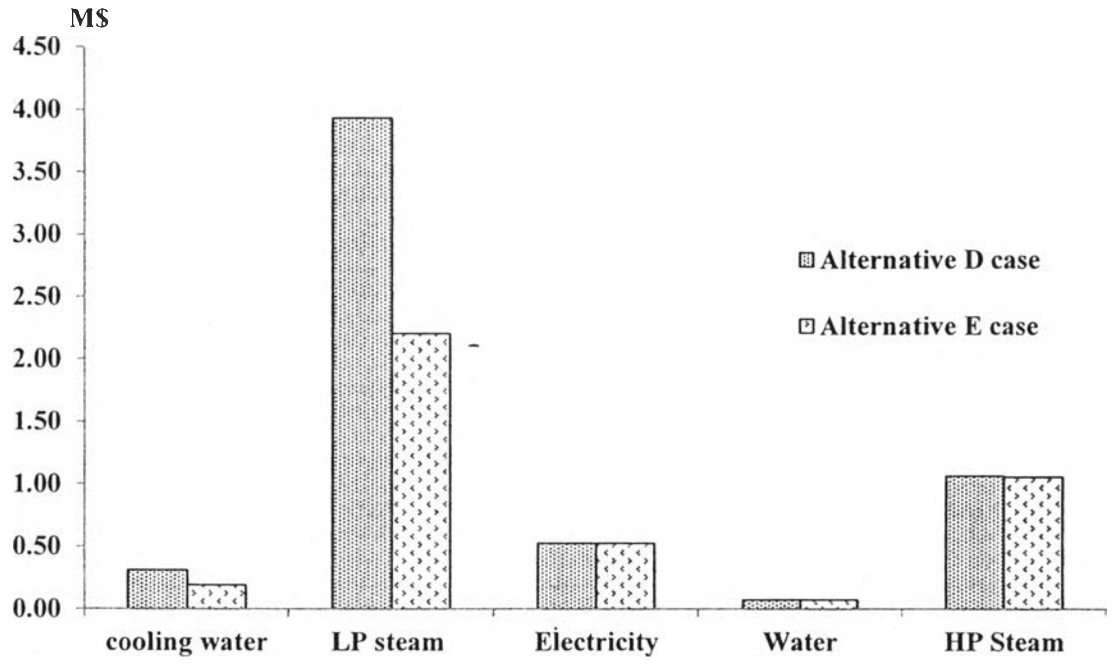

Figure 4.30 Breakdown of utility costs of alternative E case compared with the previous case.

4.5.2.3 Life Cycle Assessment of Alternative E Case

The alternative E case design that consists of heat exchanger networks in the process has the same boundary system and stages of bioethanol conversion process as alternative D case.

Life cycle inventory of this case is different from the previous case in term of energy usage (steam) that reduced by do heat integration in the process; for examples, steam usage equals zero kg of alternative E case compared with 0.237 kg of alternative D case in SSCF fermentation stage. All details of life cycle inventory of alternative E case design are shown in Appendix F.

This case was analyzed by the same as the previous case. Results of life cycle impact assessment of alternative E case design are shown in Table 4.16 compared with alternative D case.

Table 4.16 Results from life cycle impact assessment of bioethanol production of alternative E case design compared with the previous case

Life Cycle Impact Assessment		**Alternative D case**	**Alternative E case**
Impact category	**Unit**	**Total**	**Total**
abiotic depletion	kg Sb eq	1.07E-02	7.28E-03
global warming (GWP100)	kg CO_2 eq	2.66E+00	2.22E+00
ozone layer depletion (ODP)	kg CFC-11 eq	1.65E-07	1.05E-07
human toxicity	kg 1,4-DB eq	3.23E-01	2.05E-01
fresh water aquatic ecotox.	kg 1,4-DB eq	2.99E-02	1.94E-02
marine aquatic ecotoxicity	kg 1,4-DB eq	2.43E+02	1.55E+02
terrestrial ecotoxicity	kg 1,4-DB eq	6.46E-03	4.09E-03
photochemical oxidation	kg C_2H_4	4.59E-02	4.56E-02
acidification	kg SO_2 eq	4.92E-03	3.85E-03
eutrophication	kg PO_4 eq	1.06E-02	7.32E-03

As seen Table 4.16, all life cycle impact criteria of alternative E case after do heat exchanger networks are less than the previous case such as global warming potential (GWP 100) is 2.22 kg CO_2 equivalent of alternative E case compared with 2.66 kg CO_2 equivalent of alternative D case means that alternative E case is more environmental friendly than alternative E case.

4.5.3 Alternative F Case Design

The idea for alternative case is to reduce water consumption by water recycling that used treated-wastewater to reuse into the process. This alternative case will make the process more sustainable because it should reduce operating cost in term of raw material and decrease wastewater generation that affected to environment impacts when discard out of process and minimize the waste disposal cost. The process design is generated from alternative E case that modified water recycling with heat exchanger networks in the process.

4.5.3.1 Water Recycling by Membrane Treatment

In this process, membrane technology that used for the process has two series. The one is microfiltration (MF)/ultrafiltration (UF) membranes effective in removing suspended solids and larger molecules from a wastewater stream. MF/UF is a membrane filtration often used to provide pretreatment for better

RO feed and deals with the highly fouling of streams. It uses a sieving mechanism, which provides an absolute barrier to particles above the size of the MF/UF membrane pores. Nevertheless, both are quite porous membranes that are not tight enough to remove sufficient low molecular weight substances such as sugars, acids and aqueous salts. So the second is reverse osmosis (RO) that has the ability to remove small particles and produce high quality water in order to reuse at recoveries approaching 100% (Ryan *et al.*, 2009). The use of membrane not only has highly selective in wastewater treatment but it could result in considerable energy savings compared with to evaporation alone (Kavanagh *et al.*, 2006). So the use of membranes can potentially reduce the energy requirements.

