CHAPTER IV
RESULTS AND DISCUSSION

4.1 Life Cycle Inventory

A life cycle inventory (LCI) is a process of quantifying energy and raw material requirements, emission to air, emission to water, and other releases for the entire life cycle of a product, process, or activity. In this research, LCI is performed on natural gas production/separation in the gate-to-gate framework which covers three gas separation plant (GSP) units of PTT Public Company Limited at Mab-ta-phut, Rayong. These GSPs are currently producing 5 main products which are sale gas (mainly methane), ethane, propane, LPG, and NGL. This results in three life cycle inventories being generated for three gas separation plant units as shown in the following sections.

4.1.1 Gas separation plant unit 1 (GSP1)

Gas separation plant unit 1 (GSP1) is quite unique among the three gas separation plants being studied as it is the only unit that is equipped with a carbon dioxide removal unit for separating carbon dioxide as a product and reducing the amount of carbon dioxide in sale gas which can improve heating and sale values of the sale gas. The production capacity for natural gas feed of this unit is 350 MMSCFD. The LCI inventory includes all processes which involve in gas separation plant unit 1 in order to get 1 kg of product which are shown in Figure 4.1. Details of input and output data collection for the gas separation plant unit 1 are shown in Figure 4.2. Table 4.1 shows the results of the inventory analysis of the overall input-output of GSP1 for the production of 1 kg of product. As the allocation was done by using a weight-basis, all products were equally shared the loads for raw materials and energy consumption as well as the emissions to air, water and soil.

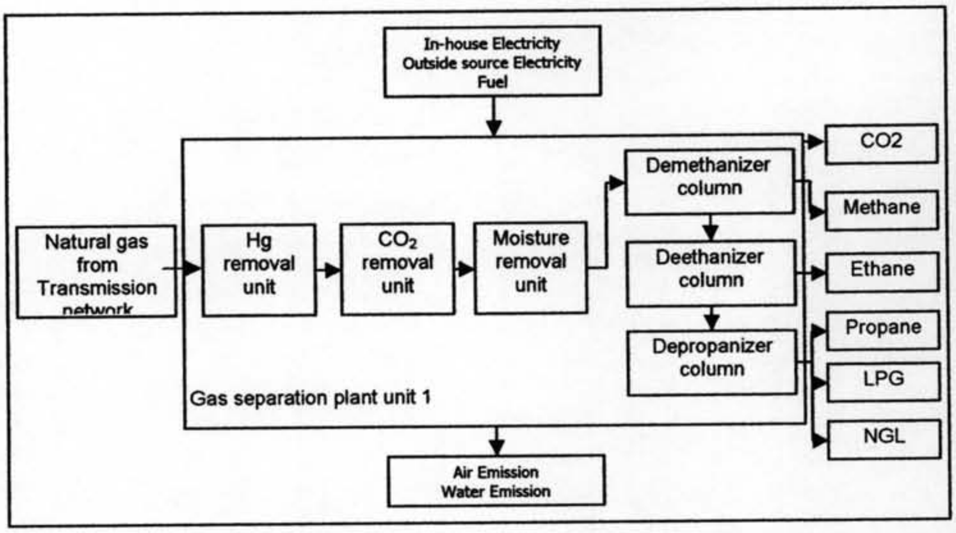

Figure 4.1 Gas separation plant unit 1 processes

Raw Material	Unit
Natural Gas	mmscf

Energy	Unit
Electricity (on site)	KW-Hr
Electricity (from outside source)	KW-Hr
Fuel Gas (Sale Gas)	mmscf

GSP 1

Product	Unit
Methane	ton
Ethane	ton
Propane	ton
LPG	ton
NGL	ton
CO_2	ton

Emission to water	Unit
SS	mg
TDS	mg
TS	mg
Oil & Grease	mg
BOD	mg
COD	mg
DO	mg
TKN	mg
Cl	mg
Hg	mg
Zn	mg

Emission to air	Unit
CO_2	kg
CO	mg
SOx	mg
NOx	mg
H_2S	mg

Figure 4.2 Input-output details of gas separation plant unit 1

Table 4.1 The input-output of overall process of the GSP1 production of 1 kg of product.

