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APPENDICES

Appendix A Life Cycle Inventory (LCI)

Table A1 Results of the inventory analysis of napier grass plantation and harvesting

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

Table A2 Results of the inventory analysis of biogas production process

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			**Air emission**		
Electricity	kWh	0.102	Methane	kg	0.020300
Fuel					
Diesel	kg	0.0017490			

Table A3 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	**Air emission** Methane	kg	0.0081199

Table A4 Results of the inventory analysis of compression and gas station (MTEC, 2012)

Unit process: Compression and gas station					
Input			Output		
Type	Unit	Quantity	Type	Unit	Quantity
Substrate Biomethane (25°C, 180 psig)	m^3	0.0855	**Product** Compressed bio-methane gas (CBG)	kg	1
Energy Electricity	kWh	0.1084	**Air emission** Methane Carbon dioxide	mg mg	532.35 206.46
Chemical Compressor oil	L	3.068E-04	**Liquid waste** Waste oil	mg	188.77

Table A5 Results of The inventory data of napier grass transportation (full load) (MTEC, 2012)

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 A6 Results of The inventory data of napier grass transportation (no-load) (MTEC, 2012)

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 A7 Results of The inventory data of CBG transportation (full load) (MTEC, 2012)

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 A8 Results of The inventory data of CBG transportation (no-load) (MTEC, 2012)

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

Table A9 Results of The inventory data of CBG combustion stage (PTT, 2012)

Inventory of CBG combustion					
Input			Output		
Type	Amount	Unit	Type	Amount	Unit
Fuel			**Emission to Air**		
CBG	1	kg	Carbon dioxide	2329.93	g
			Carbon monoxide	16.5880	g
			Nitrogen oxides	0.30872	g
			Hydrocarbons	2.07795	g

Appendix B Life Cycle Impact Assessment (LCIA)

Table B1 Results of the impact assessment of 1 MJ CBG by using CML 2 baseline 2000 V2.03 / World, 1995

Impact category	Unit	Total
abiotic depletion	kg Sb eq	1.48E-04
global warming (GWP100)	kg CO2 eq	5.68E-02
ozone layer depletion (ODP)	kg CFC-11 eq	5.74E-12
human toxicity	kg 1,4-DB eq	9.28E-05
fresh water aquatic ecotox.	kg 1,4-DB eq	2.49E-06
marine aquatic ecotoxicity	kg 1,4-DB eq	2.45E-02
terrestrial ecotoxicity	kg 1,4-DB eq	2.66E-07
photochemical oxidation	kg C2H4	2.12E-05
acidification	kg SO2 eq	4.80E-05
eutrophication	kg PO4--- eq	7.34E-06

Table B2 Results of the impact assessment of 1 MJ CBG by using Eco-indicator 95 V2.03 / Europe e

Impact category	Unit	Total
greenhouse	kg CO2	3.58E-02
ozone layer	kg CFC11	7.56E-12
acidification	kg SO2	5.60E-05
eutrophication	kg PO4	7.35E-06
heavy metals	kg Pb	7.77E-10
carcinogens	kg B(a)P	1.43E-11
winter smog	kg SPM	8.45E-04
summer smog	kg C2H4	3.13E-05
pesticides	kg act.subst	0.00E+00
energy resources	MJ LHV	2.22E-01
solid waste	kg	2.07E-05

Table B3 Results of the impact assessment of napier grass cultivation stage for producing 1 MJ of CBG by using CML 2 baseline 2000 V2.03 / World, 1995

Impact category	Unit	Total
abiotic depletion	kg Sb eq	1.09E-07
global warming (GWP100)	kg CO2 eq	4.31E-05
ozone layer depletion (ODP)	kg CFC-11 eq	2.78E-23
human toxicity	kg 1,4-DB eq	1.03E-07
fresh water aquatic ecotox.	kg 1,4-DB eq	2.62E-10
marine aquatic ecotoxicity	kg 1,4-DB eq	1.87E-09
terrestrial ecotoxicity	kg 1,4-DB eq	3.09E-11
photochemical oxidation	kg C2H4	1.73E-09
acidification	kg SO2 eq	8.29E-08
eutrophication	kg PO4--- eq	1.26E-08