The operating condition for membrane is 21 atm and 50-55 °C (Pearce, 2008). Membranes can recover water approximately 80% and remove contaminant about 95% (Koyuncu *et al.*, 2001). The process design is generated by simulation program as shown in Figure 4.31. Treated-wastewater is recycled to water usage in feedstock and ammonia conditioning section.

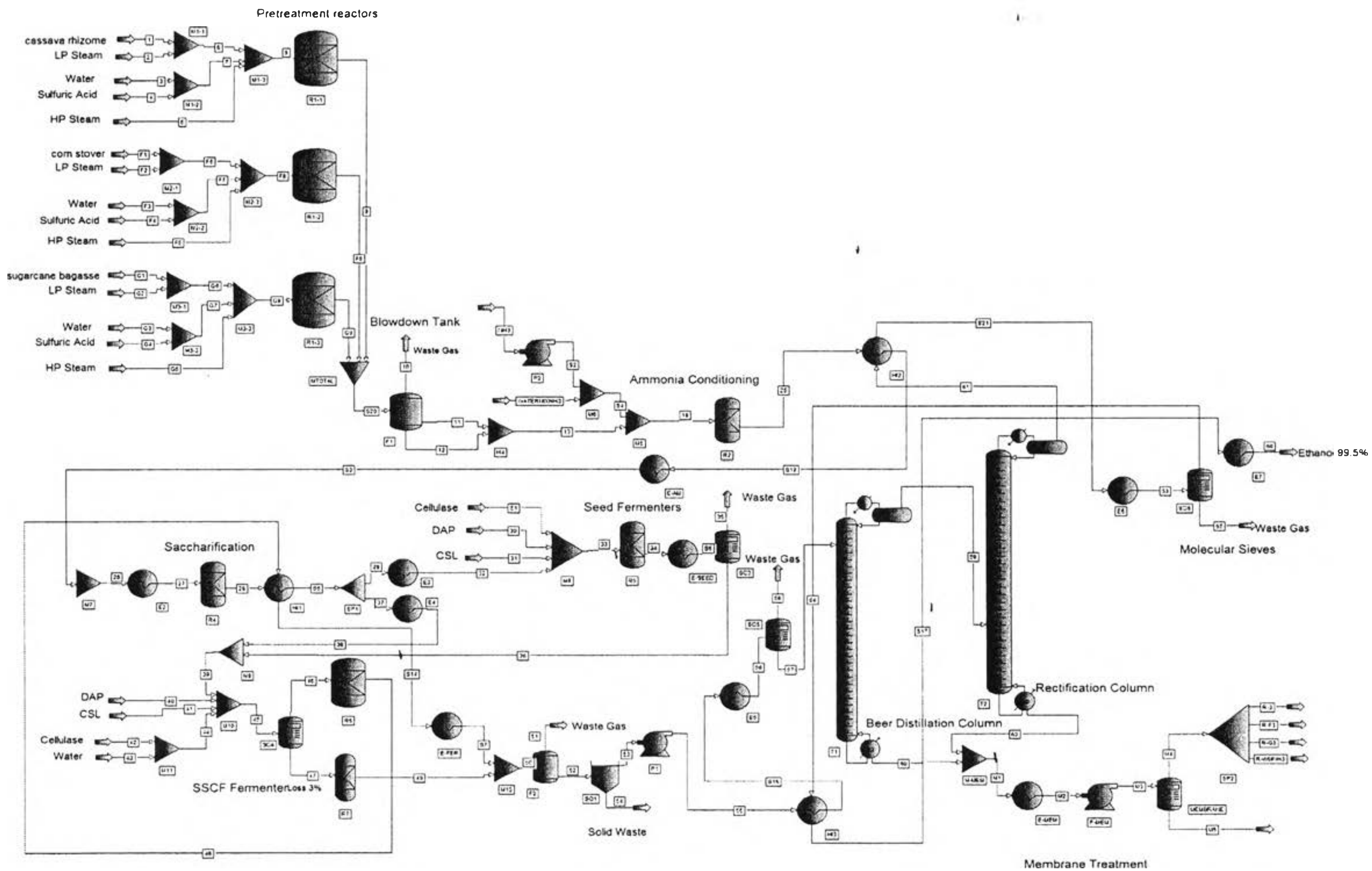

Figure 4.31 The process design of bioethanol production of alternative F case design with heat exchanger networks and water recycling.

4.5.3.2 Sustainability Analysis of Alternative F Case

Alternative F case design was analyzed by SustainPro software. It is compared with alternative E case design in term of mass consumption that indicated by MVA indicator. From Table 4.17, MVA of alternative F case in open paths after do water recycling is less than the previous case that means water recycling not only can reduce water consumption in the process but wastewater discard also decrease.

Table 4.17 The de-bottlenecks of alternative F case compared with alternative E case

Path	MVA (Alternative E case)	MVA (Alternative F case)	TVA (Alternative E case)	TVA (Alternative F case)
OP 113	-4.63393	-0.53875	-12.14525	-1.43601
OP 114	-0.01646	-0.01717	-0.06075	-0.05725
OP 115	-0.02265	-0.00267	-0.10748	-0.01364
OP 116	-0.26405	-0.03111	-1.11674	-0.14291
OP 118	-0.00736	-0.00086	-0.02672	-0.00340
OP 137	-0.54027	-0.44877	-0.83558	-0.74912
OP 138	-0.08257	-0.06975	-0.25798	-0.24051
OP 139	-0.96262	-0.81313	-2.51078	-2.38158
OP 141	-0.02685	-0.02246	-0.05388	-0.05152
OP 153	-0.46473	-0.05358	-1.28163	-0.14885
OP 154	-0.01486	-0.00171	-0.04911	-0.00589
OP 156	-0.00227	-0.00309	-0.01109	-0.01456
OP 157	-0.02648	-0.01932	-0.11562	-0.56586
OP 158	-0.00074	-0.00009	-0.00278	-0.00035
OP 180	-4.83111	-0.57702	-12.64885	-1.53705
OP 181	-0.15450	-0.01839	-0.48898	-0.06128
OP 182	-0.02361	-0.00286	-0.11199	-0.01461
OP 183	-0.27529	-0.03331	-1.16351	-0.15301
OP 185	-0.00768	-0.00092	-0.02783	-0.00364

Consequently, alternative F case design was calculated in term of economic evaluation as same as previous conditions by ECON software. The net revenue of alternative F case is 3.311 M$/year, rate of return is 16.5% and payback period is 4.65 years. The sustainability metrics of alternative F case is shown in Table 4.18 compared with previous cases.