Input data			Output data	
Type	Unit		Type	Unit
Raw Materials	m^3		**Emission to Air**	mg
Natural gas	0.97		NO_x	74.1
Energy			CO_2	4.80E+04
-Electricity	MJ		CO	121
In-house	4E-02		SO_x	0.316
EGAT	9E-03		H_2S	4.14
-Fuel	m^3		**Emission to Water**	mg
Natural gas	0.0191		SS	0.2
			TDS	6.31
			Oils	1.96E-02
			BOD	5.63E-02
			COD	0.53

4.1.2 Gas separation plant unit 2 (GSP2)

GSP2 was designed to produce only sale gas, ethane, LPG, and NGL, not propane and it was not equipped with a carbon dioxide removal unit. The inventory covers all processes involved in the production of 1 kg of product as shown in Figure 4.3. Details of input and output data collection of GSP2 are shown in Figure 4.4. Table 4.2 shows the results of the inventory analysis of the overall input-output of GSP2 for the production of 1 kg of product.

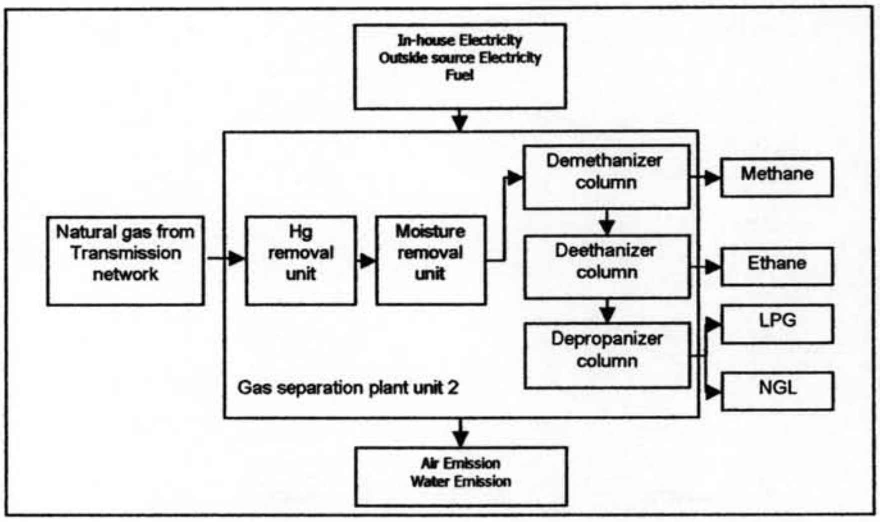

Figure 4.3 Gas separation plant unit 2 processes

Raw Material	Unit
Natural Gas	mmscf
Propylene	ton

Energy	Unit
Electricity (on site)	KW-Hr
Electricity (from outside source)	KW-Hr
Fuel Gas (Sale Gas)	mmscf

GSP 2

Product	Unit
Methane	ton
Ethane	ton
LPG	ton
NGL	ton

Emission to water	Unit
SS	mg
TDS	mg
TS	mg
Oil & Grease	mg
BOD	mg
COD	mg
DO	mg
TKN	mg
Cl	mg
Hg	mg
Zn	mg

Emission to air	Unit
CO_2	kg
CO	mg
SOx	mg
NOx	mg
H_2S	mg

Figure 4.4 Input-output details of gas separation plant unit 2

Table 4.2 The input-output of overall process of the GSP2 production of 1 kg of product.

