CHAPTER IV
RESULTS AND DISCUSSION

4.1 The Study of Compressed Biomethane Gas Production Process

According to the CBG production plant at Mae Taeng district, Chiangmai, Thailand, biogas was created from continuous stirred tank reactors (CSTRs) with the production rate of 14,400 m^3/day and it can be upgraded to CBG with the production rate of 5,422.46 kg/day. The overall process of CBG production is shown in Figure 4.1.

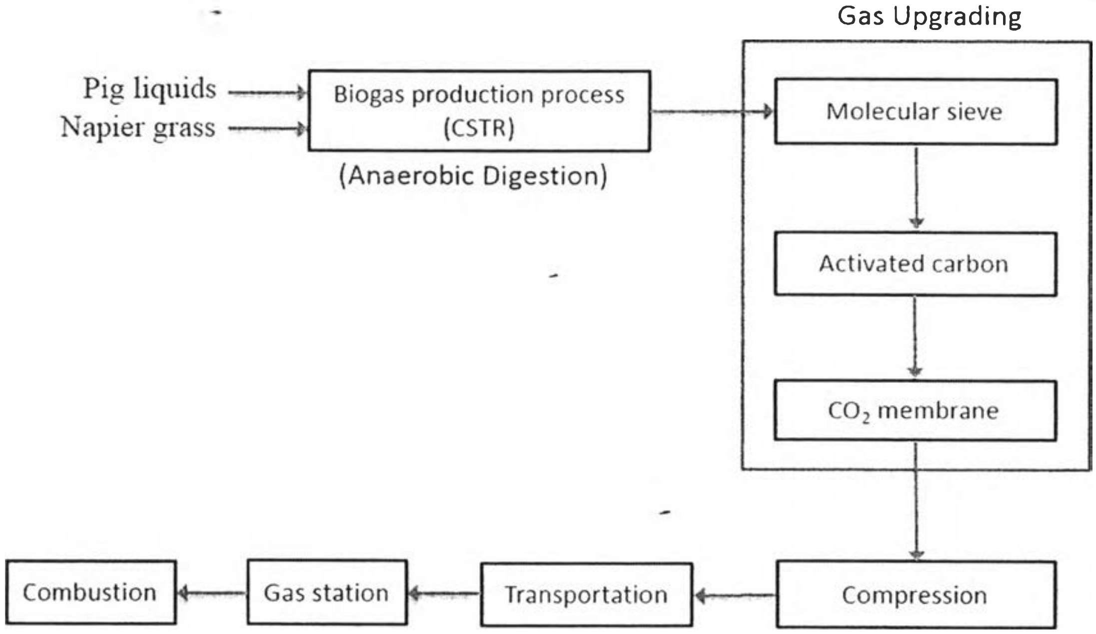


Figure 4.1 Overall process of CBG production.

4.1.1 Napier Grass Cultivation

The study of Energy Research and Development Institute (Nakornping), Chiangmai University and Energy Policy and Planning Office, Thailand Ministry of Energy mentioned that Pakchong 1 napier grass has highest yield comparing with other types of grasses (Department of Alternative Energy

Development and Efficiency, Thailand Ministry of Energy, 2013). The Pakchong 1 napier grass was developed by Dr. Krailas Kiyothong, an animal nutritionist and plant breeder from the Department of Livestock Development in Pakchong district, Nakhon Ratchasima province in Northeastern Thailand. Dr. Krailas Kiyothong crossed the ordinary napier grass, *Pennisetum purpureum*, and Pearl millet which is botanically called *Pennisetum glaucum*.

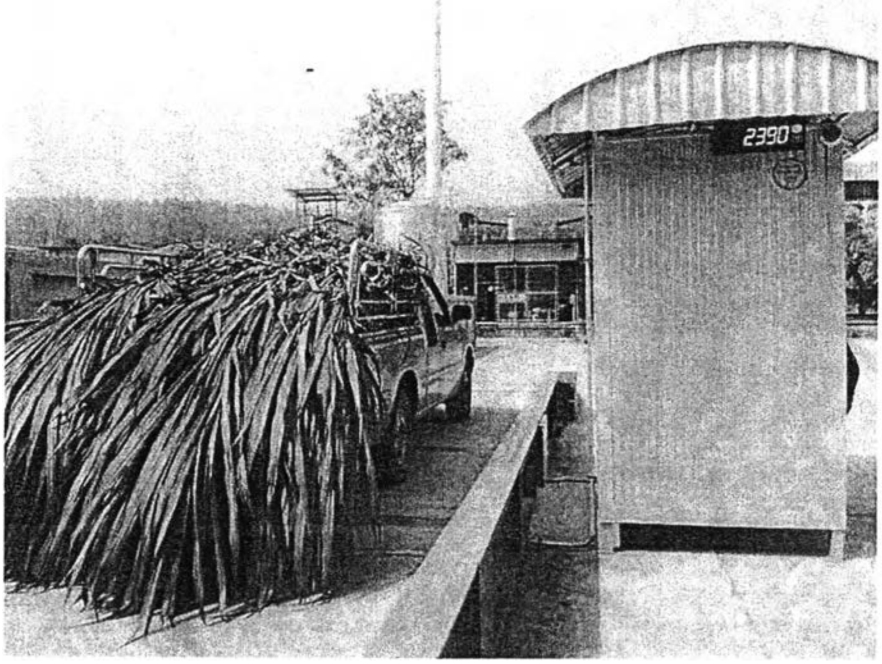


Figure 4.2 Napier grass used as feedstock in the biogas production process.

4.1.1.1 *Land Preparation*

- Plough and harrow the field well before planting.
- Use chemical fertilizer (15-15-15).

4.1.1.2 *Weeding*

- Clear up the unwanted flora after 2-3 week of planting and every time after harvesting.

4.1.1.3 *Fertilization*

- Use chemical fertilizer (46-0-0) every time after harvesting.

4.1.1.4 *Watering*

- Napier grass has 1,000 mm of water per year requirement.

4.1.1.5 *Harvest*

- Napier grass is ready for harvesting in 2-3 months after planting and harvesting can continue at an interval of 6-8 weeks.

4.1.2 Biogas Production

4.1.2.1 *Raw Materials*

Two main raw materials that are used in this process are pig manure liquids and napier grass.

1) *Pig manure liquids* from Mongkol and son farm limited company, Maetaeng district, Chiangmai, Thailand. There are 35,000 pigs which can produce fresh active substrate (pig liquids) of 169.48 m^3/day to feed into biogas production process.

2) *Napier grass* 212.74 kg/day of chopped napier grass from the previous stage.

4.1.2.2 *Fermentation Tank System*

The plant is made up of 3 continuous stirred tank reactors (CSTRs) which have total production capacity of 5,100 m^3. The temperature is set to maintain at 40 degree Celsius as shown in Figure 4.3.

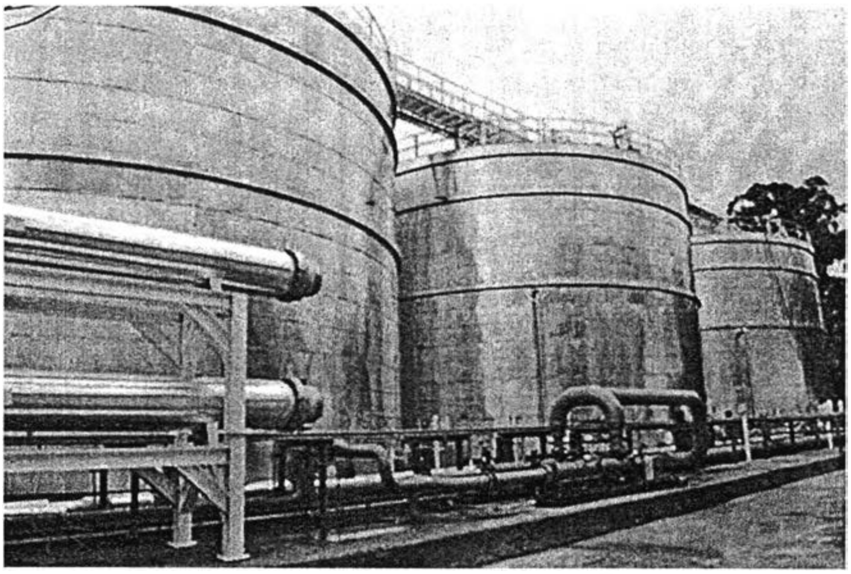


Figure 4.3 CSTR fermentation tanks.