Table 4.18 The sustainability metrics of alternative F case compared with previous cases

Variables	Alternative D	Alternative E	Alternative F
Process specification			
Feedstock type	Combined	Combined	Combined
Feedstock usage (kg/day)	437,468.049	437,303.217	437,063.519
Chemical usage (kg/day)	5,757.871	5,791.449	5,788.362
Ethanol production (liters/day)	150,000.00	150,000.00	150,000.00
Net fresh water added to the system (kg/day)	216,918.9790	217,895.1460	39,918.6620
Performance criteria			
Raw material usage (kg RM/kg EtOH produced)	3.7164	3.7153	3.7127
Net fresh water usage (kg/kg EtOH produced)	1.8188	1.8270	0.3347
Total energy usage (GJ/kg EtOH produced)	0.02027	0.01275	0.01310
Total wastes generation (kg/kg EtOH produced)	7.1519	7.1643	3.3887
Hazardous raw material (kg/kg EtOH produced)	0.0184	0.0184	0.0186
Economic criteria			
Revenue Ethanol selling without cost (x10^6\$/year)	39.222	39.2288	39.2283
Total utility cost (x10^6\$/year)	5.6495	3.7970	3.8244
Total capital investment (x10^6\$)	103.6372	105.0243	106.5366
Capital cost per year (x10^6\$/year)	5.1819	5.2512	5.3268
Total operating cost (x10^6\$/year)	30.6425	28.9622	30.5905
Minimum ethanol selling price (\$/kg EtOH produced)	0.7786	0.7359	0.7772
Net Revenue per year (x10^6\$/year)	3.4043	5.0154	3.3110
Project life time (years)	20.00	20.00	20.00
Rate of return (%)	17.00	21.00	16.50
Pay Back period (years)	4.48	3.7961	4.6537
Net Present Worth (x10^6\$)	21.3089	31.3930	20.2443
Ranking	**Base case**	**1**	**2**

From Table 4.18, net fresh water of alternative F case after do water recycling is 0.335 kg/kg ETOH produced, less than alternative D and E cases about 6 times, that means this process can save more water adding into process. Moreover, total wastes generation is less than previous cases about 2 times because waste water production was reduced. So this process is environmental-friendly more.

Focused on performance criteria, the ranking of alternative F case is the last that the process makes the least profit compared with other cases because the one that affected this process is the highest total capital cost, installed membrane treatment units section.

4.5.3.3 Life Cycle Assessment of Alternative F Case

The system boundary of alternative F case design is different from two previous cases because it consists of membrane section in process that treats wastewater to recycle treat-water into the process. System boundary of alternative F case is shown in Figure 4.32. In bioethanol conversion, this case consists of 6 stages and life cycle inventory of alternative F case design are shown in Appendix F.

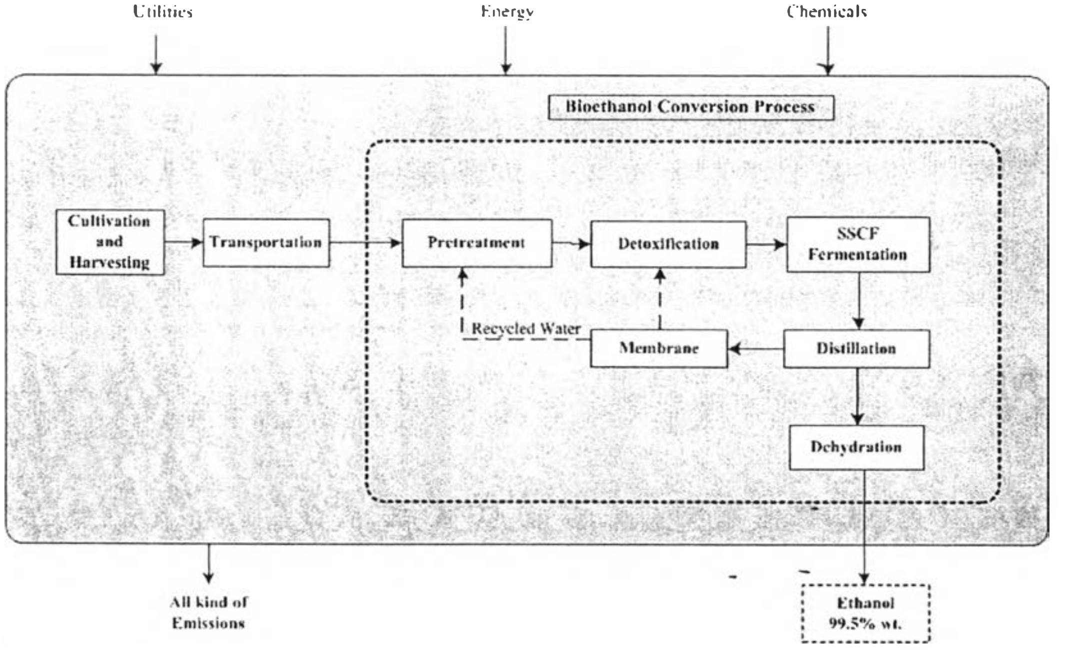

Figure 4.32 System boundary of alternative F case design.

