California Environmental Protection Agency

Air Resources Board

Detailed California-Modified GREET Pathway for Compressed Natural Gas (CNG) from Landfill Gas

Stationary Source Division

Release Date: October 8, 2008

Version: 1.0

DRAFT

The Staff of the Air Resources Boards developed this preliminary draft version as part of the Low Carbon Fuel Standard regulatory process.

The ARB acknowledges contributions from the California Energy Commission, TIAX, and Life Cycle Associates during the development of this document.

When reviewing this document, please submit comments directly to:

Anil Prabhu: aprabhu@arb.ca.gov
Chan Pham: cpham@arb.ca.gov
Michelle Werner: mwerner@arb.ca.gov

These comments will be compiled, reviewed, and posted to the LCFS website in a timely manner.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

SUMMARY

CA-GREET Model Pathway for CNG from Landfill Gas

Well-To-Tank (WTT) Life Cycle Analysis of a fuel pathway considers all fuel production steps from feedstock recovery to finished fuel. Tank-To-Wheel (TTW) analysis includes actual combustion of fuel in a motor vehicle for motive power. Together, WTT and TTW analysis are combined to provide a total Well-To-Wheel (WTW) analysis.

A Life Cycle Analysis Model called the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET)[1] developed by Argonne National Laboratory forms the core basis of the methodology used in this document. The model however, was modified by TIAX under contract to the California Energy Commission during the AB 1007 process[2]. This California-modified GREET model forms the basis of this document. It has been used to calculate the energy use and greenhouse gas (GHG) emissions generated during the process of producing compressed natural gas (CNG) from landfill gas (LFG).

The pathway includes landfill gas recovery and pipeline transport to the processing plant where it is upgraded to pipeline quality natural gas and compressed to pipeline pressures. The "natural gas" flows is transported by pipeline to a CNG refueling station where it is compressed and provided to internal combustion vehicles. The values, assumptions, and equations used in this document are from the CA modified GREET model. This pathway was added to the CA-GREET model subsequent to the AB1007 effort and is not supported by the current version of the model on the Low Carbon Fuel Standard website. The values shown in this document are preliminary draft values and staff is in the process of evaluating them. The areas that staff may revise include emission factors, energy intensity factors, % fuel shares, transport modes and their shares, agricultural chemical use factors, co-product credit methodologies, etc. Figure 1 shows the discrete components that form the CNG from LFG pathway.

This document presents all assumptions, and step by step calculations of energy consumption and GHG emissions for this CNG pathway. Several general descriptions and clarification of terminology used throughout this document are:

- GREET employs a recursive methodology to calculate energy consumption and emissions. To calculate WTT energy and emissions, the values being calculated are often utilized in the calculation. For example, crude oil is used as a process fuel to recover crude oil. The total crude oil recovery energy consumption includes the direct crude oil consumption AND the energy associated with crude recovery (which is the value being calculated).

- Btu/mmBtu is the energy input necessary in Btu to produce or transport one million Btu of a finished (or intermediate) product. This description is used consistently in

[1] http://www.transportation.anl.gov/software/GREET/
[2] http://www.energy.ca.gov/ab1007/

GREET for all energy calculations. There are 1,055 MJ in one mmBtu of energy, so to convert one million Btu into MJ, one divides by 1055.

- gCO_2e/MJ provides the total greenhouse gas emissions on a CO_2 equivalent basis per unit of energy (MJ) for a given fuel. Methane (CH_4) and nitrous oxide (N_2O) are converted to a CO_2 equivalent basis using IPCC global warming potential values and are included in the total.

- GREET assumes that VOC and CO are converted to CO_2 in the atmosphere and includes these pollutants in the total CO_2 value using ratios of the appropriate molecular weights.