The anaerobic digestion involves a complex microbiological process that can be described in 4 basic steps: hydrolysis, acidogenesis, acetogenesis and methanogenesis.

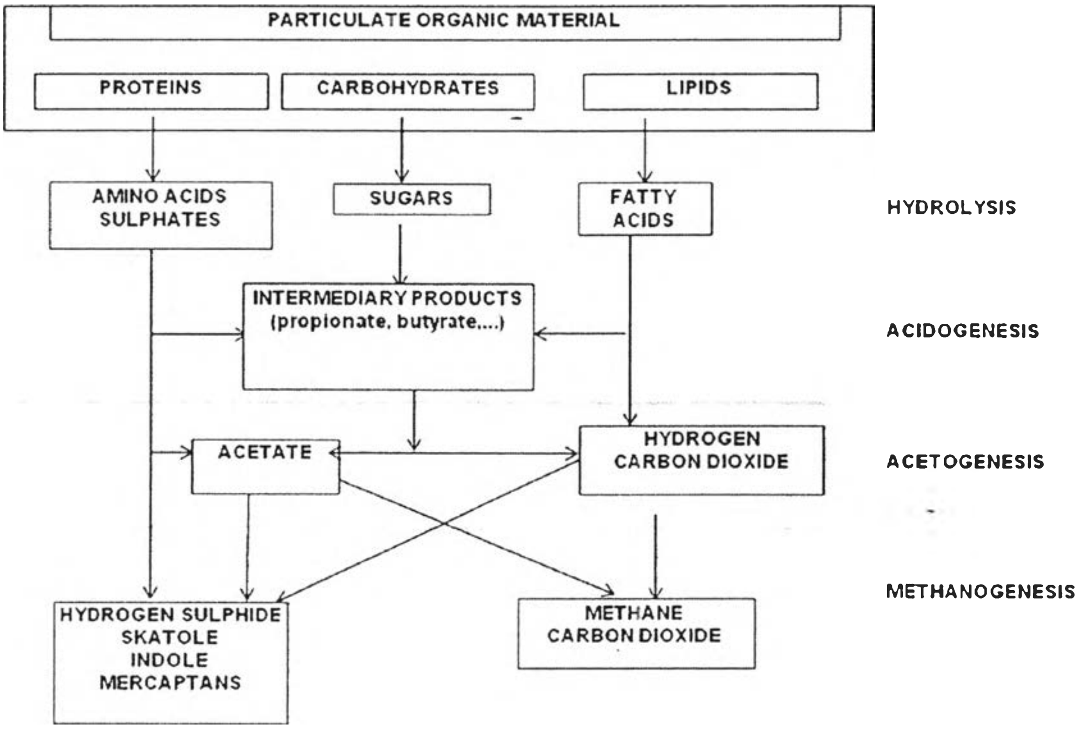


Figure 4.4 Biogas production process.

- In the hydrolysis, complex organic materials are broken down into their constituent parts. This is catalyzed by enzymes released by hydrolytic bacteria. The result is soluble monomers. While proteins, sugars and starch are easily degraded, carbon polymers are more difficult to degrade and lignin cannot be degraded anaerobically.

- During the acidogenesis, soluble organic compounds, including the monomers produced in the hydrolysis, are fermented to various intermediate products such as volatile fatty acids and alcohols by acidogenic bacteria, as well as to trace amounts of other byproducts. Acid-forming bacteria are fast-growing with a minimum doubling time of about 30 minutes.

- In the acetogenesis, many of the products created in the acidogenesis are converted to acetic acid, CO_2 and H_2 by acetogenic bacteria. Acetogenic bacteria grow rather slowly with a minimum doubling time of 1.5 to 4 days.

- The methanogenesis constitutes the final stage of the anaerobic digestion in which methanogens create methane from the final products of the acetogenesis as well as from some of the intermediate products of the other phases. There are two general pathways, the conversion of acetic acid into methane (about 60-70%), and the conversion of CO_2 and H_2 into methane. Different kinds of methanogenic bacteria are involved in these pathways. The ones involved in the production of methane out of acetic acid (acetoclastic bacteria) grow very slowly with a minimum doubling time of 2 to 3 days (Allegue and Hinge, 2012).

4.1.3 Biogas Upgrading

Biogas can be used for all applications designed for natural gas. In order that biogas can be used for feeding into a gas vehicle, the quality of biogas has to be improved. The main parameter that may require removal in an upgrading systems are H_2S, water, and CO_2.

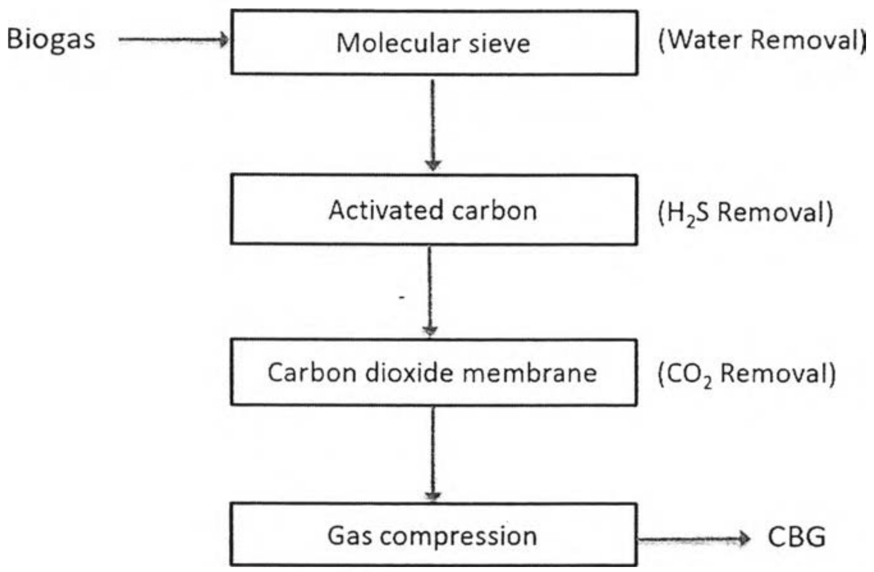


Figure 4.5 Biogas upgrading process.

Biogas upgrading process in this study consists of 3 stages which are water removal by using molecular sieve, hydrogen sulfide removal by using the activated carbon tank, and carbon dioxide removal by using carbon dioxide membrane separation technology.

4.1.3.1 *Water Removal*

Raw biogas is saturated with water vapor. Water is potentially damaging to natural gas pipeline equipment and engines.

The water removal of biogas in the analyzed plant performed by molecular sieve method. This stage consists of two molecular sieve tanks. The capacity is 3.2 m^3 per each tank. The function of this stage is to absorb water from raw biogas.

4.1.3.2 *Hydrogen sulfide Removal*

Hydrogen sulfide is a contaminant present in biogas produced during the digestion process. Depending on the biomass feedstock and biogas production process, the H_2S content of the raw biogas may vary from 50 to 3,000 ppm or higher (Chen *et al.*, 2010). H_2S should be removed from the gas stream because of its corrosive nature. In addition, the release of the compound into the atmosphere is carefully regulated as it is extremely toxic and it contributes to air pollution.

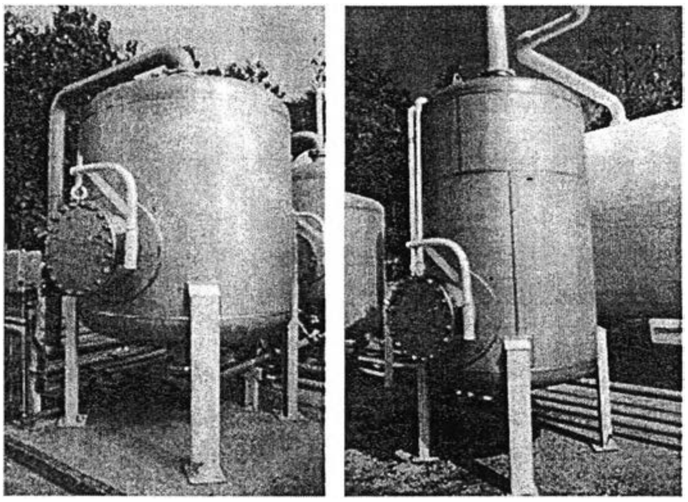


Figure 4.6 The molecular sieve tank (left) and the activated carbon tank (right).