Input data			Output data	
Type	Unit		Type	Unit
Raw Materials	m^3		**Emission to Air**	mg
Natural gas	1.07		NO_x	56.5
Energy			CO_2	2.30E+04
-Electricity	MJ		CO	82.7
In-house	1.10E-02		SO_x	0.412
EGAT	2.70E-03		H_2S	13.8
-Fuel	m^3		**Emission to Water**	mg
Natural gas	1.10E-02		SS	0.2
			TDS	6.49
			Oils	1.43E-02
			BOD	4.98E-02
			COD	0.53

4.1.3 Gas separation plant unit 3 (GSP3)

GSP3 is quite similar to GSP1 in terms of process as well as the capacity. The only difference is that GSP3 is not equipped with a carbon dioxide removal unit, and thus, most of carbon dioxide is not separated out and being released along with the sale gas product. The LCI inventory includes all processes which involve in gas separation plant unit 3 to get 1 kg of product as shown in Figure 4.5. Details of input and output data collection of gas separation plant unit 3 are shown in Figure 4.6. Table 4.3 shows the results of the overall input-output of GSP3 for the production of 1 kg of product.

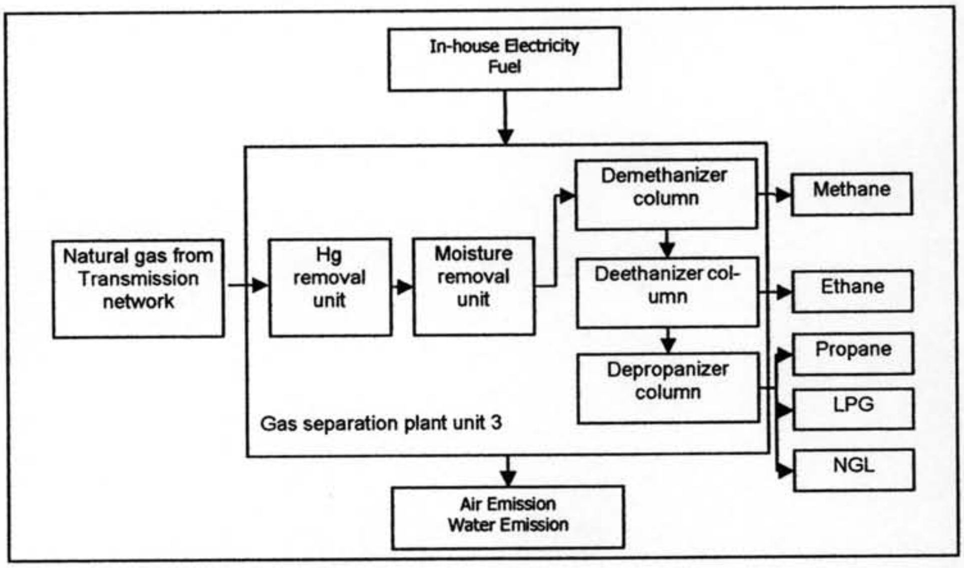

Figure 4.5 Gas separation plant unit 3 processes

Raw Material	Unit
Natural Gas	mmscf
Propylene	ton

Energy	Unit
Electricity (on site)	KW-Hr
Electricity (from outside source)	KW-Hr
Fuel Gas (Sale Gas)	mmscf

GSP 3

Product	Unit
Methane	ton
Ethane	ton
Propane	ton
LPG	ton
NGL	ton

Emission to water	Unit
SS	mg
TDS	mg
TS	mg
Oil & Grease	mg
BOD	mg
COD	mg
DO	mg
TKN	mg
Cl	mg
Hg	mg
Zn	mg

Emission to air	Unit
CO_2	kg
CO	mg
SOx	mg
NOx	mg
H_2S	mg

Figure 4.6 Input-output details of gas separation plant unit 3

Table 4.3 The input-output of overall process of the GSP3 production of 1 kg of product.