Results of life cycle impact assessment of alternative F case design are shown in Table 4.19 after it was analyzed by the same conditions as two previous cases. Focused on GWP 100, alternative F case combined heat exchanger networks with membrane treatment in the process equals 1.79 kg CO_2 equivalent that is the least value compared with two previous cases. Other main life cycle impact values of alternative F case, such as acidification (0.00291 kg SO_2 equivalent), eutrophication (0.0457 kg PO_4 equivalent) are less than alternative D and E case. So this alternative case design is more environmental friendly than other cases.

Table 4.19 Results from life cycle impact assessment of bioethanol production of alternative F case design compared with previous cases

Life Cycle Impact Assessment		**Alternative D case**	**Alternative E case**	**Alternative F case**
Impact category	**Unit**	**Total**	**Total**	**Total**
abiotic depletion	kg Sb eq	1.07E-02	7.28E-03	4.26E-03
global warming (GWP100)	kg CO_2 eq	2.66E+00	2.22E+00	1.79E+00
ozone layer depletion (ODP)	kg CFC-11 eq	1.65E-07	1.05E-07	5.62E-08
human toxicity	kg 1,4-DB eq	3.23E-01	2.05E-01	1.10E-01
Fresh water aquatic ecotox.	kg 1,4-DB eq	2.99E-02	1.94E-02	1.08E-02
marine aquatic ecotoxicity	kg 1,4-DB eq	2.43E+02	1.55E+02	8.44E+01
terrestrial ecotoxicity	kg 1,4-DB eq	6.46E-03	4.09E-03	2.18E-03
photochemical oxidation	kg C_2H_4	4.59E-02	4.56E-02	4.46E-02
acidification	kg SO_2 eq	4.92E-03	3.85E-03	2.91E-03
eutrophication	kg PO_4 eq	1.06E-02	7.32E-03	4.57E-03

4.5.4 Alternative G Case Design

4.5.4.1 Solid Waste Combustion of Alternative G Case

To make more sustainable process design, the idea for this alternative case used solid waste as lignin from process to combust for generate steam such as low pressure and high pressure steam that used for pre-heat feedstocks so the process should reduce energy consumption because total operating cost should be decreased. The process was continued generated from alternative F case that added solid waste combustion units section to the process. The process design was generated by simulation program is shown in Figure 4.33.

4.5.4.2 Sustainability Analysis of Alternative G Case

Alternative G case design was analyzed by SustainPro software. It is compared with alternative F case design in term of energy consumption and energy loss that indicated by EWC indicator. Table 4.20 is shown de-bottlenecks of alternative G case compared with alternative F case in open path of process in term of EWC.

As seen Table 4.20, EWC of alternative G case in all open paths equal zero because this process recycles use whole solid waste sent to combustion process. Moreover, TVA in this process equal zero that means no mass loss and energy out of process in term of steam usage. Their values are less than alternative F case design so alternative G case design is more sustainable in terms of mass and energy. This process is compared sustainability results with previous cases in Table 4.21.