- Process Efficiency for any step in GREET is defined as:

Efficiency = energy output / (energy output + energy consumed)

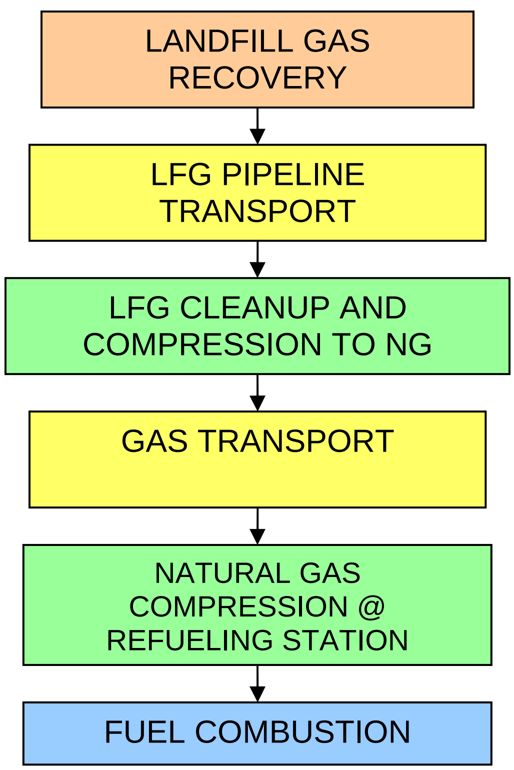

Figure 1. Discrete Components of the Landfill Gas to CNG Pathway

Table A below provides a summary of the results for this LFG to CNG pathway. The WTW analysis results in 185,104 Btu of energy required to produce 1 (one) mmBtu of available fuel energy. From a GHG perspective, 11.01 gCO_2e/MJ of GHG emissions are generated during the production and use of CNG in a passenger vehicle. Note that rounding of values has not been performed in several tables in this document. This is to allow stakeholders executing runs with the GREET model to compare actual output values from the CA-modified model with values in this document.

Table A. Summary of Energy Consumption and GHG Emissions per mmBtu of CNG Produced from LFG

	Energy Required (Btu/mmBtu)	**% Energy Contribution**	**GHG Emissions (gCO_2e/MJ)**	**%Emissions Contribution**
Landfill Gas Recovery	9,335	5.0%	0.49	4.5%
Landfill Gas Transport	35	0.0%	0.00	0%
Landfill Gas Processing	-864,788	-4.7%	-49.34	-4.5%
Transport & Distribution	530	0.3%	0.06	0.5%
Compression at Station	39,992	21.6%	2.10	19.1%
Total (WTT)	**-814,896 (see note below)**	**-440%**	**-46.69 (see note below)**	**-424%**
Carbon in Fuel	1,000,000	540%	55.2	501.4%
Vehicle CH_4 and N_2O			2.5	22.7%
Total WTW	**185,104**	**100%**	**11.01** (see note below)	**100%**

Note: percentages may not add to 100 due to rounding

The values in Table A are used to show pictorially in Figures 2 and 3 the relative contributions of each of the discrete components of this pathway. From an energy viewpoint, energy in fuel as carbon makes up the bulk of the WTW analysis. From a GHG perspective, CO_2 in fuel is the dominant source for GHG emissions for this pathway. The large negative credit for landfill gas processing is because the gas that would have been flared is otherwise being captured and not released into the atmosphere.