Input data			Output data	
Type	Unit		Type	Unit
Raw Materials	m^3		**Emission to Air**	mg
Natural gas	0.98		NO_x	127
Energy			CO_2	6.26E+04
-Electricity	MJ		CO	337
In-house	8.90E-02		SO_x	0.188
EGAT	-		H_2S	16.7
-Fuel	m^3		**Emission to Water**	mg
Natural gas	2.00E-02		SS	0.19
			TDS	6.1
			Oils	1.45E-02
			BOD	4.61E-02
			COD	0.5

4.2 Comparison between GSP1, GSP2 and GSP3

As a result of the inventory analyses performed in the previous section, the comparison between the three GSPs in terms of feed, energy consumption and emissions can be done as shown in Table 4.4. From the table, it can be seen that GSP2 uses the highest amount of natural gas feed but consumes the lowest energy and, consequently, emits the lowest emissions when compared to the other two GSPs on the same 1 kg-product basis. This is probably due to the fact that GSP2 has the smallest production capacity among the three GSPs and the least complicated process. As illustrated in Fig. 4.3, this GSP 2 does not have the CO_2 removal unit and also does not produce propane. The results show that GSP1 is quite comparable to GSP3 both in terms of natural gas feed and energy utilization but releases much lower emissions, especially CO_2. This can be contributed the CO_2 removal unit installed on GSP1 and the use of both in-house and EGAT electricity whereas GSP3 utilizes only electricity from PTT's in-house gas turbine which seems to be not as efficient as that of EGAT's combined-cycle electricity generation system.

Table 4.4 Comparison between GSPs in terms of feed, energy consumption and emissions for production of 1 kg products

Type	Unit	GSP1	GSP2	GSP3
Feed gas				
Natural gas	m^3	0.97	1.07	0.98
Energy				
Natural gas	MJ	6.9E-01	3.5E-01	6.2E-01
In-house gas turbine	MJ	4.0E-02	1.1E-02	8.9E-02
EGAT	MJ	9.0E-03	2.7E-03	-
Total	MJ	0.739	0.3637	0.709
Emission to Air				
NO_x	mg	74.1	56.5	127
CO_2	mg	4.8E+04	2.3E+04	6.3E+04
CO	mg	121	82.7	337
SO_x	mg	0.316	0.412	0.188
H_2S	mg	4.14	13.8	16.7
Emission to Water				
SS	mg	0.2	0.2	0.19
TDS	mg	6.31	6.49	6.1
Oils	mg	1.96E-02	1.43E-02	1.45E-02
BOD	mg	5.63E-02	4.98E-02	4.61E-02
COD	mg	0.53	0.53	0.5
Sources of CO2 Emission				
NG combustion	g	35.1	19.8	37.4
Electricity(In-house)	g	10.8	2.9	24.1
Electricity(EGAT)	g	1.4	0.4	0

4.3 Life Cycle Environmental Impact Assessment (LCIA)

After the life cycle inventory was carried out, life cycle impact assessment (LCIA) could then be performed based on the quantitative information attained from LCI study in order to identify the environmental impacts from natural gas production. The raw materials used, energy consumption and all emissions were characterized into various environmental impact categories. This was done by using the commercial LCA software "SimaPro 7.0" with Eco-indicator 95 and Eco-indicator 99 for environmental impact assessment. Eco-indicator 95 is a mid-point approach to the impact assessment whereas Eco-indicator 99 is an end-point approach. The environmental impact categories being the focus in this research are global warming, respiration of inorganics, acidification, and resources depletion. As the allocation-by-weight method was used, the environmental loads are the same for each 1 kg of product from the same plant. Figure 4.7 shows the environmental impact categories of the production of 1 kg ethane from GSP1, GSP2, and GSP3 by using Eco-indicator 95. Table 4.5 shows the environmental impact assessment using Eco-indicator 95 as presented in terms of equivalent units for each impact category for 1 kg of ethane.