In this stage, the activated carbon tank which has the capacity of 2 m^3 can remove H_2S in biogas to be less than 1 ppm before sending it to biogas storage which has capacity of 200 m^3. The pressure is increased to 20 barg by gas compressor before entering to carbon dioxide removal.

4.1.3.3 *Carbon dioxide Removal*

Reducing the relative amount of CO_2 in the biogas is the main task of the biogas upgrading process. Since the methane content of the gas is directly proportional to its energy content, increasing the relative methane content by removing CO_2 results in gas with a higher heating (calorific) value.

In order to reduce carbon dioxide, the separation technology from UOP LLC., USA which consists of filter coalescers, electric heater, guard bed, partical filter and CO_2 membrane (Figure 4.7) is used in this stage.

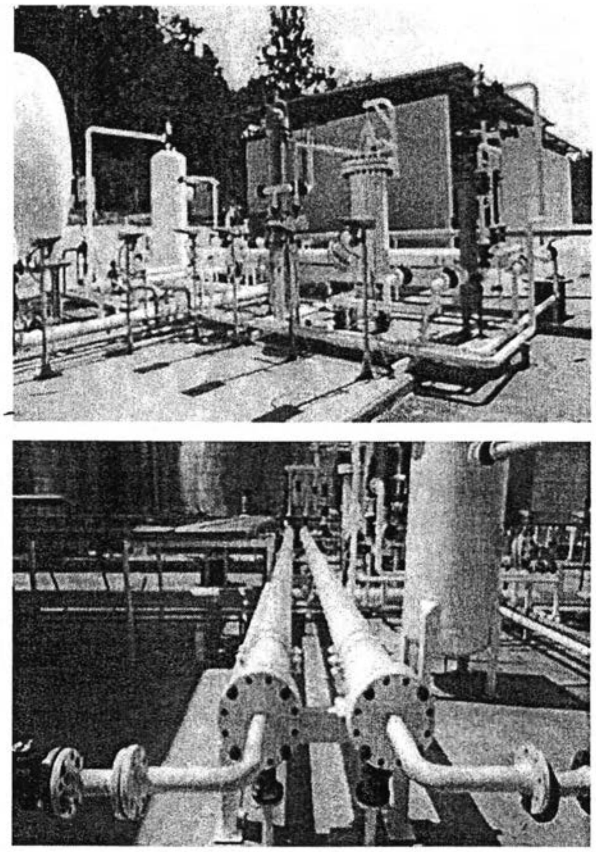


Figure 4.7 CO_2 removal unit and CO_2 membrane.

The membrane is a porous material that let some gases permeate through its structure. CO_2 and other components as H_2O, H_2S and NH_3 are transported through a thin membrane in more or less extent while CH_4 is retaining, due to difference in particle size and affinity. The driving force behind this process is a difference in partial pressures. The properties of this separation technique are highly dependent on the type of membrane used (Allegue and Hinge, 2012).

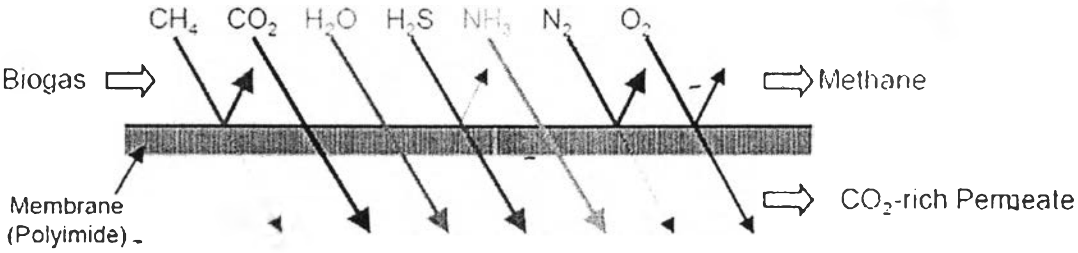


Figure 4.8 Membrane separation principle (Persson, 2003).

4.1.4 Compression

To compress the upgraded biogas, booster compressor is use to compress the upgraded biogas into ground storage at the pressure of 250 barg, volumetric flow rate of 330 m^3/hr. Then, the upgraded is sent to CBG decant panel and sold as CBG in PTT gas stations in Chiangmai province.

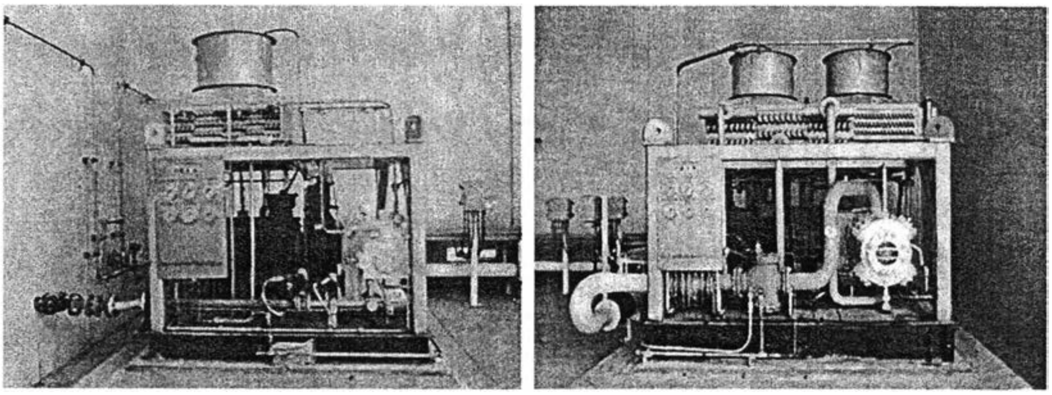


Figure 4.9 Gas compressor and booster compressor.

4.1.5 Efficiency of System

CH_4, CO_2, O_2 and H_2S content before upgrading are 61.89%, 34.12%, 0.10% by volume and 1,578 mg/m^3 respectively. After passing through the biogas upgrading process, CH_4, CO_2 and O_2 content are 87.49%, 12.31%, 0.02% by volume respectively and H_2S content is less than 0.01 ppm which does not exceed the standard of the Department of Energy Business of Thailand.

Table 4.1 The efficiency of biogas upgrading process (data from the analyzed plant)

Component	Results from the analysis		
	Before upgrading	After upgrading	Efficiency
CH_4 (% vol.)	61.89	87.49	-
CO_2 (% vol.)	34.12	12.31	63.92
O_2 (% vol.)	0.10	0.02	80
H_2S (mg/m^3)	1,578	< 0.046	100

4.2 Life Cycle Inventory

The inventory data of this study were from CBG production system as shown in this Figure.

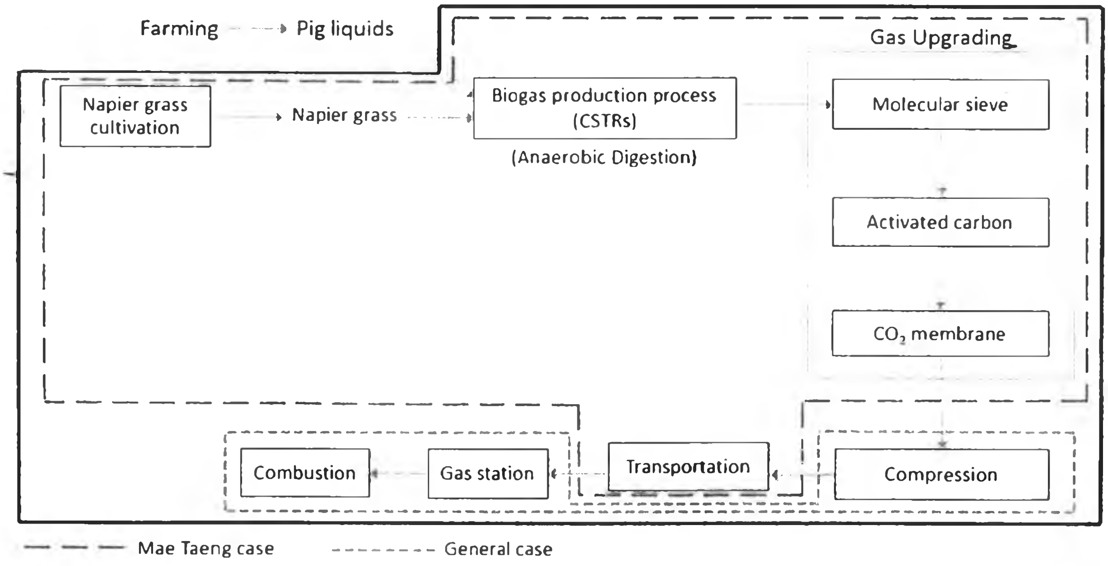


Figure 4.10 The CBG production system for collecting inventory data.