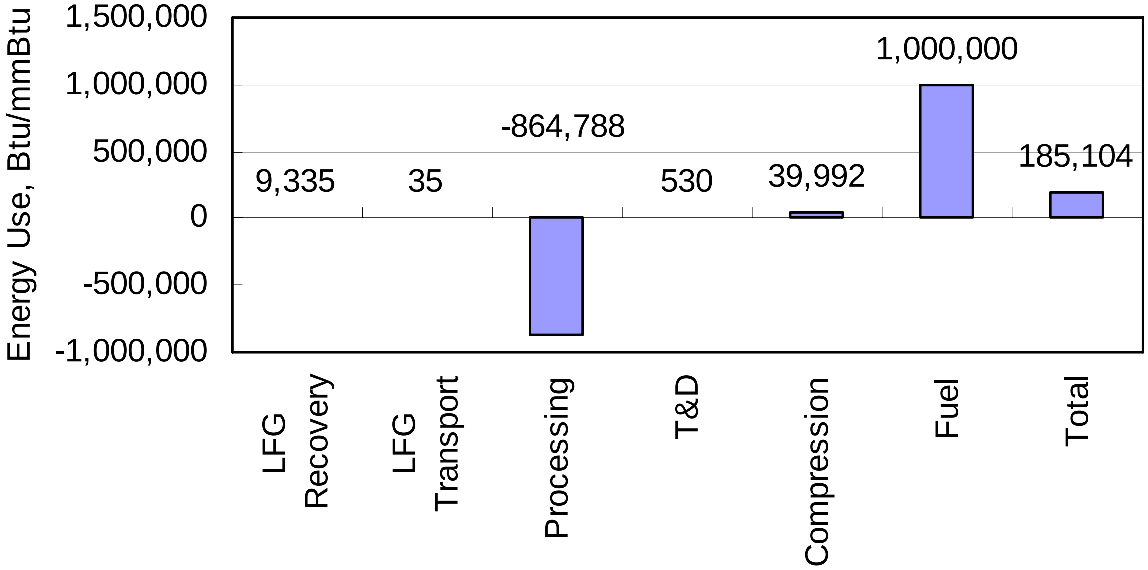

Figure 2. Energy Contributions for the CNG from LFG Pathway

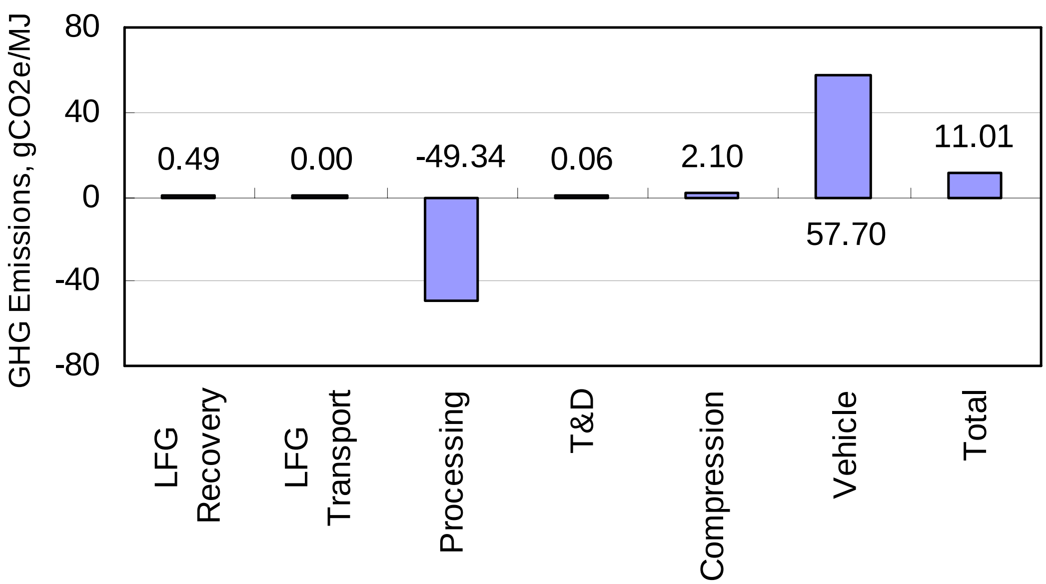

Figure 3. GHG Contributions for the CNG from LFG Pathway

The following sections provide summaries of each of the five WTT components as well as the TTW values. Expanded details are provided in Appendix A. A table of all input values is provided in Appendix B.