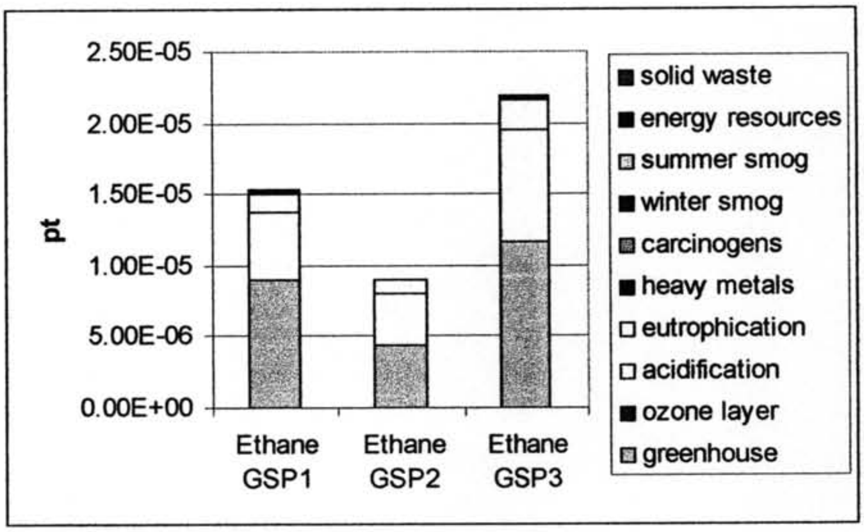

Figure 4.7 Environmental impact categories of production of 1 kg ethane from GSP1, GSP2, and GSP3 by using Eco-indicator 95

Table 4.5 Environmental impact in equivalent units for each category using Eco-indicator 95 for 1 kg of ethane

Impact category	Unit	Ethane GSP1	Ethane GSP2	Ethane GSP3
greenhouse	kg CO2	0.0481	0.0234	0.0627
ozone layer	kg CFC11	1.44E-11	4.22E-12	6.23E-13
acidification	kg SO2	5.44E-05	4.06E-05	8.91E-05
eutrophication	kg PO4	9.69E-06	7.41E-06	1.65E-05
heavy metals	kg Pb	5.71E-10	1.65E-10	6.59E-10
carcinogens	kg B(a)P	1.01E-11	2.73E-12	1.80E-11
winter smog	kg SPM	2.86E-06	1.14E-06	8.86E-07
summer smog	kg C2H4	4.79E-07	1.30E-07	7.88E-07
pesticides	kg act.subst	0	0	0
energy resources	MJ LHV	37.6	41.4	38.9
solid waste	Kg	3.17E-06	9.24E-07	3.42E-07

General observation can be made from the LCIA results that the three GSPs have the same trend of the environmental impacts where the major impact category is the greenhouse effect followed by acidification and eutrophication. CO_2 emissions from combustion and electricity utilization are the main cause of the greenhouse effect while NO_x from electricity utilization is the major contributor to acidification and eutrophication. In this aspect, GSP3, which has the highest electricity consumption and mainly from the in-house gas turbine, has the highest scores in these environmental impact categories as seen in Fig. 4.7.

For Eco-indicator 99, the method is good in a sense that this method accounts for resource depletion which is not accounted for in Eco-indicator 95. In Eco-indicator 99, the environmental impact is allocated into damage assessment for resources, ecosystem quality, and human health. Therefore, the LCI of the three GSPs shown in the previous section could be further analyzed for the damage assessment for the production of 1 kg ethane from GSP1, GSP2, and GSP3 by using Eco-indicator 99 as illustrated in Figure 4.8. It is not surprised to learn that, using this Eco-indicator 99 method, the damages are mainly in the resources depletion which comes from the consumption of natural gas. Figure 4.9 shows the impact assessment in terms of the environmental impact categories. It can be seen that the main environmental impact from Eco-indicator 99 is the depletion of fossil fuels.

