Life-Cycle Assessment of Pinnacle Landfill Gas to Delivered LNG and L/CNG in California

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Submitted to:

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Prepared by

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General Information

(This Section contains Confidential Business Information)

Pinnacle Gas Producers, LLC, operates a landfill gas (LFG) refinery at Pinnacle Road Landfill located in Moraine, OH. The refinery recovers methane from both the Pinnacle Road Landfill and the Stony Hill Landfill, which are operated by Waste Management of Ohio.

The refinery uses the Kryosol process to remove the impurities in the landfill gas and produces commercially saleable natural gas. Pinnacle purchases natural gas from Vectren Corporation to provide startup fuel for the compressor and thermal oxidizer. Pinnacle purchases electricity from Dayton Power and Light to serve the plant's electrical demand.

The nominal capacity of the Pinnacle refinery is [redacted] mmscf per day. The Final Permit to Install and Operate issued by the Ohio Environmental Protection Agency (OEPA) October 2011 limits the amount of gas that can be processed to [redacted] million standard cubic feet per day, or [redacted] mmBtu at the lower heating value. This limit is further reduced by the average buyback quantity of [redacted] mmBtu per day, resulting in a daily production limit of [redacted] mmBtu per day. The annual permitted peak capacity would be [redacted] mmBtu (LHV) of biogas. The permit limit corresponds to a calculated EPA Permitted Capacity of [redacted] equivalent gallons renewable fuel per year. The EPA Permitted Capacity of the plant was determined based upon the recovery rates achieved from January through November of 2013 and using [redacted] hours per year as directed by USEPA (See Attachment F of the EPA RIN Application).

Based on EPA guidance received, the "contracted volume" of the biogas facility was calculated using the most restrictive contract for sale of biogas for use as transportation fuel. This volume will be used in lieu of the EPA Permitted capacity for purposes of CDX registration. The annual contracted volume was calculated to be [redacted] equivalent gallons renewable fuel which is greater than the EPA Permitted.

The following pathway was produced using two (2) years (January 2012 – December 2013) of landfill gas production data and two (2) years (2011 – 2012) of liquefaction data.

Process Description

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The process train for the production of pipeline quality natural gas from this project includes a gas collection system under a vacuum to collect landfill gas. The landfill gas is transferred to the refinery via pipe and blowers. The biogas is then purified using the Kryosol process:

1) Chilling and pressurizing the gas to remove condensate
2) Liquid methanol injected into gas to absorb remaining water

3) Cold methanol is used to absorb CO2 and other impurities
4) Gas passed through catalyst bed to deoxidize gas
5) Gas is cooled and passed through triethylene glycol to absorb water created in deoxidation process

The landfill gas with [redacted] methane content is processed to approximately [redacted] methane purity, the balance being the inerts of N2 and CO2. Gas not meeting specifications for pipeline natural gas or unable to be accepted by the pipeline may be combusted by flare.

CO2 and other flash gas streams from the purification process are disposed of in a thermal oxidizer while liquid waste is returned to the landfill. Heavy hydrocarbons collected in the process are disposed of as RCRA hazardous waste.

Data Collection and Process Results

To estimate GHG emissions, the energy and materials necessary for the following processes needs to be determined: LFG Production Plant, Transport of Gas to California (Pipeline), and Liquefaction.

LFG Production Plant

(This Section contains Confidential Business Information)

The plant has a stated capacity of [redacted] mmscf per day at [redacted] methane which is equivalent to a potential product of [redacted] mmscf per day of biogas at [redacted] methane. The permitted capacity is [redacted] equivalent gallons renewable fuel per year of purified biogas. Pinnacle imports the necessary electricity to purify the landfill gas and uses an onsite thermal oxidizer and open flares to combust off-gases generated during the regeneration steps and when the plant is not operating. Pinnacle does not have process heaters. The refinery uses natural gas to power the compressor, thermal oxidizer, and flare pilot.