Landfill Gas Recovery

Tables B and C provide a summary of the energy consumption and associated GHG emissions from LFG recovery. Calculation details are provided in Appendix A.

Table B. Total Energy Consumption by Fuel Type for LFG Recovery

Fuel Type	Btu/mmBtu
Electricity	9,335
Total	**9,335**

Table C. Total GHG Emissions from LFG Recovery

	CO_2 g/mmBtu	CH_4 g/mmBtu	N_2O g/mmBtu	Total GHG gCO_2e/mmBtu	Total GHG gCO_2e/MJ
Electricity	489.181	1.104	0.012	518.173	0.491
Total	**489.181**	**1.104**	**0.012**	**518.173**	**0.491**

Landfill Gas Transport to Processing Plant

Tables B and C provide a summary of the energy consumption and associated GHG emissions from LFG recovery. Calculation details are provided in Appendix A.

Table D. Total Energy Consumption by Fuel Type for LFG Transport to Processing

Fuel Type	Btu/mmBtu
Electricity	34
Total	**34**

Table E. Total GHG Emissions for LFG Transport to Processing

	CO_2 g/mmBtu	CH_4 g/mmBtu	N_2O g/mmBtu	Total GHG gCO_2e/mmBtu	Total GHG gCO_2e/MJ
Electricity	1.821	0.004	0.000	1.929	0.002
Total	**1.821**	**0.004**	**0.000**	**1.929**	**0.002**

Landfill Gas Processing

Tables F and G provide the energy consumption and associated GHG emissions from LFG processing. Calculation details are provided in Appendix A.

Table F. Total Energy Consumption for the LFG Processing Step

Fuel Type	Btu/mmBtu
Landfill Gas	144,853
Electricity	133933
Avoided Flaring Credit	-1,143,574
Total Energy	**-864,788**

Table G. Total GHG Emissions from LFG Processing

	CO_2 g/mmBtu	CH_4 g/mmBtu	N_2O g/mmBtu	Total GHG gCO_2e/mmBtu	Total GHG gCO_2e/MJ
Landfill Gas	8,404	0.32,1	0.05	8,424	7.986
Electricity	7,018	15.84,2	0.17	7,434	7.047
Flaring Credit	-66,253	-56.04	-1.26	-67,914	-64.374
Total	-50,831	-39.87	-1.04	**-52,055**	**-49.341**

Natural Gas Transport

Tables H and I summarize energy consumption and GHG emissions from natural gas transport. Calculation details are provided in Appendix A.

Table H. Energy Use for NG Transport

Total T&D Energy Use = 530 Btu/mmBtu

Table I. GHG Emissions from Natural Gas Transport to Refueling Station

	CO_2	CH_4	N_2O	Total GHG gCO_2e/mmBtu	Total GHG gCO_2e/MJ
Total	**27.240**	**1.462**	**0.001**	**61.096**	**0.058**

Natural Gas Compression

Tables J and K provide a summary of energy consumption and GHG emissions from natural gas compression at the refueling station. Calculation details are provided in Appendix A.

Table J. Energy Use for NG Compression, Btu/mmBtu

Total electricity use for compression is 39,992 Btu/mmBtu

Table K. Total GHG Emissions Associated with Natural Gas Compression

	CO_2 g/mmBtu	CH_4 g/mmBtu	N_2O g/mmBtu	Total GHG gCO_2e/mmBtu	Total GHG gCO_2e/MJ
Total	**2,095.682**	**4.73**	**0.052**	**2220**	**2.10**

Natural Gas Tank to Wheel

This section provides a summary of GHG emissions from combusting NG in an engine. Details of calculations are provided in Appendix A. Table L provides details of WTT GHG emissions from combusting NG in a light duty vehicle.

Table L. Tank to Wheel GHG Emissions for NG

TTW = Vehicle = 57.7g CO_2e/MJ

Table K below provides an expanded summary of all the GHG species and their emissions in each of the discrete steps of the CNG from LFG pathway.