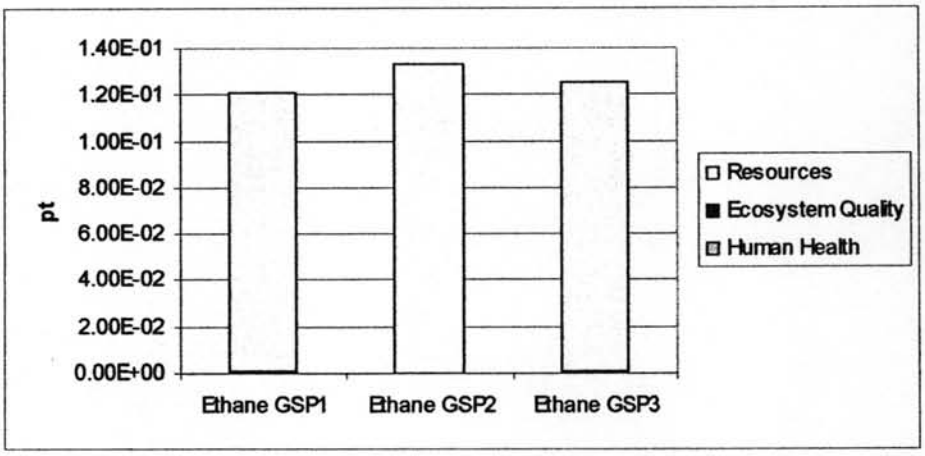

Figure 4.8 Damage assessment of production of 1 kg ethane from GSP1, GSP2, and GSP3 by using Eco-indicator 99

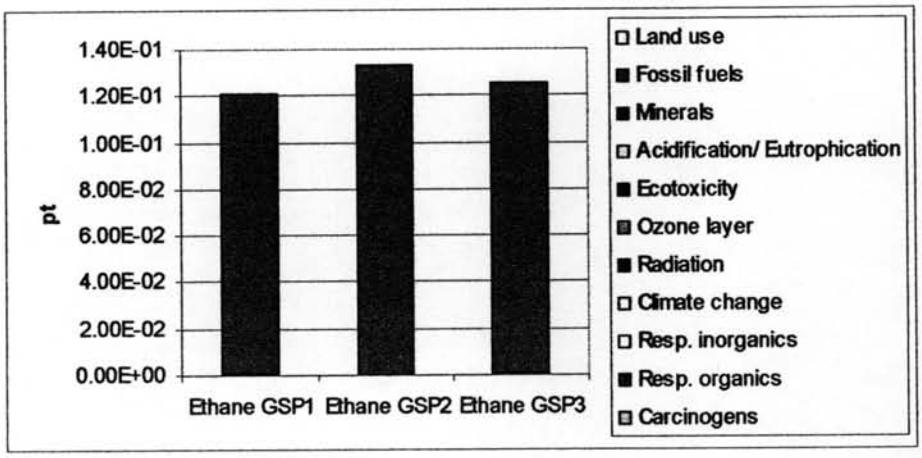

Figure 4.9 Environmental impact categories of production of 1 kg ethane from GSP1, GSP2, and GSP3 by using Eco-indicator 99

At this point, it is worthwhile to further analyze to see the results if the impact on the depletion of fossil fuels is ignored. Figure 4.10 and Table 4.6 show the environmental impact categories and the environmental impact assessment using Eco-indicator 99 for the production of 1 kg ethane if fossil fuel depletion category is not included.

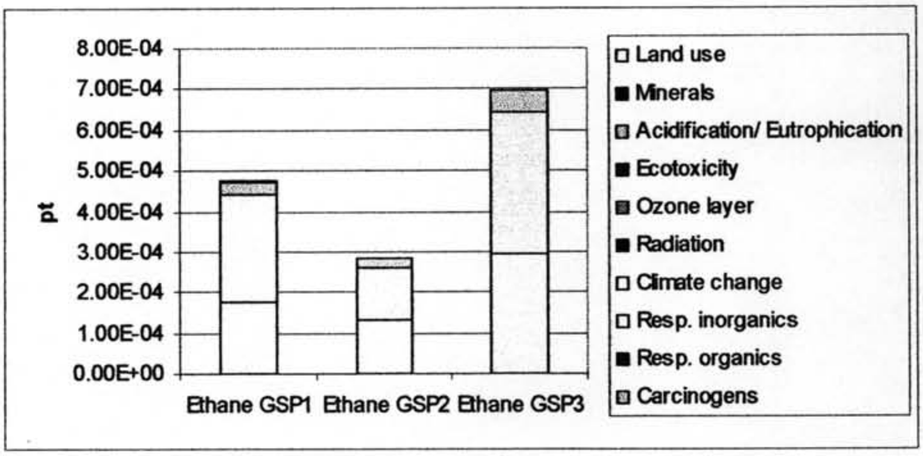

Figure 4.10 Environmental impact categories of production of 1 kg ethane without fossil fuel depletion category