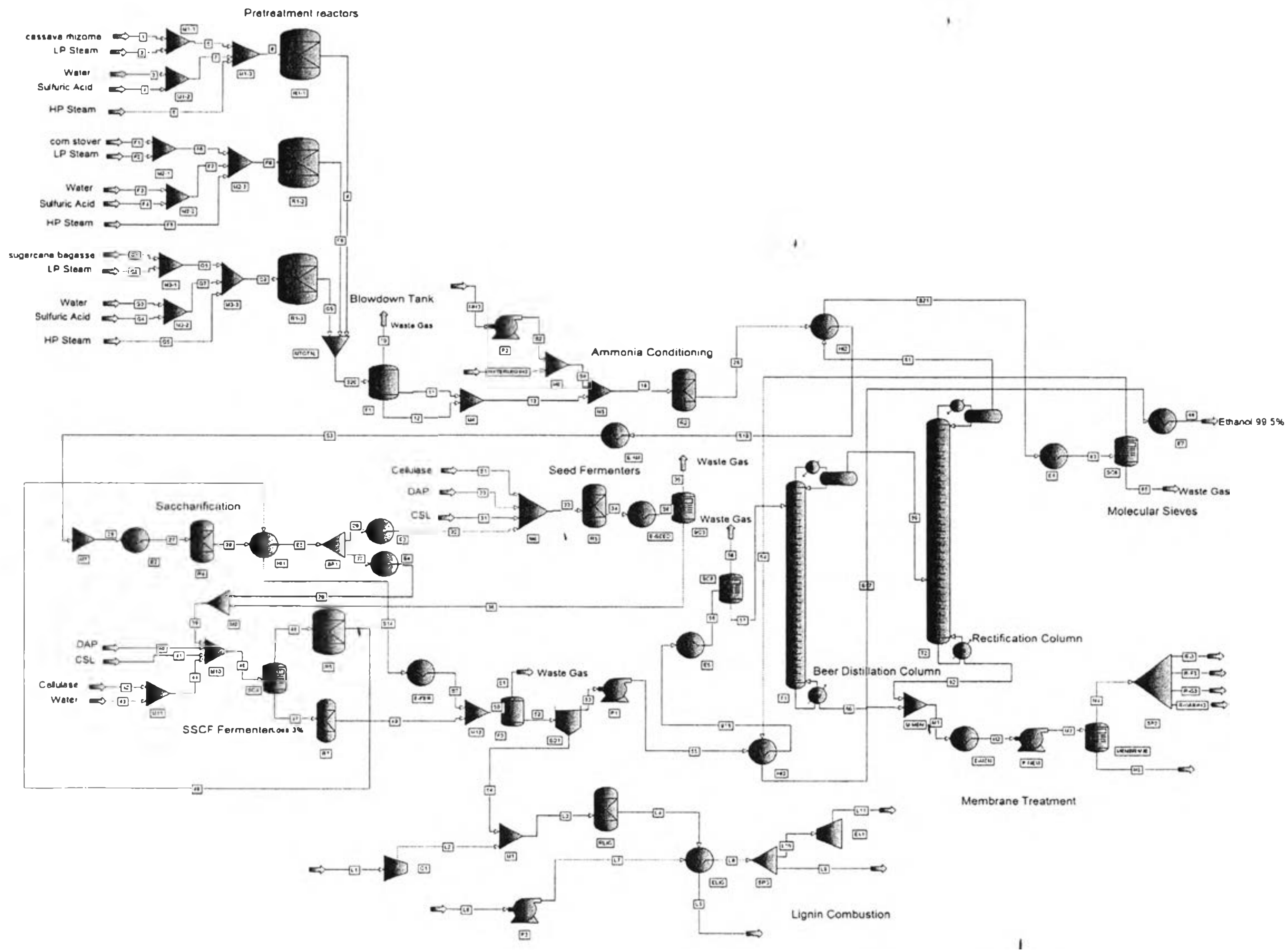

Figure 4.33 The process design of bioethanol production of alternative G case design with heat exchanger networks, water recycling and solid waste combustion.

Table 4.20 The de-bottlenecks of alternative G case compared with alternative F case

Path	EWC (Alternative F case)	EWC (Alternative G case)	TVA (Alternative F case)	TVA (Alternative G case)
OP 104	2.15161	0	-3.44352	0
OP 105	0.09611	0	-0.13728	0
OP 106	0.02632	0	-0.03272	0
OP 107	0.26810	0	-0.34269	0
OP 108	13.12467	0	-13.59039	0
OP 109	0.00610	0	-0.00816	0
OP 110	0.02873	0	-0.02873	0
OP 111	0.29915	0	-0.29915	0
OP 112	0.78073	0	-0.78073	0
OP 122	8.31250	0	-13.30361	0
OP 123	0.37132	0	-0.53036	0
OP 124	0.10168	0	-0.12640	0
OP 125	1.03579	0	-1.32395	0
OP 126	50.70555	0	-52.50478	0
OP 127	0.02355	0	-0.03151	0
OP 128	0.11100	0	-0.11100	0
OP 129	1.15572	0	-1.15572	0
OP 130	3.01624	0	-3.01624	0
OP 144	0.22605	0	-0.35319	0
OP 145	0.00991	0	-0.01397	0
OP 146	0.00266	0	-0.00329	0
OP 147	0.02721	0	-0.03455	0
OP 148	1.29677	0	-1.34261	0
OP 149	0.00062	0	-0.00083	0
OP 150	0.00300	0	-0.00300	0
OP 151	0.03134	0	-0.03134	0
OP 152	0.06384	0	-0.06384	0
OP 162	0.88526	0	-1.38316	0
OP 163	0.03883	0	-0.05469	0
OP 164	0.01042	0	-0.01289	0
OP 165	0.10656	0	-0.13531	0
OP 166	5.07845	0	-5.25794	0
OP 167	0.00244	0	-0.00323	0
OP 168	0.01175	0	-0.01175	0
OP 169	0.12272	0	-0.12272	0
OP 170	0.25001	0	-0.25001	0
OP 171	10.45691	0	-16.74196	0
OP 172	0.46725	0	-0.66752	0
OP 173	0.12799	0	-0.15912	0
OP 174	1.30370	0	-1.66657	0

OP 175	63.84713	0	-66.11281	0
OP 176	0.02964	0	-0.03966	0
OP 177	0.13965	0	-0.13965	0
OP 178	1.45393	0	-1.45393	0
OP 179	2.76142	0	-2.76142	0
OP 189	0.78267	0	-1.25309	0
OP 190	0.03497	0	-0.04996	0
OP 191	0.00958	0	-0.01191	0
OP 192	0.09758	0	-0.12474	0
OP 193	4.77879	0	-4.94837	0
OP 194	0.00222	0	-0.00297	0
OP 195	0.01045	0	-0.01045	0
OP 196	0.10882	0	-0.10882	0
OP 197	0.20668	0	-0.20668	0

From Table 4.21, all alternative cases are quite same raw materials usage that has a little bit different values because their values got from process simulation program that program cannot fix values constantly. Total energy usage and total wastes generation of alternative G case are the lowest value because this process has the solid waste combustion and waste water treatment section in the process. For net fresh water added to the process, alternative G case is less than other cases excepted alternative F case because more net fresh water is used for produce steam in a solid waste combustion section that used to preheat feedstocks. Steam that was produced in solid waste combustion can be used instead of steam that purchased from outsource.

Alternative G case makes the most profitability in term of performance criteria which net revenue is 6.2645 M$/year, rate of return is 27%, payback period is 2.54 years and net present worth is 39.22 M$. Thus, alternative G case is the best process in term of process specification, performance and economic criteria.

Table 4.21 The sustainability metrics of alternative G case compared with previous cases