All activities based on the system boundary concerning about all energy inputs, raw materials, chemicals, utilities, and emissions in each stage are described in this section. The inventory data are summarized in Table 4.2. Details of the conditions and data used for each stage are given in the following subsections.

Table 4.2 Summary of the inventory data of CBG production process in this study

Stage	Key parameter	Ave. data	Source
Napier grass cultivation and feedstock preparation	Fertilizers	2.26 kg/Ton napier grass	[1],[9]
	Diesel	1.568 L/Ton napier grass	[1],[9]
Biogas production	Electricity	0.103 kWh/m_n^3 biogas	[1]
	Methane losses	5%	[1]
Biogas upgrading	Electricity	0.320 kWh/m_n^3 biogas	[2],[4],[6],[8]
	Methane losses	2%	Onsite, [3],[4],[5],[6],[8]
Compression and gas station	Electricity	0.108 kWh/kg CBG	[1]
Transportation for napier grass	Distance	5 km	Onsite
	Diesel truck	2.39 Ton/trip	Onsite
Transportation for CBG	Distance	10 km	Onsite
	Diesel truck	8.5 Ton/trip	Onsite
Combustion	Fuel economy	3.754 MJ/km	[7]

[1] Previous reports and studies by National Metal and Materials Technology Center (MTEC).
[2] Scholz M. et al. (2012). Transforming biogas into biomethane using membrane technology. Renewable and Sustainable Energy Reviews. 17, 199-212.
[3] Sternovem. Committee for Green-Gas. From biogas to green gas. Upgrading techniques and suppliers. 2ETPNG0840
[4] Jonsson S. and Westman J. (2011). Cryogenic biogas upgrading using plate heat exchangers. Master's thesis within the Sustainable Energy System Master's programme. Chalmers University of Technology. Sweden.
[5] Allegue L.B. and Hinge J. (2012). Biogas and bio-syngas upgrading report, Danish Technological Institute.
[6] UOP LLC.
[7] Emission and fuel consumption test results from PTT Public Company Limited.
[8] Deng L. and Hägg M. (2010). Techno-economic evaluation of biogas upgrading process using CO_2 facilitated transport membrane. International Journal of Greenhouse Gas Control, 4(4), 638–646.
[9] Bureau of Animal Nutrition Development, Department of Livestock Development. (2011). หญ้าเนเปียร์ปากช่อง 1.

4.2.1 Napier Grass Cultivation Stage

Napier grass was used as one of the feedstock for biogas production process. One rai (1,600 m^2) of cultivation yielded 60 tons per year of napier grass. The inventory data for napier grass cultivation were gathered and adapted from

National Metal and Materials Technology Center (MTEC) and the napier grass plantation handbook of Animal Nutrition Division, Department of Livestock Development, Thailand Ministry of Agriculture and Cooperatives.

Table 4.3 shows the results of inventory analysis of one ton of napier grass (70-80% of moisture) plantation and harvesting. This stage included the preparation of napier grass before the fermentation. Napier grass was chopped into small pieces (1-2-inch) and then piled up for one week before entering to CSTRs.

Table 4.3 Results of the inventory analysis of one ton of napier grass

Unit process: Napier grass plantation and harvesting					
Input			**Output**		
Type	**Unit**	**Quantity**	**Type**	**Unit**	**Quantity**
Material			**Product**		
Fertilizer (N)	kg	2	Napier grass (Curb weight)	Ton	1
Fertilizer (P)	kg	0.13			
Fertilizer (K)	kg	0.13			
			Emission to air		
Fuel			Carbon dioxide	kg	4.247
Diesel	L	1.568	Dinitrogen monoxide	kg	0.03143
Resource					
Surface water	L	26,666.67			

4.2.2 Biogas Production Process

For one day of biogas production process, 169.48 m^3 of pig liquids and 212.74 kg of napier grass can generate 9,605.36 m^3 of biogas (39.36°C, 1.01 bar). To produce 1 m^3 of biogas, 0.103 kWh of electricity was consumed for the biogas plant operation (Papong *et al.*, 2013). The methane loss of biogas production stage was assumed to emit to the atmosphere up to 5% of biogas yield (Prapaspongsa, 2009). Biogas from anaerobic digestion contains CH_4, CO_2, and O_2 content of 61.89%, 34.12%, and 0.10% by volume respectively and 1,578 mg H_2S per 1 m^3 of biogas.

The results of inventory analysis of the biogas production process is shown in Table 4.4.

Table 4.4 Results of the inventory analysis of one cubic meter of biogas

Unit process: Biogas production					
Input			Output		
Type	**Unit**	**Quantity**	**Type**	**Unit**	**Quantity**
Substrate			**Product**		
Pig liquids	m^3	0.017644	Biogas	m^3	1
Napier grass	kg	0.022148	(39.36°C, 1.01 bar)		
Energy			**Emission to air**		
Electricity	kWh	0.103	Methane	kg	0.020300
Fuel					
Diesel	kg	0.0017490			

4.2.3 Biogas Upgrading Process

When CO_2 and other impurities are removed during the upgrading process, the methane concentration increases and thus the resulting biomethane can be utilized as an alternative to natural gas.

In this study, biogas was passed through the molecular sieve stage and the activated carbon tank before entering to the membrane separation system. The energy requirement for water removal in the molecular sieve tanks and H_2S removal in the activated carbon tank were from the energy consumption of the air pump and the regeneration process. Although a membrane-based separation plant is mainly designed to remove CO_2 from the CH_4 bulk, it can consider that the molecular sieve tanks and the activated carbon tank are the parts of this upgrading plant (Energy Research and Development Institute (Nakornping), 2013; Scholz *et al.*, 2012). So the energy consumption for the air pump of water removal and H_2S removal belong to the energy consumption for CO_2 removal in the membrane-based separation upgrading system.

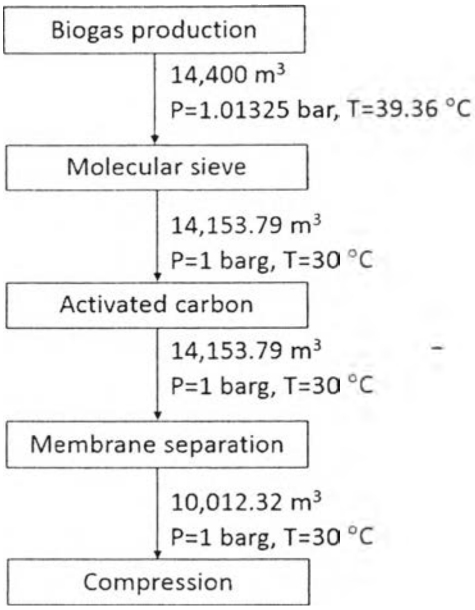


Figure 4.11 Volume of gas in each upgrading stage.

Table 4.5 Results of the inventory analysis of biogas upgrading process

Unit process: Biogas upgrading					
Input			**Output**		
Type	**Unit**	**Quantity**	**Type**	**Unit**	**Quantity**
Substrate Biogas (39.36°C, 1.01 bar)	m^3	1.43823	**Product** Biomethane (30°C, 1 barg)	m^3	1
Energy Electricity	kWh	0.45257	**Emission to air** Methane	kg	0.011479

The inventory data of biogas upgrading process were collected based on the CBG production plant in Mae Taeng district, Chiangmai province and based on the studies as shown in Table 4.2. Seeing that the operating pressure was 20 barg and the temperature of membrane separation stage was approximately 42 °C, the energy requirement for this processes was assumed to be 0.277 kWh/m_n^3 of raw biogas (Scholz *et al.*, 2012; Deng and Hägg, 2010). Since the biogas upgrading process consisted of not only the membrane separation stage but also the water removal stage and the H_2S removal stage, there was the additional energy requirement for the regeneration of the molecular sieve tanks, accounting for 0.0431 kWh/m_n^3 of raw biogas (UOP LLC.). This study omitted the energy consumption for the regeneration of the activated carbon as it was the disposable apparatus in this plant. For the methane loss, the percentage of methane remained in waste gas, it was evaluated as 2% which was considered as air emission although the plant used the regeneration process. Results of the inventory analysis of the biogas upgrading process from CO_2 membrane-based technology in this study is shown in Table 4.5.