Table 4.6 The environmental impact assessment using Eco-indicator 99 for each impact category for 1 kg of ethane without fossil fuel depletion category

Impact category	Unit	Ethane GSP1	Ethane GSP2	Ethane GSP3
Carcinogens	DALY	2.91E-12	8.27E-13	1.61E-12
Resp. organics	DALY	1.46E-12	3.96E-13	2.40E-12
Resp. inorganics	DALY	6.75E-09	5.08E-09	1.13E-08
Climate change	DALY	1.01E-08	4.94E-09	1.33E-08
Radiation	DALY	1.19E-13	3.47E-14	1.62E-16
Ozone layer	DALY	1.14E-14	3.35E-15	4.91E-16
Ecotoxicity	PAF*m2yr	1.01E-05	2.83E-06	1.04E-05
Acidification/ Eutrophication	PDF*m2yr	4.26E-04	3.24E-04	7.24E-04
Land use	PDF*m2yr	3.37E-06	9.30E-07	4.73E-06
Minerals	MJ surplus	1.27E-05	3.40E-06	2.58E-05
Fossil fuels	MJ surplus	5.08E+00	5.60E+00	5.26E+00

It can be seen that, when the depletion of fossil fuel is omitted, the results of the environmental impact are quite similar to the results using Eco-indicator 95. The most significant environmental impact is the climate change which comes mainly from CO_2. The second and third major impacts are respiration inorganics and acidification/eutrophication which are mainly the results of NO_x emission.

As the main environmental loads come from the utilization of electricity of the GSPs, the further analysis on this matter is needed. The electricity used in the GSPs can be divided into two parts: one that is generated by an in-house gas turbine and another is the grid-mixed electricity of EGAT. Figure 4.11 shows the comparison of the environmental impacts of 1 MJ electricity generated by an in-house gas turbine of PTT and the grid-mixed electricity of EGAT (based on TEI's data). It can be obviously seen that the electricity generated by the gas turbine plant has more environmental impacts than EGAT's grid-mixed electricity which generated mainly from an efficient combined cycle system.

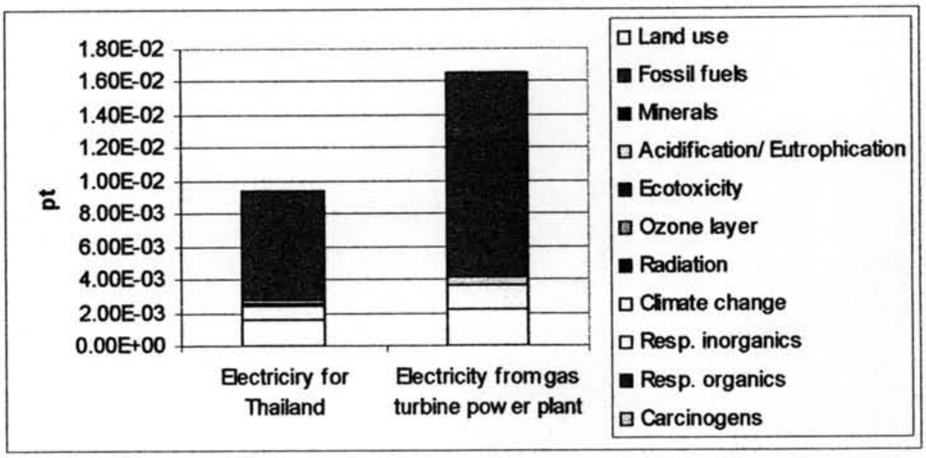

Figure 4.11 The comparison of environmental impacts of 1 MJ electricity between electricity generated by an in-house gas turbine and generated by EGAT

4.4 Suggestions for Improvement

In this section, suggestions for the improvement of the production of natural gas in Thailand based on PTT GSPs data provided and the results obtained from LCI and LCIA conducted in this study are being discussed.