The table below shows the available data provided by Pinnacle for input biogas, product biogas, consumed biogas, and imported electricity from January 2012 to December 2013. The balance of the biogas consumed in the thermal oxidizer and flare is calculated. The table also shows the provided data converted to GREET model inputs. The Pinnacle pathway utilizes the CA-GREET default values for LFG recovery. After the table is a simplified process diagram of the facility. The value of [redacted] MMBtu in Table 1 below is the amount of product pipeline quality biogas produced. All supporting data and calculations for Table 1 and Figure 1 below can be found in [redacted] spreadsheet on the “Summary” tab. To determine combustion emissions from the consumed natural gas and landfill gas at the landfill gas plant, the GREET default values for natural gas combustion process during natural gas liquefaction (100% natural gas turbine) were chosen since they represent the processes more closely than natural gas compression (100% natural gas engine).

Table 1. Pinnacle LFG Plant Operating Energy and Flare Credit

(This Table contains Confidential Business Information)

	January 2012 – December 2013 Data	Btu/MMBtu of Product Gas	Input Value	Changed Cells – NG Tab
LFG Produced	[redacted] MMBtu	1,000,000		
Imported Electricity	[redacted] kWh	[redacted] Btu	= [redacted]	AI79 (via C184)
LFG Consumed (Energy + Flare)	[redacted] MMBtu	[redacted] Btu	= [redacted] %	AI75 (via C183)
Imported Natural Gas	[redacted] MMBtu	[redacted] Btu	= [redacted] %	AI76 (via C185)
Processing Efficiency	-	[redacted] %	[redacted] %	AI66 (via C182)
Flare Credit	-	[redacted] Btu	Calculated w/in GREET	