Table B4 Results of the impact assessment of napier grass cultivation stage for producing 1 MJ of CBG by using Eco-indicator 95 V2.03 / Europe e

Impact category	Unit	Total
greenhouse	kg CO2	4.02E-05
ozone layer	kg CFC11	3.70E-23
acidification	kg SO2	9.32E-08
eutrophication	kg PO4	1.22E-08
heavy metals	kg Pb	6.81E-16
carcinogens	kg B(a)P	2.44E-15
winter smog	kg SPM	2.50E-08
summer smog	kg C2H4	9.53E-10
pesticides	kg act.subst	0.00E+00
energy resources	MJ LHV	2.25E-04
solid waste	kg	6.60E-09

Table B5 Results of the impact assessment of biogas production process for producing 1 MJ of CBG by using CML 2 baseline 2000 V2.03 / World, 1995

Impact category	Unit	Total
abiotic depletion	kg Sb eq	3.49E-05
global warming (GWP100)	kg CO2 eq	3.17E-02
ozone layer depletion (ODP)	kg CFC-11 eq	3.99E-13
human toxicity	kg 1,4-DB eq	1.79E-05
fresh water aquatic ecotox.	kg 1,4-DB eq	4.24E-07
marine aquatic ecotoxicity	kg 1,4-DB eq	4.61E-03
terrestrial ecotoxicity	kg 1,4-DB eq	5.27E-08
photochemical oxidation	kg C2H4	7.47E-06
acidification	kg SO2 eq	1.01E-05
eutrophication	kg PO4--- eq	1.45E-06

Table B6 Results of the impact assessment of biogas production process for producing 1 MJ of CBG by using Eco-indicator 95 V2.03 / Europe e

Impact category	Unit	Total
greenhouse	kg CO2	1.72E-02
ozone layer	kg CFC11	5.32E-13
acidification	kg SO2	1.16E-05
eutrophication	kg PO4	1.45E-06
heavy metals	kg Pb	1.53E-10
carcinogens	kg B(a)P	3.08E-12
winter smog	kg SPM	1.90E-04
summer smog	kg C2H4	8.65E-06
pesticides	kg act.subst	0.00E+00
energy resources	MJ LHV	5.36E-02
solid waste	kg	4.96E-06

Table B7 Results of the impact assessment of biogas upgrading process for producing 1 MJ of CBG by using CML 2 baseline 2000 V2.03 / World, 1995

Impact category	Unit	Total
abiotic depletion	kg Sb eq	9.97E-05
global warming (GWP100)	kg CO2 eq	2.26E-02
ozone layer depletion (ODP)	kg CFC-11 eq	1.22E-12
human toxicity	kg 1,4-DB eq	5.44E-05
fresh water aquatic ecotox.	kg 1,4-DB eq	1.30E-06
marine aquatic ecotoxicity	kg 1,4-DB eq	1.41E-02
terrestrial ecotoxicity	kg 1,4-DB eq	1.61E-07
photochemical oxidation	kg C2H4	3.49E-06
acidification	kg SO2 eq	3.03E-05
eutrophication	kg PO4--- eq	4.40E-06

Table-B8 Results of the impact assessment of biogas upgrading process for producing 1 MJ of CBG by using Eco-indicator 95 V2.03 / Europe e

Impact category	Unit	Total
greenhouse	kg CO2	1.69E-02
ozone layer	kg CFC11	1.63E-12
acidification	kg SO2	3.48E-05
eutrophication	kg PO4	4.40E-06
heavy metals	kg Pb	4.66E-10
carcinogens	kg B(a)P	9.39E-12
winter smog	kg SPM	5.80E-04
summer smog	kg C2H4	3.88E-06
pesticides	kg act.subst	0.00E+00
energy resources	MJ LHV	1.48E-01
solid waste	kg	1.39E-05

Table B9 Results of the impact assessment of compression and gas station phase for producing 1 MJ of CBG by using CML 2 baseline 2000 V2.03 / World, 1995

Impact category	Unit	Total
abiotic depletion	kg Sb eq	1.31E-05
global warming (GWP100)	kg CO2 eq	1.81E-03
ozone layer depletion (ODP)	kg CFC-11 eq	4.12E-12
human toxicity	kg 1,4-DB eq	1.16E-05
fresh water aquatic ecotox.	kg 1,4-DB eq	7.72E-07
marine aquatic ecotoxicity	kg 1,4-DB eq	5.83E-03
terrestrial ecotoxicity	kg 1,4-DB eq	5.24E-08
photochemical oxidation	kg C2H4	1.57E-07
acidification	kg SO2 eq	3.99E-06
eutrophication	kg PO4--- eq	5.76E-07