4.2.4 Compression and Gas Station

The compression of biomethane gas was assumed to occur at the CBG production plant in Mae Taeng, Chiangmai. It was assumed that the gas station received CBG transported by CBG trailers from the CBG production plant. CBG products were then sold in unit of kilogram through dispensers. However, the inventory data of this stage in this study were gathered data from two mother stations from the previous study of MTEC, which combined the inventory data of the compression stage and gas station stage together. The energy consumption for the compression process and the gas station was estimated to be 0.108 kWh per kg CBG.

Table 4.6 Results of the inventory analysis of compression and gas station

Unit process: Compression and gas station					
Input			**Output**		
Type	**Unit**	**Quantity**	**Type**	**Unit**	**Quantity**
Substrate			**Product**		
Biomethane (25°C, 180 psig)	m^3	0.0855	Compressed biomethane gas (CBG)	kg	1
Energy					
Electricity	kWh	0.10842	**Emission to air**		
			Methane	mg	532.35
Chemical			Carbon dioxide	mg	206.46
Compressor oil	L	3.068E-04			
			Liquid waste		
			Waste oil	mg	188.77

4.2.5 Transportation

In this study, the transportation was divided in 2 parts: transportation for napier grass and transportation for CBG distribution in Mae Taeng, Chiangmai (see from Table 4.7 to Table 4.10). The inputs of transportation stage covered in fuel consumption per ton per kilometer transported (tkm) and fuel consumption for truck with empty trip. This stage included not only the acquirement of diesel but also the diesel combustion in the transportation.

The transportation of napier grass from the glass plots to the CBG production plant was assumed to be done by four-wheel trucks. The average traveling distance for one-way trip was 5 kilometers.

The transportation of CBG for distribution from the CBG production plant to gas stations was assumed to be done by using 8.5 ton trailers. The average traveling distance for one-way trip was approximately 10 kilometers.

Table 4.7 Results of The inventory data of napier grass transportation (full load)

Inventory of napier grass transportation (full load)					
Input			Output		
Type	Amount	Unit	Type	Amount	Unit
Fuel			**Product**		
Diesel	7.769E-02	kg	Napier grass	318.932	kg
			Emission to Air		
			Carbon dioxide	2.29E+02	g
			Carbon monoxide	2.84E+00	g
			Nitrogen oxides	6.13E-01	g
			Particulate matter	1.91E-02	g
			Hydrocarbons	5.30E-01	g
			Methane	1.28E-02	g
			Benzene	1.00E-02	g
			Toluene	4.31E-03	g
			Xylene	4.31E-03	g
			Non – methane volatile organic compounds	2.76E-01	g
			Sulfur oxides	5.25E-02	g
			Nitrous Oxide	9.41E-03	g
			Cadmium	7.48E-07	g
			Copper	1.27E-04	g
			Chromium	3.75E-06	g
			Nickel	5.25E-06	g
			Selenium	7.48E-07	g
			Zinc	7.48E-05	g
			Lead	8.23E-09	g
			Mercury	1.50E-09	g

Table 4.8 Results of The inventory data of napier grass transportation (no-load)

Inventory of napier grass transportation (no-load)					
Input			Output		
Type	Amount	Unit	Type	Amount	Unit
Fuel			**Product**		
Diesel	5.758E-07	kg	Napier grass	-	kg
			Emission to Air		
			Carbon dioxide	1.65E-03	g
			Carbon monoxide	2.04E-05	g
			Nitrogen oxides	4.41E-06	g
			Particulate matter	1.38E-07	g
			Hydrocarbons	3.82E-06	g
			Methane	9.15E-08	g
			Benzene	7.25E-08	g
			Toluene	3.05E-08	g
			Xylene	3.05E-08	g
			Non – methane volatile organic compounds	2.05E-06	g
			Sulfur oxides	3.89E-07	g
			Nitrous Oxide	7.00E-08	g
			Cadmium	5.55E-12	g
			Copper	9.45E-10	g
			Chromium	2.78E-11	g
			Nickel	3.89E-11	g
			Selenium	5.55E-12	g
			Zinc	5.55E-10	g
			Lead	6.10E-14	g
			Mercury	1.11E-14	g

Table 4.9 Results of The inventory data of CBG transportation (full load)

Inventory of CBG transportation (full load)					
Input			Output		
Type	Amount	Unit	Type	Amount	Unit
Fuel			**Product**		
Diesel	1.03851	kg	CBG	5422.46	kg
			Emission to Air		
			Carbon dioxide	3.27E+03	g
			Carbon monoxide	6.88E+00	g
			Nitrogen oxides	1.32E+01	g
			Particulate matter	6.83E-01	g
			Hydrocarbons	1.59E+00	g
			Methane	3.81E-02	g
			Benzene	3.02E-02	g
			Toluene	1.27E-02	g
			Xylene	1.27E-02	g
			Non – methane volatile organic compounds	4.86E+00	g
			Sulfur oxides	6.99E-01	g
			Nitrous Oxide	1.26E-01	g
			Cadmium	1.00E-05	g
			Copper	1.70E-03	g
			Chromium	5.01E-05	g
			Nickel	6.99E-05	g
			Selenium	1.00E-05	g
			Zinc	1.00E-03	g
			Lead	1.10E-07	g
			Mercury	2.01E-08	g

Table 4.10 Results of The inventory data of CBG transportation (no-load)

Inventory of CBG transportation (no-load)					
Input			**Output**		
Type	**Amount**	**Unit**	**Type**	**Amount**	**Unit**
Fuel			**Product**		
Diesel	1.29E-06	kg	CBG	-	kg
			Emission to Air		
			Carbon dioxide	3.77E-03	g
			Carbon monoxide	7.93E-06	g
			Nitrogen oxides	1.52E-05	g
			Particulate matter	7.85E-07	g
			Hydrocarbons	1.83E-06	g
			Methane	4.40E-08	g
			Benzene	3.48E-08	g
			Toluene	1.47E-08	g
			Xylene	1.47E-08	g
			Non – methane volatile organic compounds	6.06E-06	g
			Sulfur oxides	8.74E-07	g
			Nitrous Oxide	1.57E-07	g
			Cadmium	1.25E-11	g
			Copper	2.12E-09	g
			Chromium	6.24E-11	g
			Nickel	8.74E-11	g
			Selenium	1.25E-11	g
			Zinc	1.25E-09	g
			Lead	1.37E-13	g
			Mercury	2.50E-14	g

4.2.6 CBG Combustion

The inventory data for CBG combustion were gathered from emission and fuel consumption test results of Toyota Altis 1.6 liters (2010 edition) based on EURO III standard (PTT Public Company Limited). This study was not included the emissions that are associated with the vehicle manufacture, maintenance, and disposal because their impacts were not significant (Beer *et al.*, 2007).

Table 4.11 Emission and fuel consumption test results of CBG used in this study

Pollutants (g/km)	**Emission**
Hydrocarbons	0.175
Carbon monoxide	1.397
Nitrogen oxides	0.026
Carbon dioxide	196.22

Fuel consumption: 11.874 km/kg

4.3 Net Energy Ratio (NER)

The energy using for producing CBG in this research was divided into 5 stages; energy use in napier grass cultivation, energy use in biogas production or anaerobic digestion, energy use in biogas upgrading which consists of molecular sieve, activated carbon tank, and CO_2 membrane separation, energy use in compression and gas station, and energy use in transportation stage. The Eco-indicator 95 method was used to analyze the overall process in the energy aspect. The energy analysis results are shown in Table 4.12 and energy resources of each stage are shown in Figure 4.12.