Variables	Alternative D	Alternative E	Alternative F	Alternative G
Process specification				
Feedstock type	Combined	Combined	Combined	Combined
Feedstock usage (kg/day)	437,468.049	437,303.217	437,063.519	437,160.644
Chemical usage (kg/day)	5,757.871	5,767.114	5,788.362	5,765.713
Ethanol production (liters/day)	150,000.5280	150,000.0930	150,000.1120	150,000.1510
Net fresh water added to the system (kg/day)	216,918.9790	217,895.1460	39,918.6620	134,807.1210
Performance criteria				
Raw material usage (kg RM/kg EtOH produced)	3.716	3.715	3.713	3.713
Net fresh water ysage (kg/kg EtOH produced)	1.8188	1.8215	0.3347	1.1303
Total energy usage (GJ/kg EtOH produced)	0.02027	0.01271	0.01310	0.01171
Total wastes generation (kg/kg EtOH produced)	7.1519	7.1425	3.3887	3.1012
Hazardous raw material (kg/kg EtOH produced)	0.0184	0.0184	0.0186	0.0184
Economic criteria				
Revenue Ethanol selling without cost ($x10^6$\$/year)	39.222	39.222	39.222	39.222
Total utility cost ($x10^6$\$/year)	5.6495	3.7970	3.8244	3.1396
Total capital investment ($x10^6$\$)	103.6372	105.0243	106.5366	110.4533
Capital cost per year ($x10^6$\$/year)	5.1819	5.2512	5.3268	5.5227
Total operating cost ($x10^6$\$/year)	30.6425	28.9622	30.5905	27.4356
Minimum ethanol selling price (\$/kg EtOH produced)	0.7786	0.7337	0.7772	0.6971
Net Revenue per year ($x10^6$\$/year)	3.4043	5.0154	3.3110	6.2645
Project life time (years)	20.00	20.00	20.00	20.00
Rate of return (%)	17.00	21.00	16.50	27.00
Pay Back period (years)	4.4843	3.7961	4.6537	2.5354
Net Present Worth ($x10^6$\$)	21.3089	31.3930	20.2443	39.2118
Ranking	**Base case**	**2**	**3**	**1**

For more obviously, alternative G case is shown breakdown of raw material prices and utility costs in Figure 4.34 and 4.35 respectively.

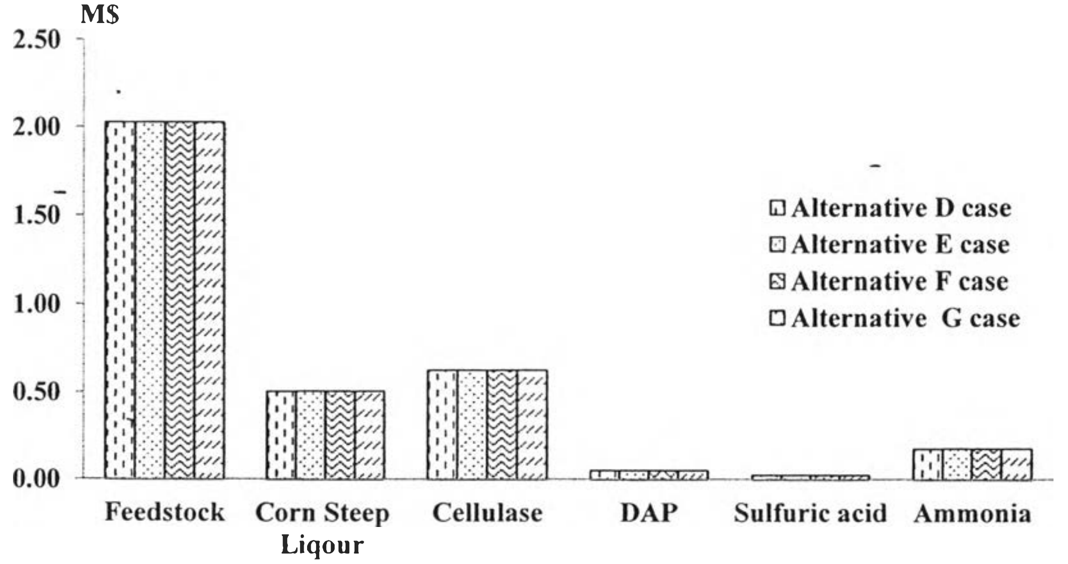

Figure 4.34 Breakdown of raw material prices of alternative G case compared with previous cases.

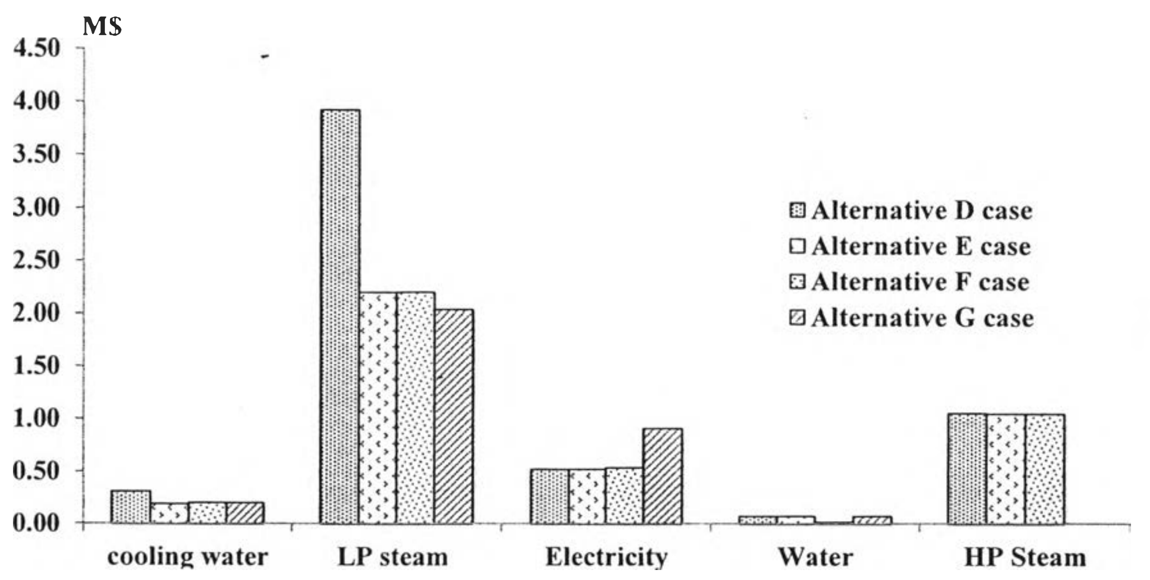

Figure 4.35 Breakdown of utility costs of alternative G case compared with previous cases.