Table B10 Results of the impact assessment of compression and gas station phase for producing 1 MJ of CBG by using Eco-indicator 95 V2.03 / Europe e

Impact category	Unit	Total
greenhouse	kg CO2	1.66E-03
ozone layer	kg CFC11	5.40E-12
acidification	kg SO2	4.57E-06
eutrophication	kg PO4	5.76E-07
heavy metals	kg Pb	1.56E-10
carcinogens	kg B(a)P	1.84E-12
winter smog	kg SPM	7.53E-05
summer smog	kg C2H4	1.86E-07
pesticides	kg act.subst	0.00E+00
energy resources	MJ LHV	1.98E-02
solid waste	kg	1.81E-06

Table B11 Results of the impact assessment of transportation phase for producing 1 MJ of CBG by using CML 2 baseline 2000 V2.03 / World, 1995

Impact category	Unit	Total
abiotic depletion	kg Sb eq	9.90E-08
global warming (GWP100)	kg CO2 eq	1.61E-05
ozone layer depletion (ODP)	kg CFC-11 eq	7.33E-23
human toxicity	kg 1,4-DB eq	4.43E-07
fresh water aquatic ecotox.	kg 1,4-DB eq	1.99E-09
marine aquatic ecotoxicity	kg 1,4-DB eq	9.23E-06
terrestrial ecotoxicity	kg 1,4-DB eq	1.56E-10
photochemical oxidation	kg C2H4	1.54E-09
acidification	kg SO2 eq	3.95E-08
eutrophication	kg PO4--- eq	7.98E-09

Table B12 Results of the impact assessment of transportation phase for producing 1 MJ of CBG by using Eco-indicator 95 V2.03 / Europe e

Impact category	Unit	Total
greenhouse	kg CO2	1.59E-05
ozone layer	kg CFC11	9.78E-23
acidification	kg SO2	5.03E-08
eutrophication	kg PO4	7.98E-09
heavy metals	kg Pb	2.23E-12
carcinogens	kg B(a)P	8.70E-15
winter smog	kg SPM	7.33E-09
summer smog	kg C2H4	1.24E-08
pesticides	kg act.subst	0.00E+00
energy resources	MJ LHV	2.22E-04
solid waste	kg	1.74E-08

Table B13 Results of the impact assessment of combustion phase for producing 1 MJ of CBG by using CML 2 baseline 2000 V2.03 / World, 1995

Impact category	Unit	Total
abiotic depletion	kg Sb eq	0.00E+00
global warming (GWP100)	kg CO2 eq	5.69E-04
ozone layer depletion (ODP)	kg CFC-11 eq	0.00E+00
human toxicity	kg 1,4-DB eq	8.31E-06
fresh water aquatic ecotox.	kg 1,4-DB eq	0.00E+00
marine aquatic ecotoxicity	kg 1,4-DB eq	0.00E+00
terrestrial ecotoxicity	kg 1,4-DB eq	0.00E+00
photochemical oxidation	kg C2H4	1.00E-05
acidification	kg SO2 eq	3.46E-06
eutrophication	kg PO4--- eq	9.00E-07

Table B14 Results of the impact assessment of combustion phase for producing 1 MJ of CBG by using Eco-indicator 95 V2.03 / Europe e

Impact category	Unit	Total
greenhouse	kg CO2	0.00E+00
ozone layer	kg CFC11	0.00E+00
acidification	kg SO2	4.85E-06
eutrophication	kg PO4	9.00E-07
heavy metals	kg Pb	0.00E+00
carcinogens	kg B(a)P	0.00E+00
winter smog	kg SPM	0.00E+00
summer smog	kg C2H4	1.86E-05
pesticides	kg act.subst	0.00E+00
energy resources	MJ LHV	0.00E+00
solid waste	kg	0.00E+00

Appendix C The Regeneration Process of 4A Molecular Sieve (UOP LLC.)