Table 4.12 Summary of energy analysis results of 1 MJ CBG

Description	Unit	Amount
CBG density	kg/m^3	0.717
CBG heating value (87.49%CH_4)	MJ/m^3	31.961
	MJ/kg	44.576
CBG fuel economy	MJ/km	3.754
Total energy input	MJ	0.2223
Energy of fuel	MJ	1

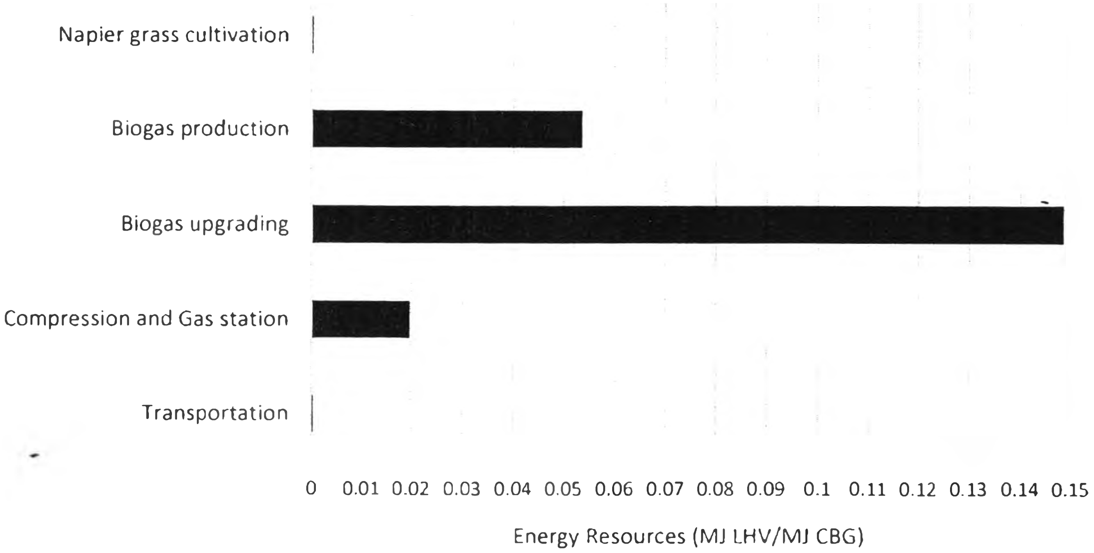


Figure 4.12 The energy input of each stage in CBG system.

The product system of 1 MJ of CBG required the total energy input of 0.2223 MJ. The energy use for biogas upgrading was the highest which is 66.79% of total energy input. It mainly came from the power consumption. The second was the energy use in biogas production process, accounting for 24.12% of total energy input, came from the power consumption. While the energy of fuel or the energy output of 1 MJ of CBG, the NER was 4.498. This energy analysis result showed that the NER value of CBG was higher than one, indicating the net energy gain for this CBG system as shown in Figure 4.13 and 4.14.

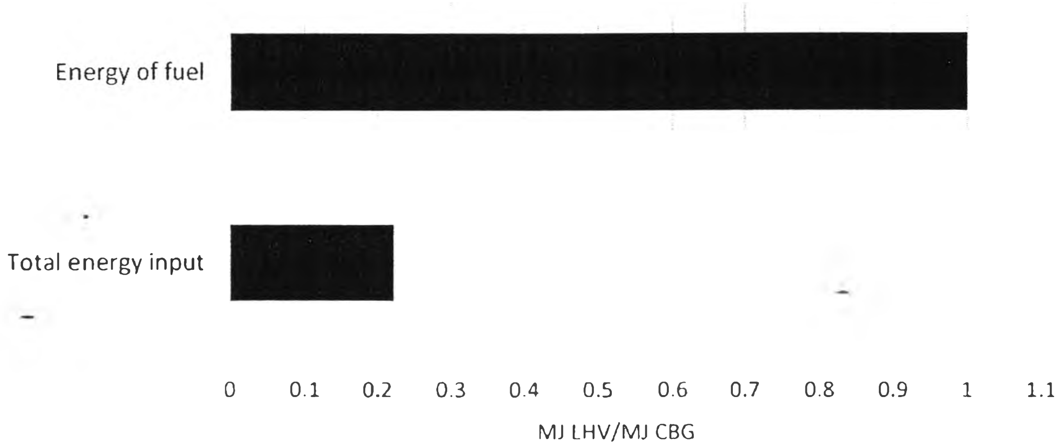


Figure 4.13 The energy input-output of CBG system.

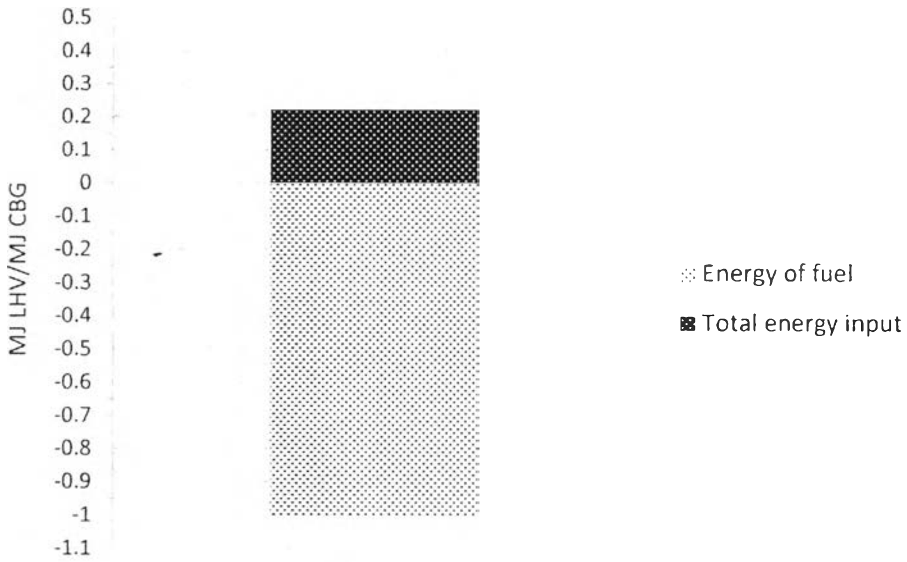
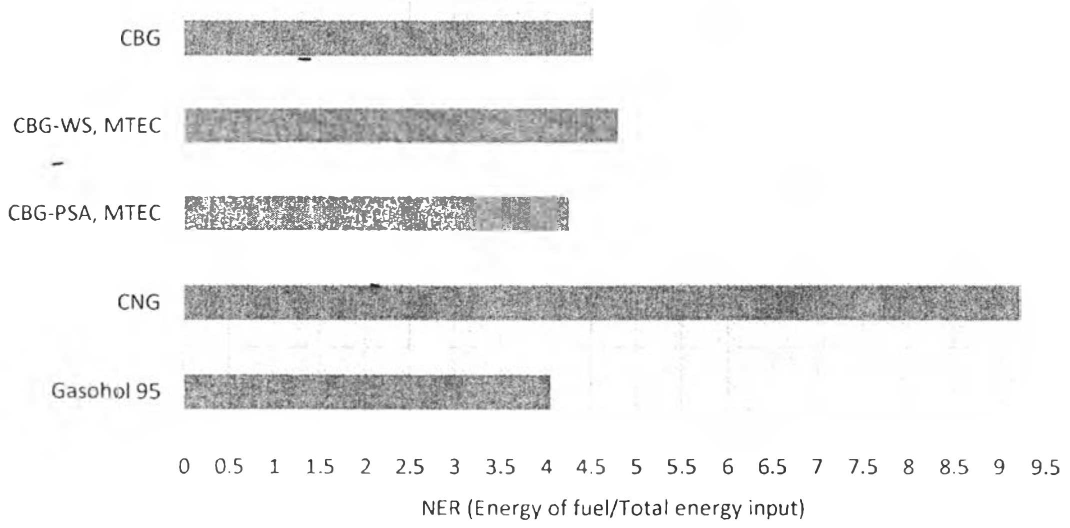


Figure 4.14 Comparison of total energy input and energy output of CBG production.

When comparing the result of the energy analysis of CBG with different upgrading technology and the conventional fuels (previous studies of MTEC). It is clear that NER of CBG system in this study is competitive with NER of CBG from other systems. For the CBG fuel, Figure 4.15 shows that the production of CBG with water scrubbing upgrading technology (CBG-WS) consumed the lowest energy input whereas the production of CBG with pressure swing adsorption upgrading technology (CBG-PSA) consumed higher energy than this study.



Note: Biogas upgrading technology; WS – water scrubbing, PSA – pressure swing adsorption.

Figure 4.15 NER comparison of CBG systems and conventional fuels.