4.5.4.3 Life Cycle Assessment of Alternative G Case Design

The system boundary of alternative G case design is added solid waste combustion section from alternative F case design as shown in Figure 4.36. The idea of this alternative case is to reduce energy usage and solid waste discard out of process. Stages of bioethanol conversion process and results of life cycle inventory of alternative G case are shown in Appendix F.

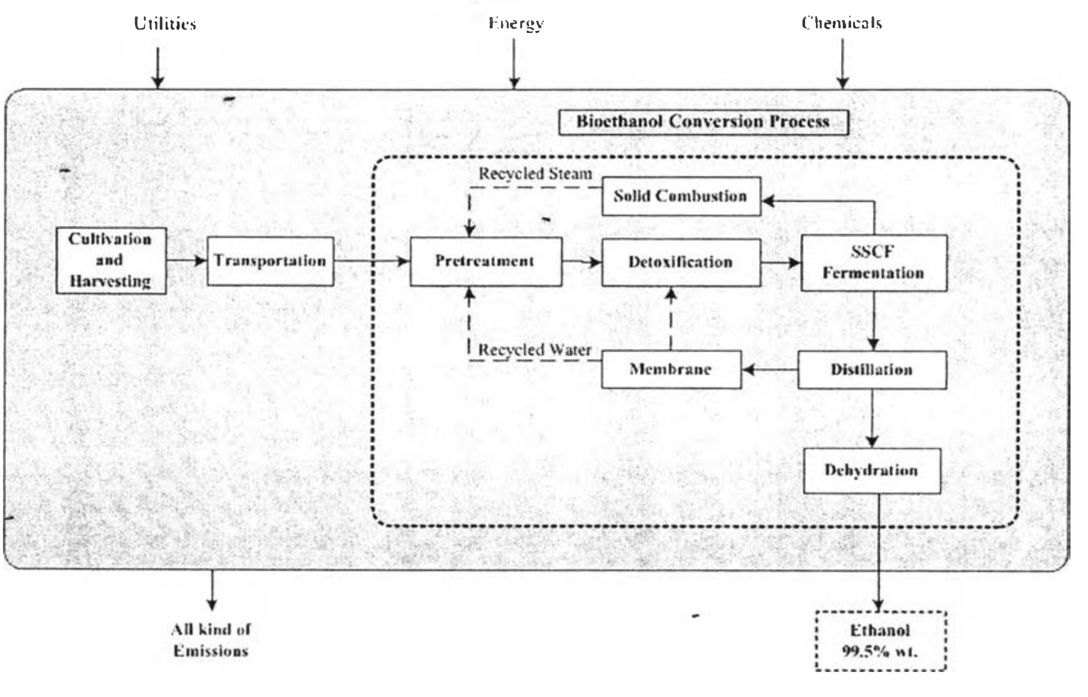

Figure 4.36 System boundary of alternative G case design.

Results of life cycle impact assessment of alternative G case design are shown in Table 4.22 that analyzed by the same conditions as previous cases. Values of life cycle impacts of alternative G case are less than all previous cases such as acidification, 0.00258 kg SO_2 equivalent, compared with 0.00492, 0.00385 and 0.00291 kg SO_2 equivalent of alternative D, E and F case, respectively and GWP100 equals 1.37 kg CO_2 equivalent compared with 2.66, 2.22 and 1.79 kg CO_2 equivalent of alternative D, E and F case respectively.

From scopes of this work, they focus on main environmental impacts (acidification, eutrophication and GWP100) so alternative G case is the lowest impacts of them. So we can conclude that alternative G case would be preferred for the best environmental aspects.

Table 4.22 Results from life cycle impact assessment of bioethanol production of alternative G case design compared with previous cases

Life cycle impact assessment		**Alternative D case**	**Alternative E case**	**Alternative F case**	**Alternative G case**
Impact category	**Unit**	**Total**	**Total**	**Total**	**Total**
abiotic depletion	kg Sb eq	1.07E-02	7.28E-03	4.26E-03	3.19E-03
global warming (GWP100)	kg CO_2 eq	2.66E+00	2.22E+00	1.79E+00	1.37E+00
ozone layer depletion (ODP)	kg CFC-11 eq	1.65E-07	1.05E-07	5.62E-08	3.24E-08
human toxicity	kg 1,4-DB eq	3.23E-01	2.05E-01	1.10E-01	6.02E-02
fresh water aquatic ecotox.	kg 1,4-DB eq	2.99E-02	1.94E-02	1.08E-02	6.97E-03
marine aquatic ecotoxicity	kg 1,4-DB eq	2.43E+02	1.55E+02	8.44E+01	5.01E+01
terrestrial ecotoxicity	kg 1,4-DB eq	6.46E-03	4.09E-03	2.18E-03	1.18E-03
photochemical oxidation	kg C2H4	4.59E-02	4.56E-02	4.46E-02	3.41E-02
acidification	kg SO_2 eq	4.92E-03	3.85E-03	2.91E-03	2.58E-03
eutrophication	kg PO_4 eq	1.06E-02	7.32E-03	4.57E-03	4.01E-03

4.6 Overall Alternative Cases Design Comparison

To find the best sustainable case design, all cases design of multi-feedstocks are compared in term of sustainability that consists of seven main factors (net water consumption, total energy usage, total wastes generation, net present value, acidification, eutrophication and global warming potential) from results of sustainability metrics and life cycle impact assessment in Table 4.21 and 4.22 respectively. Main factors of each alternative case design are compared by normalization of each factor as shown in Figure 4.37.