Type 4A molecular sieve can be regenerated for re-use by purging or evacuating at elevated temperatures. The degree of regeneration (water removal) is dependent on the temperature and humidity of the purge gas.

4A molecular sieve is available in granular, spherical or extrudate form. The nominal sizes of the granules and spheres or "beads" are shown below. The diameters for the extrudates or "pellets" are also shown; the length is approximately twice the diameter.

Table C1 Physical properties of 4A molecular sieve

	14 x30 granular	10x20 Beads	8x12 Beads	4x8 Beads	1/16" Pellets	1/8" Pellets
Nominal Pore Diameter (angstroms)	4	4	4	4	4	4
Particle Size Diameter (mm)	0.8	1.4	2.0	4.0	1.6	3.2
Bulk Density (lbs/ft^3)	44	44	44	44	44	44
Heat of Adsoption (Btu lb H_2O)	1800	1800	1800	1800	1800	1800
Crush Strength (lbs)	N/A	N/A	7	18	10	20
Equilibrium H_2O Capacity* (wt-%)	22	22	22	22	22	22
Moisture content (wt-%)	1	1	1	1	1	1

*Measured at 17.5 mm Hg and 25°C

Appendix D Land Use Change Calculation (Commission decision of 10 June 2010, The European Commission)

Calculation of Carbon Stocks

For the calculation of the carbon stock of the reference land use (CS_R) and the carbon stock of the actual land use (CS_A) the following rule shall apply:

$$CS_i = (SOC + C_{VEG}) \times A$$

where:

CS_i = the carbon stock per unit area associated with the land use i (measured as mass of carbon per unit area, including both soil and vegetation);

SOC = soil organic carbon (measured as mass of carbon per hectare);

C_{VEG} = above and below ground vegetation carbon stock (measured as mass of carbon per hectare);

A = factor scaling to the area concerned (measured as hectares per unit area).

Soil Organic Carbon Stock

For the calculation of SOC the following rule may be used:

$$SOC = SOC_{ST} \times F_{LU} \times F_{MG} \times F_I$$

where:

SOC = soil organic carbon (measured as mass of carbon per hectare);

SOC_{ST} = standard soil organic carbon in the 0-30 centimeter topsoil layer (measured as mass of carbon per hectare);

F_{LU} = land use factor reflecting the difference in soil organic carbon associated with the type of land use compared to the standard soil organic carbon;

F_{MG} = management factor reflecting the difference in soil organic carbon associated with the principle management practice compared to the standard soil organic carbon;

F_I = input factor reflecting the difference in soil organic carbon associated with different levels of carbon input to soil compared to the standard soil organic carbon.

Actual land use;

For grassland:

- Soil type = Low activity clay soils
- Climate region = Tropical, moist
- Land use = Savannah
- Management = Improved
- Input = Medium

So, SOC_{ST} = 47 tons C/ha

F_{LU} = 1

F_{MG} = 1.17

F_{I} = 1

$SOC = SOC_{ST} \times F_{LU} \times F_{MG} \times F_{I}$

SOC = 54.99 tons C/ha

And C_{VEG} = 8.1 tons C/ha

So, CS_{A} = 63.09 tons C/ha

Reference land use;

For forest land:

- Climate region = Tropical, moist
- Land use = Shifting cultivation-mature fallow

So, SOC_{ST} = 47 tons C/ha

F_{LU} = 0.8

$SOC = SOC_{ST} \times F_{LU}$

SOC = 37.6 tons C/ha

And

- Forest land, having more than 30% canopy cover
- Ecological zone = Tropical moist deciduous forest
- Continent = Asia (continental)