4.4 Life Cycle Environmental Performance

The assessment of the CBG in the whole life cycle covers in acquirement of raw materials, production process, transportation, and the use of a fuel in the vehicle. The environmental impact was analyzed based on the LCI results by SimaPro 7.1 software with CML 2 baseline 2000 method. The results of the global warming potential are described as follows:

Figure 4.16 and Figure 4.17 show the distribution of GWP of CBG product system. The GWP impact was mainly resulting from CO_2 emission from power consumption and methane loss. The overall GWP from feedstock to combustion in a vehicle was approximately 56.76 g CO_2 equivalent per 1 MJ CBG. The results indicated that the biogas production process had the highest GWP impact (55.81% of total GWP) resulting from high methane loss and the energy consumption. The biogas production process includes the methane leakage from the digesters which accounts for 5% of total methane that generated from anaerobic digestion. The GWP of biogas upgrading stage was the second (39.90% of total GWP) which came from high energy consumption. The energy for both of the biogas production process and the biogas upgrading process is supplied in the form of electricity from the grid, which contributes significantly to the GHG emissions.

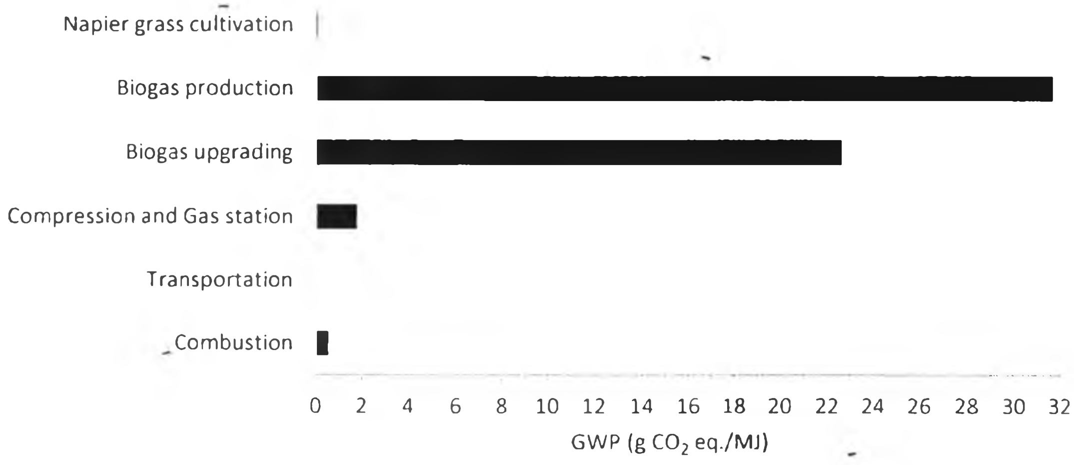


Figure 4.16 GWP of each stage in CBG system.

The biomethane compression and gas station stage had a significant impact because these processes required electricity in operating the system. Air emissions from electricity generation were contributed to this impact. In the transportation phase, all air emissions were caused by diesel fuel combustion for transportation of napier grass feedstock and CBG product. For the CBG combustion stage, CO_2 emission was assumed to be biogenic carbon. So it was not accounted as GWP contribution.

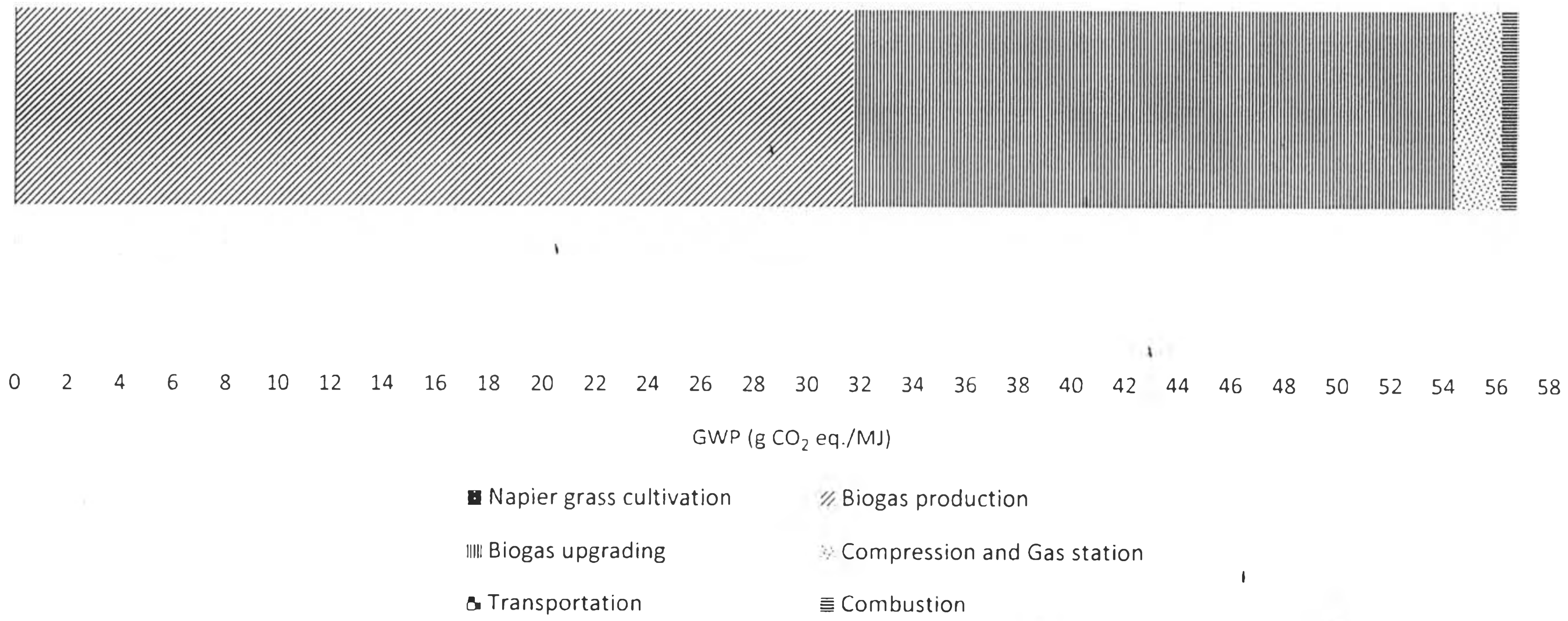
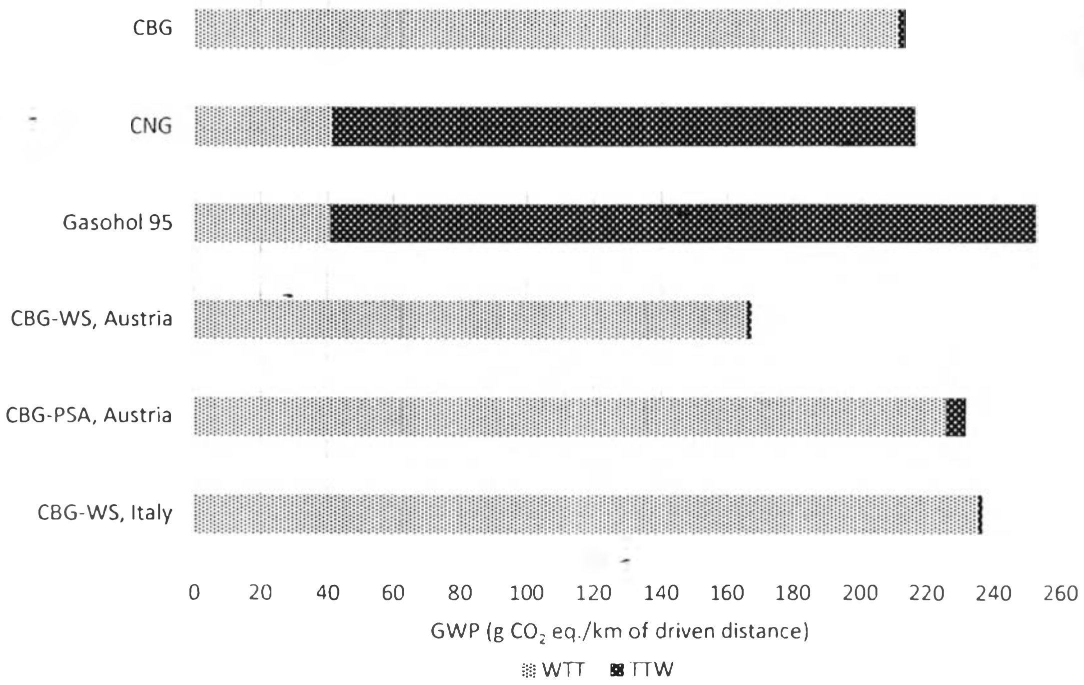


Figure 4.17 Total GWP of CBG WTW phase.