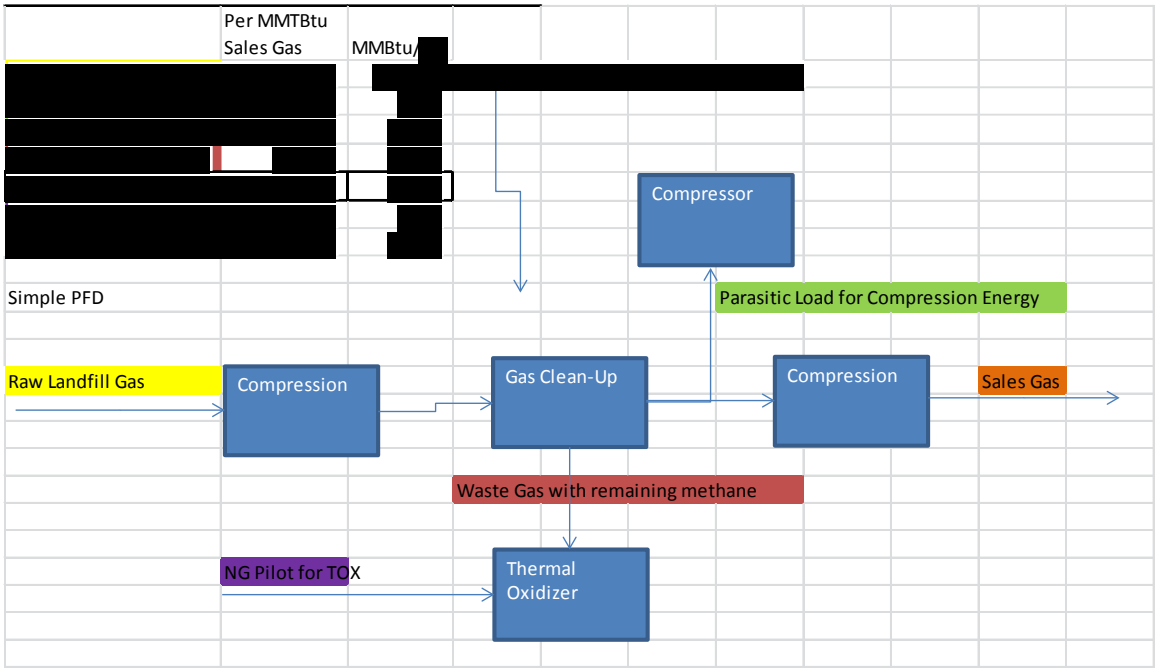

Figure 1. Pinnacle Process per MMBtu and MMBtu/day Energy Flows

The GREET model LFG pathway was then modified to adjust efficiency gas and process energy shares as listed in Table 1. The Southeast Asia region on the Regional LT tab was changed to the RFCW Region to represent the eGRID (8th Edition[1]) where Moraine is located and this was used for Pinnacle. The ARB methodology of converting eGRID

[1] eGrid 8th Edition Version 1.0, Year 2009 Summary Tables, created May 2012. www.epa.gov/cleanenergy/documents/egridzips/eGRID_8th_edition_V1-0_year_2009_Summary_Tables.pdf

electricity mix to marginal mix was employed. This changed the electric mix cells of J83-J88 on the Regional LT tab to those shown in Table 2. The remaining values from the Southeast Asia Region (now the RFCW Region) were changed to match the US Average.

Table 2. RFCW Electricity Grid Mix

	eGRID Grid Mix	Marginal Grid Mix	CA-GREET Cell Regional LT Tab
Residual oil	0.8%	0.8%	J83
Natural gas	3.5%	27.9%	J84
Coal	69.9%	69.9%	J85
Nuclear	23.6%	0%	J86
Biomass	0.5%	0.5%	J87
Other (renewables)	1.8% (w/ hydro)	0.9% (w/o hydro)	J88

This produced the results for LFG to biomethane shown in the table below taken from cells on the NG Tab. Conversion from g/MMBtu to g/MJ was done using the conversion factor of 1,055.055 MJ/MMBTU as is done in the CA-GREET model.

The recovery energy and emissions are based on ARB LFG pathway defaults of 4,621.25 Btu of electricity/MMBtu of landfill gas for recovery and 17.32 Btu electricity/MMBtu of landfill gas for transport.

Table 3. Pinnacle LFG Plant Greenhouse Gas Emissions

(This Table contains Confidential Business Information)

	Recovery Emissions	Pinnacle LFG Processing	CA-GREET Cell NG Tab
gVOC/MMBTU	[redacted]	[redacted]	B163/C163
gCO/MMBTU	[redacted]	[redacted]	B164/C164
gCH4/MMBTU	[redacted]	[redacted]	B165/C165
gN2O/MMBTU	[redacted]	[redacted]	B166/C166
gCO2/MMBTU	[redacted]	[redacted]	B167/C167
gCO2e/MMBTU	[redacted]	[redacted]	B168/C168
gCO2e/MJ	[redacted]	[redacted]	B169/C169
gCO2e/MJ Flare Credit		[redacted]	D169
Total gCO2e/MJ Recovery + Processing		[redacted]	E169

Transportation to California by Pipeline

The pipeline transport distance was modified to 2,114 miles from Moraine, OH to Boron, CA where the gas will be liquefied. The distance was determined by the using the driving route most similar to the pipeline map. Google Maps was used to determine the driving routes with the I-40 route most similar to the pipeline map. The emissions were determined by linked cell E148 on the NG tab to cell F479 on the T&D_Flowcharts tab for LFG to CNG. The table below shows the pipeline transport emissions from cells F163-F169 on the NG Tab.