C_{VEG} = 110 tons/ha

So, CS_R = 147.6 tons C/ha

Emission from land use change $= (CS_R - CS_A) \times (3.664/20)$

$= 15.4935$ tons CO_2 eq. ha^{-1} $year^{-1}$

$= 2.479$ tons CO_2 eq. rai^{-1} $year^{-1}$

Appendix E The Analyzed CBG Production Plant, Mae Taeng, Chiang Mai, Thailand

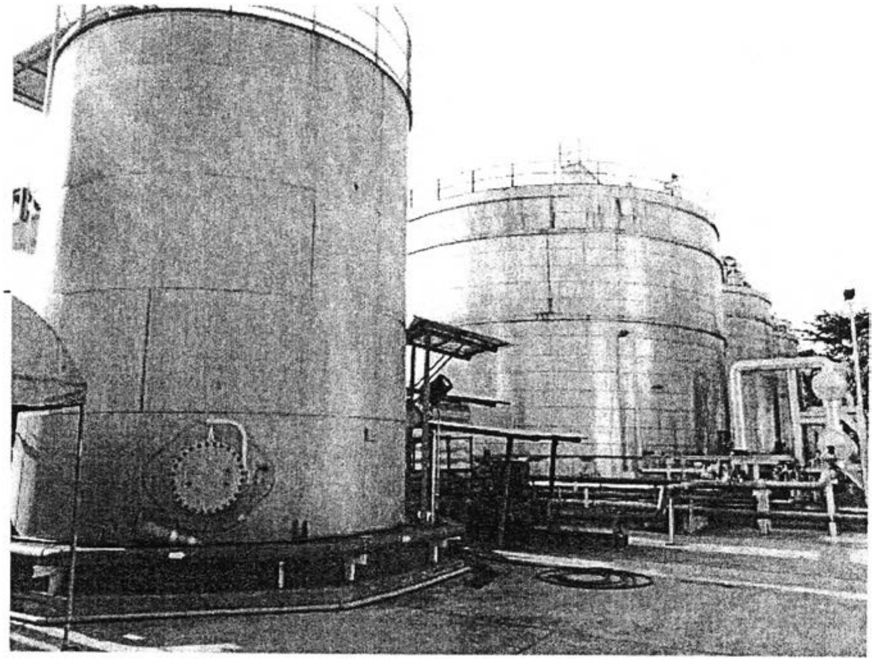

Figure E1 The analyzed CBG production plant (1).

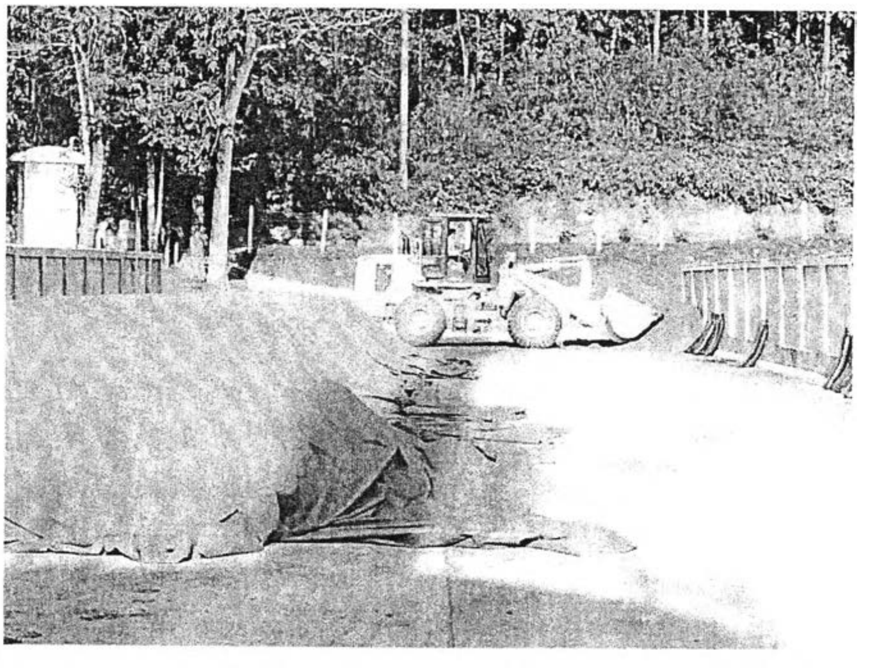

Figure E2 The analyzed CBG production plant (2).