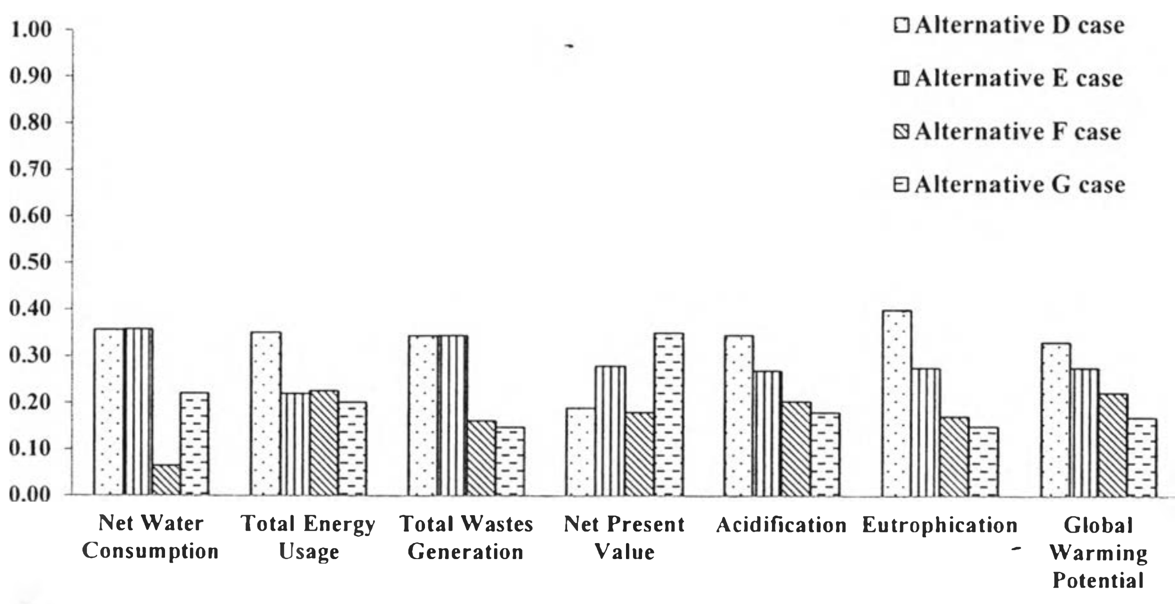

Figure 4.37 Seven main factors comparison of sustainability in overall alternative cases design.

As seen Figure 4.37, first three factors (net water consumption, total energy usage and total wastes generation) get from performance criteria of sustainability metric. Alternative G case is the best process in term of performance criteria that is the lowest values of total energy usage and total wastes generation. Even though net water consumption is not the lowest as alternative F case because alternative G case used more water for produce steam that used to preheat feedstocks that can reduce steam purchasing from outsource, utility and energy consumption in the process.

Focused on the forth factor, it is NPV from economic criteria of sustainability metric. The highest profit is alternative G case because this process has the highest performance that made the lowest operating cost and the highest net revenue per year.

The last three factors (acidification, eutrophication and GWP100) are life cycle impact assessment criteria. Acidification and eutrophication are presented as indicators for air and water pollution, respectively. Alternative G case is the lowest environmental impacts in terms of acidification, eutrophication and GWP100.

So this work give an importance of each factor at the same level, alternative G case is the best values which gave six out of seven main sustainability factors. More clearly, Figure 4.38 shows overall comparison of seven main sustainability factors in all cases designs. Thus, the comparison of overall criteria in terms of seven main factor of sustainability, the best sustainable process design is alternative G case for bioethanol production.

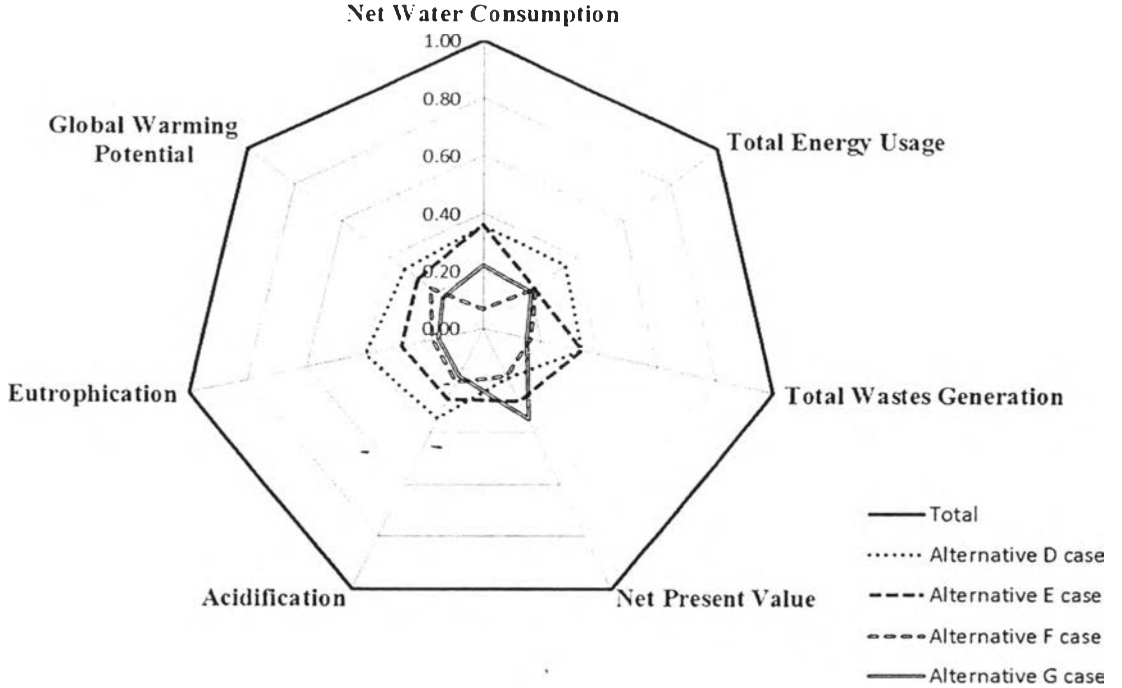

Figure 4.38 Overall comparison of overall criteria of seven main sustainability factors.