Table 4. Pinnacle LFG Transport Greenhouse Gas Emissions

(This Table contains Confidential Business Information)

Transport Emissions	Pinnacle LFG Transport
gVOC/MMBTU	
gCO/MMBTU	
gCH4/MMBTU	
gN2O/MMBTU	
gCO2/MMBTU	
gCO2e/MMBTU	
gCO2e/MJ	

Liquefaction

(This Section contains Confidential Business Information)

Based on the submitted Confidential Business Information from Clean Energy Fuels for two (2) years (2011-2012), the Boron facility requires kWh/gal of LNG for liquefaction kWh/gal LNG) found in . The data and efficiency in the excel file have been previously approved in Pathway . Only electricity is required for the process making the fuel shares . For the Boron LNG facility, the feed gas is the same as the product LNG gas. 80,968 Btu is the energy content of one gallon of LNG. All excess gas that is not converted to LNG is sent to the neighboring natural gas power plant. Table 5 below shows the calculation from kWh per gallon to process efficiency and the cells that were changed. Table 6 shows the results from cells G163- G169.

Table 5. Boron LNG Plant Operating Energy

(This Table contains Confidential Business Information)

All Units in Btus per Gal of LNG	Boron LNG Plant	Input Value	Changed Cells – NG Tab
Feed Gas	80,968		
Liquefaction Electricity		%	AD79
Liquefaction Natural Gas		%	AD75
Liquefaction Efficiency	%	%	AD66

Table 6. Boron LNG Plant Greenhouse Gas Emissions

(This Table contains Confidential Business Information)

Recovery and Processing Emissions	Boron LNG Plant
gVOC/MMBTU	
gCO/MMBTU	
gCH4/MMBTU	
gN2O/MMBTU	
gCO2/MMBTU	
gCO2e/MMBTU	
gCO2e/MJ	

LNG Transport to Refueling Station

In addition the CA-GREET default LNG transport distance of 50 miles was used but the fuel shares were modified to utilize the Westport HPDI trucks consuming 90% LNG and 10% diesel with an EER of 1.0. The numbers were inputted in cells CD95 (% diesel consumption) and CD97 (% LNG consumption) on the "T&D" tab and the results were taken from cells H163-H169 on the "NG" tab.

Table 7. LNG Transport Greenhouse Gas Emissions

(This Table contains Confidential Business Information)

	California LNG Plant – 50 miles 10% Diesel and 90% LNG
gVOC/MMBTU	
gCO/MMBTU	
gCH4/MMBTU	
gN2O/MMBTU	
gCO2/MMBTU	
gCO2e/MMBTU	
gCO2e/MJ	

LNG Storage

In addition the CA-GREET default for LNG storage was used. The default values are listed in Table 8 below and yield the results in Table 9 (the results were taken from cells I163-I169 on the "NG" tab.).

Table 8. LNG Storage CA-GREET Default Values

	Bulk Terminal Storage	CA-GREET Cells Inputs Tab	Distribution	CA-GREET Cells Inputs Tab
Boil-Off Rate: % per Day	0.05	E171	0.1	F171
Duration of Storage or Transit: Days	5	E174	0.1	F174
Recovery Rate for Boil-Off Gas	80%	E179	80%	F179

Table 9. LNG Storage Greenhouse Gas Emissions

	LNG Storage
gVOC/MMBTU	-
gCO/MMBTU	-
gCH4/MMBTU	11.10
gN2O/MMBTU	-
gCO2/MMBTU	-
gCO2e/MMBTU	277
gCO2e/MJ	0.26

L/CNG Conversion

To convert from LNG to CNG, LNG is re-vaporized and then compressed to cylinder pressure (at about 3000psi). According to ARB default LNG and CNG pathways (as sent to Clean Energy and ICF by ARB Staff):

- Re-gasified to LNG: + 0.75 gCO2e/MJ[2]
- Compressed to CNG: +2.14 gCO2e/MJ[3]
- Total: 2.89 gCO2e/MJ

[2] http://www.arb.ca.gov/fuels/lcfs/092309lcfs_lng.pdf
[3] http://www.arb.ca.gov/fuels/lcfs/022709lcfs_cng.pdf

Pinnacle Fuel Pathway Results

When the CA-GREET model is run completely with the modifications listed above, the table below shows the complete pathway results. The WTT pathway gCO2e/MJ results were taken from cell J170 which is the sum of cells E170 – I170 on the "NG" tab for LNG. The TTW gCO2e/MJ was taken from the Detailed California-Modified GREET Pathway for Liquefied Natural Gas (LNG) from Landfill Gas[4].