The results of this study show that the environmental impacts of the natural gas production come mainly from the depletion of fossil fuel or natural gas which is the raw material of GSPs and the CO_2 emission as the result of electricity utilization. Therefore, the possible improvements can be done on these two points. Firstly, for electricity utilization, a more efficient use of electricity and the use of cleaner electricity should improve the environmental performance of the natural gas production. Secondly, installing the CO_2 removal unit would lead to not only the efficient use of natural gas feed to produce sale gas and other products but also the reduction of CO_2 being released to the environment.

4.4.1 Selection of the sources of electricity generation

From the analysis in the previous section, the utilization of electricity in the production of natural gas products has shown to be the main cause of environmental burden. Significant amount of CO_2, a greenhouse gas, is being released from the use of electricity which results in greenhouse effect and global warming. From the data provided by PTT, electricity used in the GSPs comes from two parts: one generated by an in-house gas turbine and another from EGAT's grid-mixed. Being not so efficient, the electricity generated by the gas turbine plant emits CO_2 and NO_x approximately 1.8 and 1.7 times higher than the grid-mix electricity of EGAT as shown in Figure 4.12. CO_2 is the main cause of global warming whereas NO_x is the main cause of respiration inorganics and acidification. Therefore, the use of cleaner electricity such as from EGAT's combined cycle system should lead to a reduction in CO_2 and NO_x emissions. GSP3 is an example which uses only EGAT's grid-mix electricity, and thus, has approximately 17% lower environmental impacts than other units.

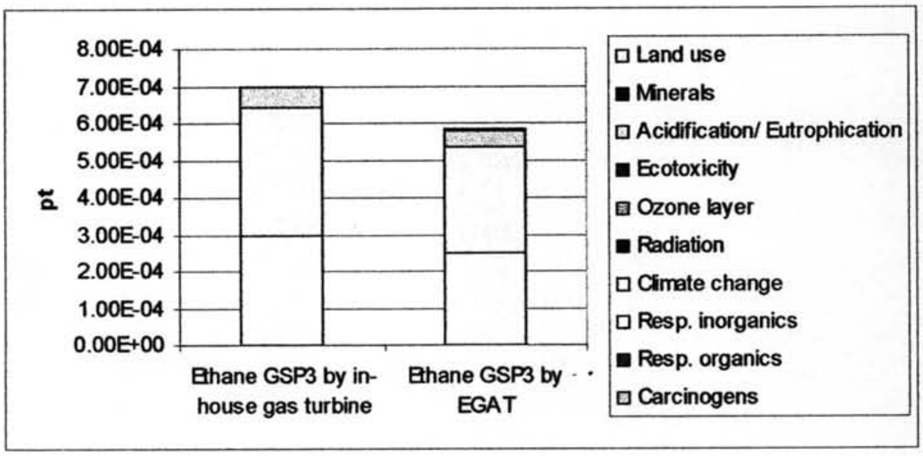

Figure 4.12 The comparison of environmental impacts between using in-house gas turbine and EGAT

4.4.2 Installation of the CO_2 removal unit

The performance of sale gas produced from the gas separation plant is often reported as the heating value in MJ/m unit. Table 4.7 compares the performance of the sale gas from GSP units 1-3. It can be seen that GSP1 produces sale gas which has much higher performance than the sale gas from the other two plants. Approximately 15% higher in sale gas performance from the GSP1 process is expected to be from the CO_2 removal unit installed to separate out the CO_2. Based on the same weight-basis of feed and product, higher sale gas performance should result in lower environmental impacts. Therefore, installing the CO_2 removal unit would result not only in higher sale gas performance but also in lower the CO_2 emission as it can be sold as a co-product within the Mab-ta-put petrochemical complex.

Table 4.7 The performance of sale gas from GSP1-3

(Sources: PTT public company limited)

GSP	Performance (MJ/m^3)
1	36.313
2	31.820
3	31.120