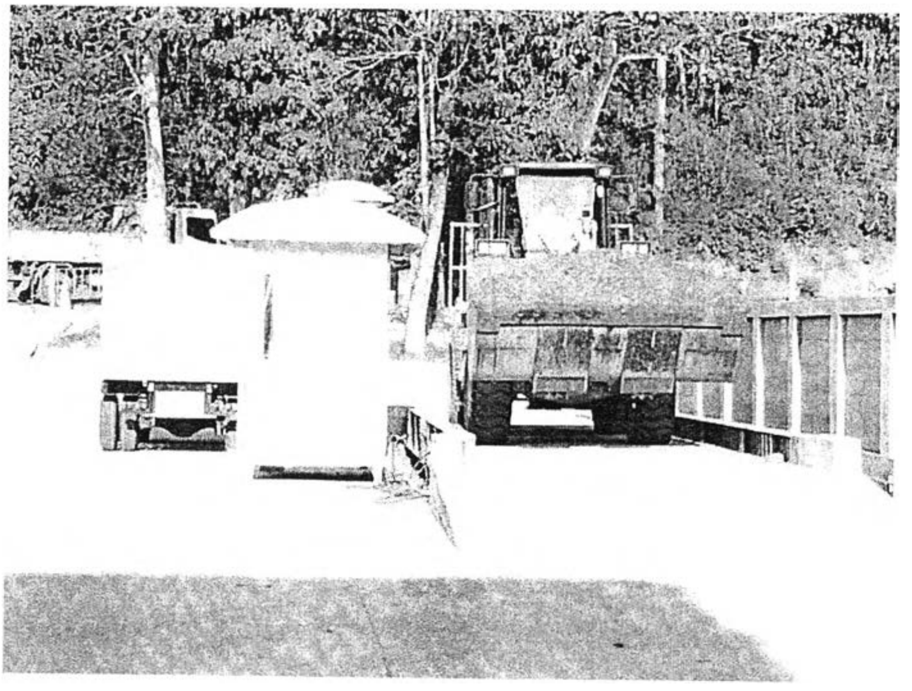

Figure E3 The analyzed CBG production plant (3).

Figure E4 The analyzed CBG production plant (4).

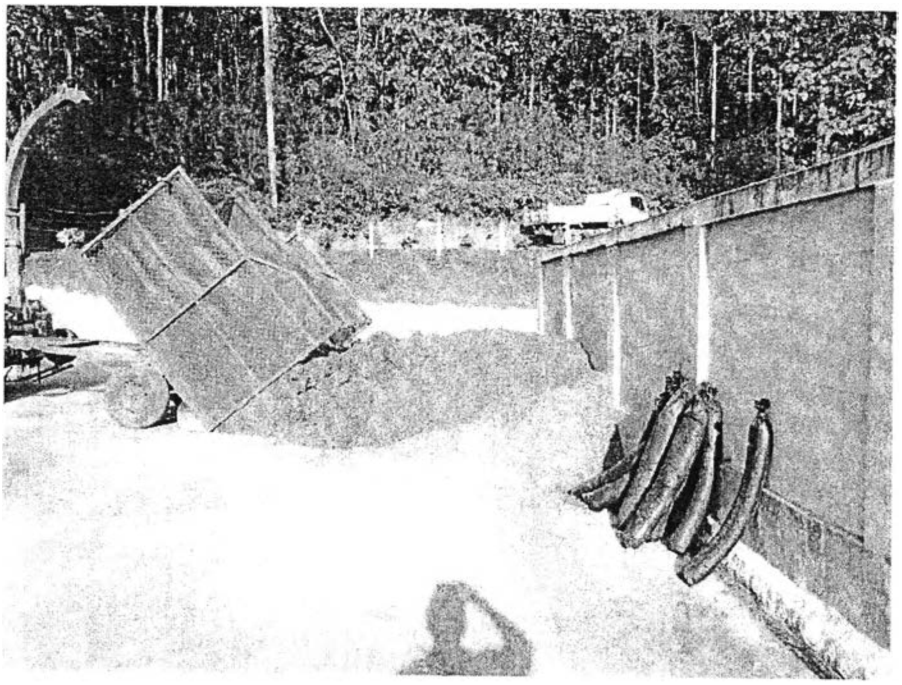

Figure E5 The analyzed CBG production plant (5).

Figure E6 The analyzed CBG production plant (6).