Table 10 - Pathway Results

GHG Emissions (gCO2e/MJ)	Pinnacle LFG Plant to LNG	Pinnacle LFG Plant to L/CNG
Landfill Gas Recovery	[redacted]	[redacted]
Landfill Gas Processing	[redacted]	[redacted]
Flare Credit	[redacted]	[redacted]
Landfill Gas Transport	[redacted]	[redacted]
Liquefaction	[redacted]	[redacted]
LNG Transport	[redacted]	[redacted]
LNG Storage	[redacted]	[redacted]
L/CNG Conversion		2.89
gCO2e/MJ WTT	[redacted]	[redacted]
Carbon in Fuel	[redacted]	[redacted]
Vehicle CH4 and N2O	[redacted]	[redacted]
gCO2e/MJ TTW	[redacted]	[redacted]
gCO2e/MJ WTW	25.50	27.62

[4] http://www.arb.ca.gov/fuels/lcfs/092309lcfs_lfg_lng.pdf

Appendix A: Summary of CA-GREET Inputs

Parameter	Unit	Value	CA-GREET Cell Changed
LFG Recovery and Transport			
Thermal	Btu/MMBtu	[redacted]	CA-GREET Default (L85)
Electricity	Btu/MMBtu	[redacted]	CA-GREET Default[5] (L91)
Total Energy	Btu/MMBtu	[redacted]	N/A
LFG Plant			NG Tab
LFG Processing Efficiency	%	[redacted]	AI66 (via C182)
Electricity Fuel Share	%	[redacted]	AI79 (via C184)
LFG Fuel Share	%	[redacted]	AI75 (via C183)
Natural Gas Fuel Share	%	[redacted]	AI76 (via C185)
Electricity	kWh/MMBtu	[redacted]	N/A
Electricity	Btu/MMBtu	[redacted]	Calculated in CA-GREET (AI91)
Natural Gas	Btu/MMBtu	[redacted]	Calculated in CA-GREET (AI85)
LFG	Btu/MMBtu	[redacted]	Calculated in CA-GREET (AI87)
Credit for Not Flaring	Btu/MMBtu	[redacted]	Calculated in CA-GREET (AJ88)
Total Energy	Btu/MMBtu	[redacted]	N/A
Electricity Grid Mix			Regional LT Tab
Residual oil	%	0.8	J83
Natural gas	%	27.9	J84
Coal	%	69.9	J85
Nuclear	%	0	J86
Biomass	%	0.5	J87
Other (renewables)	%	0.9	J88
Natural Gas Transport			T&D Flowcharts Tab (via NG Tab)
Pipeline Distance	mi	2,114	F479 (via E148)
Liquefaction			NG Tab
Electricity	kWh/Gallon	[redacted]	N/A
Liquefaction Efficiency	%	[redacted]	AD66
Electricity Fuel Share	%	[redacted]	AD79
Natural Gas Fuel Share	%	[redacted]	AD75
Electricity	Btu/MMBtu	[redacted]	Calculated in CA-GREET (AD91)

[5] http://www.arb.ca.gov/fuels/lcfs/022709lcfs_lfg.pdf, pages 9-10.

LNG Transport			T&D Tab
Truck LNG Fuel Share	%	90	CD97
Truck Diesel Fuel Share	%	10	CD95
LNG Storage			Inputs Tab
Boil-Off Rate: % per Day	%/day	0.05 / 0.1	E171 / F171
Duration of Storage or Transit: Days	Days	5 / 0.1	E174 / F174
Recovery Rate for Boil-Off Gas	%	80% / 80%	E179 / F179
L/CNG			NG Tab
L/CNG Conversion	gCO2e/MJ	2.89	J171