4.5 GWP Comparison of CBG and Conventional Fuels

The life cycle GWP comparison of CBG and conventional fuels (MTEC, 2010) is shown in Figure 4.18.



Note: Biogas upgrading technology; WS – water scrubbing, PSA – pressure swing adsorption.

Figure 4.18 GWP comparison of CBG with conventional fuels.

The GWP of CBG was higher than those of fossil-based CNG and gasohol 95 for the WTT phase. For CBG, 99 percent of the GWP impact came from WTT phase whereas more than 80 percent of the life cycle GWP emissions of conventional fuels came from TTW phase. The result shows that if biogenic carbon was not accounted, the comparative result of GWP in the TTW phase was opposite to the WTT phase. The GWP of CBG was much lower than those of CNG and gasohol 95 for the TTW phase. When combining WTT and TTW phase, the GWP of CBG WTW phase was lower than those of CNG and gasohol 95.

When comparing the results of this study with other similar studies, it was found that the GWP reported in the Italian study (Buratti *et al.*, 2013) is the highest comparing with the same type of fuel. Even though the most significant contribution is due to the biogas production phase, the step caused that GWP emission to be more bountiful than those of other studies is the cultivation step. The greatest weight of GHG emissions in that cultivation step is constituted by the N_2O emissions (59.4% of the cultivation step), resulting from the application of nitrogen fertilizers (The GWP value of CBG from the water scrubbing upgrading technology (CBG-WS) in the Italian study was estimated based on fuel consumption from PTT and it was assumed that the GWP TTW value was the same as the value of CBG-WS in the Austrian study).

For the CBG from the Austrian study (Pertl *et al.*, 2010), the GWP values they reported were estimated based on fuel consumption from PTT. The GWP emission of CBG-WS is 167.5 g CO_2 eq. per km of driven distance which is less than the GWP emission observed in this study. It is due to the influence of the dissimilar system boundary. The methane loss from biogas production process was excluded in their study whereas this point was considered in this study. For the CBG from pressure swing adsorption upgrading technology (CBG-PSA), the GWP emission is higher than the value of CBG-WS by reason of the higher methane loss from biogas upgrading process. The methane loss from upgrading process of CBG-PSA was accounted for 4% whereas it was 1.5% for CBG-WS. It is clear that the greenhouse gas emission resulting from methane loss is significantly effect on GWP.

4.6 Land Use Change (LUC)

When biofuel cultivation expands to new growing areas, the carbon stock in vegetation and soil changes. Carbon is stored in the vegetation in form of leaves and branches, in form of dead wood on the ground and in roots and humus in soils. Where the carbon stock is larger before the establishment of the plantation than thereafter, the difference is released as CO_2 by burning or microbial decomposition of above and below ground carbon. This has a negative influence on the GHG balance, i.e. GHG emissions increase (Hennecke *et al.*, 2012).

Expansion of napier grass cultivation can lead to large additional GHG emissions. LUC impact in this study was evaluated by using methodology developed by intergovernmental panel on climate change (IPCC). The calculations made use of guidelines as published in the commission decision of June 10, 2010 of the European commission.

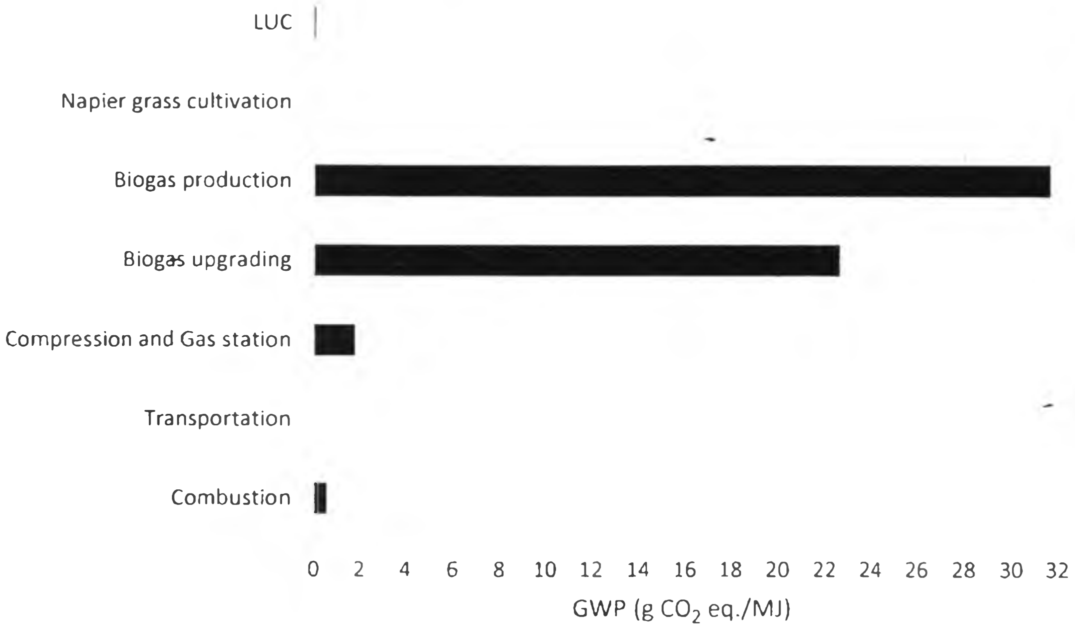
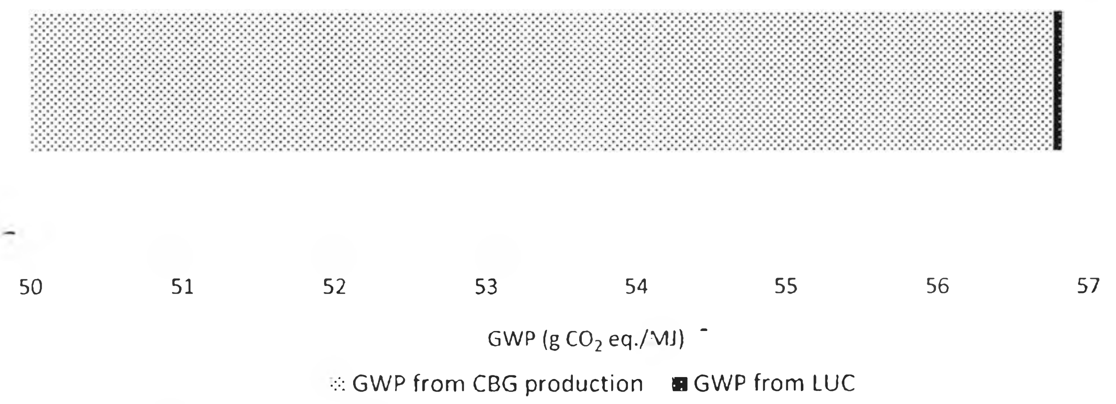


Figure 4.19 GWP from LUC and other stages.

The resulting GHG emissions from LUC of napier grass cultivation of the area in Mae Taeng, Chiangmai was 2.479 tons CO_2 eq. rai^{-1} $year^{-1}$. One rai of napier grass plantation yields 10 tons per harvest and since there are 6 cuttings a year, there are 60 tons per rai per year. So 1 MJ of CBG (from pig manure liquids and napier grass feedstock), the GHG emissions from LUC was 0.0545 g CO_2 eq. per MJ CBG.



Note: This figure shows the GWP value starting from 50 g CO_2 eq./MJ CBG.

Figure 4.20 Total GWP of CBG WTW phase including the LUC factor.

When GHG emissions from LUC were combined to GHG emissions from CBG production, the total GWP of CBG WTW phase was increased from 56.76 g CO_2 eq. per MJ CBG to 56.82 g CO_2 eq. per MJ CBG. That was 0.1 percent of total GWP of CBG production system was from LUC. It is nevertheless clear that the effect of LUC cannot be ignored. The displacement of agricultural activity is significant from a GHG perspective.