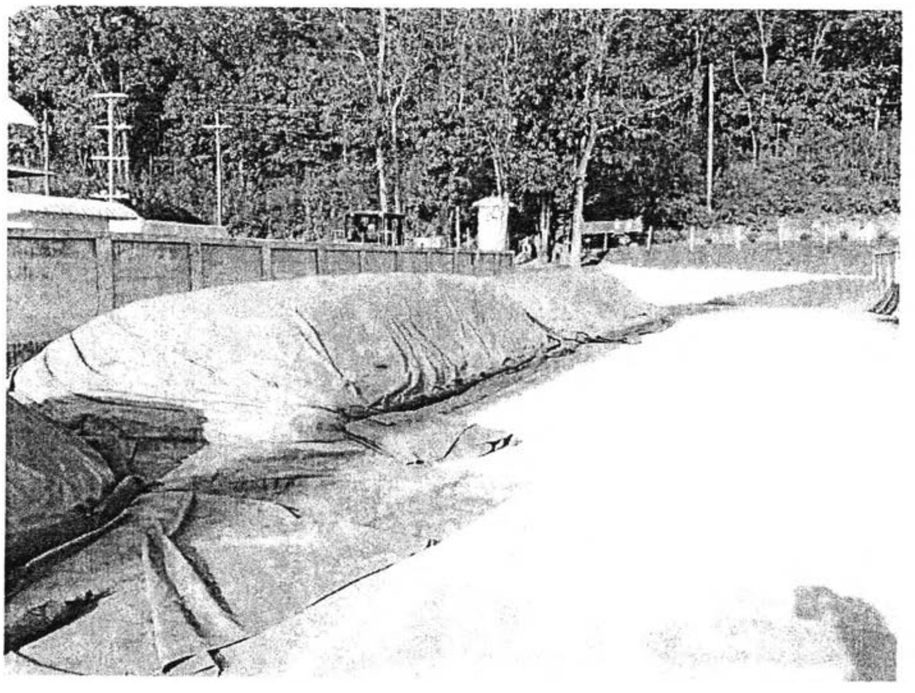

Figure E7 The analyzed CBG production plant (7).

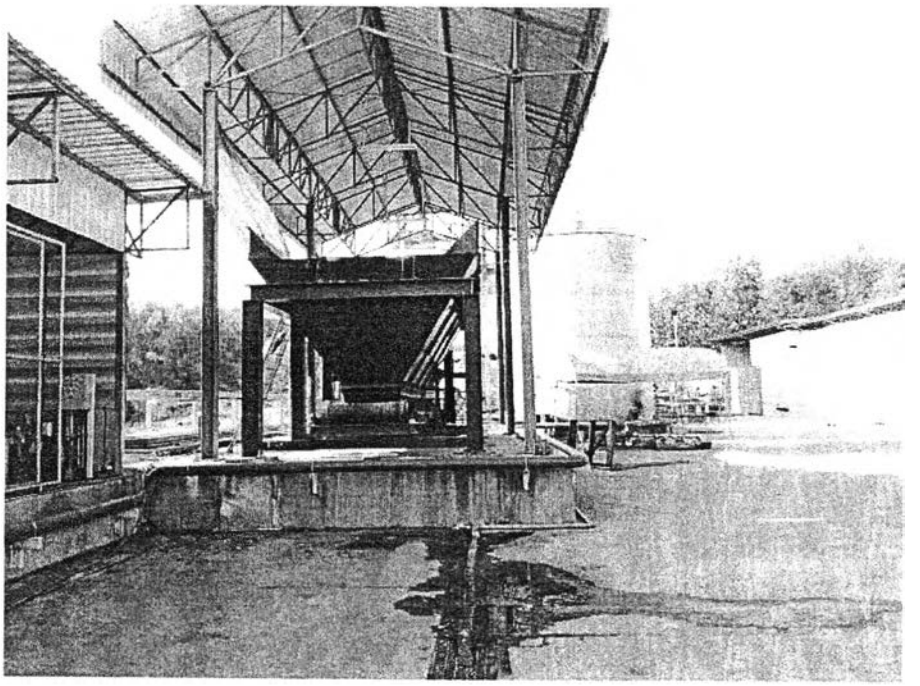

Figure E8 The analyzed CBG production plant (8).

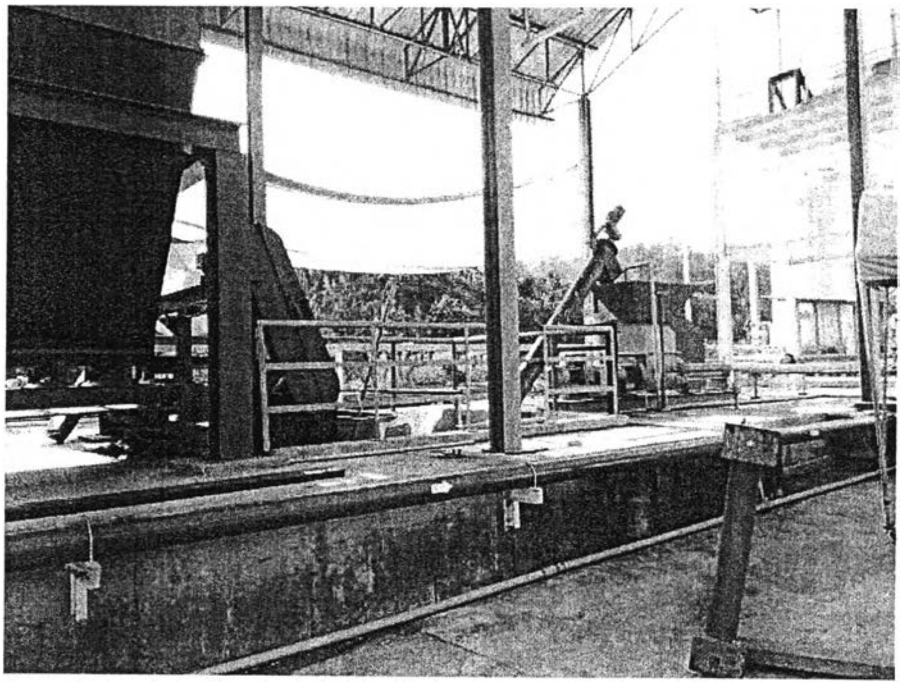

Figure E9 The analyzed CBG production plant (9).

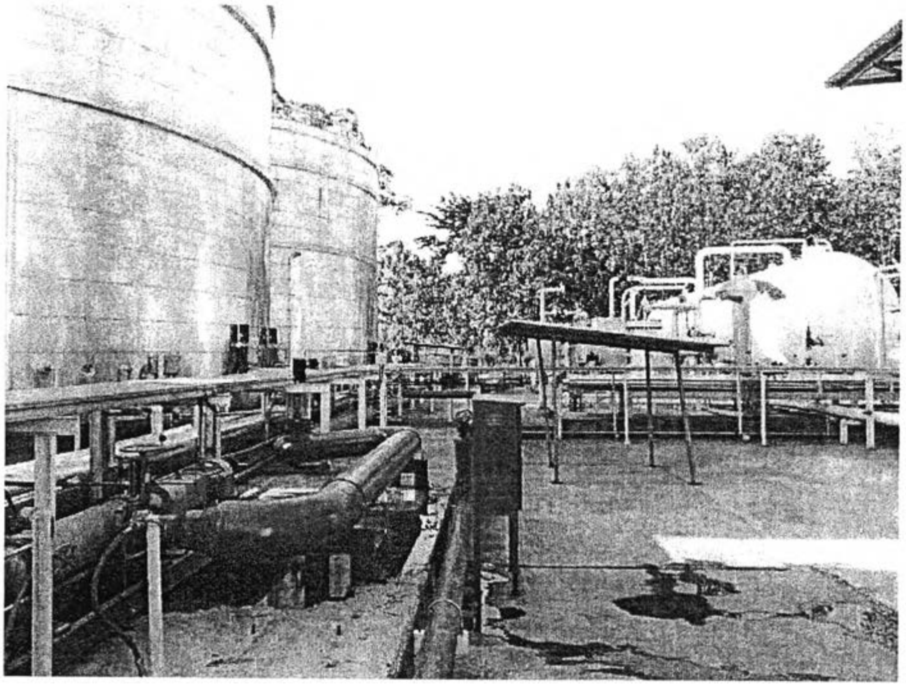

Figure E10 The analyzed CBG production plant (10).

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1. Promchaona, P.; Malakul, P.; and Chatchupong, T. (2014, April 22) Life Cycle Assessment of Compressed Biomethane Gas (CBG) As Second Generation Biofuel in Thailand. Proceedings of the 5th Research Symposium on Petroleum, Petrochemicals, and Advanced Materials and the 20th PPC Symposium on Petroleum, Petrochemicals, and Polymers, Bangkok, Thailand.