Table K. GHG Emissions by Pathway Step for CNG from Landfill Gas

	Units	LFG Recovery	LFG Transport	LFG Processing	NG T&D	NG Compression	Total
CO_2	g/mmBtu	489.181	1.821	-50,831	27.240	2,095.682	-48,217
CH_4	g/mmBtu	1.104	0.004	-39.872	1.462	4.730	-32.571
N_2O	g/mmBtu	0.012	0.000	-1.037	0.001	0.052	-0.971
CH_4	gCO_2e/mmBtu	25.396	0.095	-917.057	33.634	108.799	-749.133
N_2O	gCO_2e/mmBtu	3.596	0.013	-306.862	0.222	15.404	-287.626
Total GHGs	**gCO_2e/mmBtu**	**518.173**	**1.929**	**-52,055**	**61.096**	**2,219.886**	**-49,254**
Total GHGs	**gCO_2e/MJ**	**0.491**	**0.002**	**-49.342**	**0.058**	**2.104157**	**-46.686**

APPENDIX A

SECTION 1. LANDFILL GAS RECOVERY

1.1 Energy Use for Landfill Gas Recovery

The first step in the CNG from LFG pathway is LFG recovery. There are three key assumptions made to calculate direct energy consumption for landfill gas recovery:

- Process efficiency (99.54%, TIAX Estimate[3])
- Fuel Shares (split of total energy consumed by fuel type)
- Leak Rate (0%, TIAX Estimate[4])

To recover the LFG, a hermetically sealed electric blower is utilized. The assumed process efficiency of 99.54% means that it takes 0.0046 mmBtu of energy to recover 1 mmBtu of LFG. Because the blower is hermetically sealed and the landfill cap is under negative pressure, it is assumed that no LFG leaks during the recovery process. The efficiency assumption is coupled with an assumed split of fuels used in landfill gas recovery that is the same as the direct energy use by fuel to recover NA NG. The results of this calculation are provided in Table 1.01.

Table 1.01 Calculation of Direct Energy Consumption (Btu/mmBtu) to Recover LFG from Assumed Values for Recovery Efficiency and Fuel Shares

Process Fuel Type	Fuel Shares	Relationship of Recovery Efficiency (0.9954) and Fuel Shares	Direct Energy Consumption, Btu/mmBtu
Electricity	100%	$(10^6)(1/0.9954 - 1) * 100\%$	4,651
Total Direct Energy Consumption for LFG recovery			**4,651**

The value provided in Table 1.01 is direct energy consumption for the LFG recovery step. This is not the total energy required however, since GREET accounts for the "upstream" energy associated with each of the fuels utilized. For example, 4,651 Btu of electricity are required to recover each mmBtu of LFG. The total energy associated with the 4,651 Btu of electricity includes the energy used to produce the electricity and the energy used to recover and deliver the fuels to the power plants.

Table 1.02 demonstrates how the direct energy value shown in Table 1.01 is utilized to calculate total energy required to recover LFG. Table 1.03 provides details on the values used in Table 1.02.

[3] Based on data provided by Prometheus-Energy for the Bowerman landfill in Orange County, California. 37.5 hp are required to recover 770 scfm LFG with an LHV of 446 Btu/scf.
[4] Standard practice for many years is to use hermetically sealed blowers to transfer landfill and digester gases. Verbal information from Bruce at Spencer Turbine Company (1-800-232-4321) 7/08.

Table 1.02 Total Energy Consumption from Direct Energy Consumption for LFG Recovery

Fuel Type	Formula	Btu/mmBtu
Electricity	$A (B + C)/ 10^6$	9,335
Total energy for LFG recovery		**9,335**

Table 1.03 Values Used in Table 1.02

Fuel Type	Description
A	4,651 Btu of direct electricity used to recover 1 mmBtu LFG. (see Table 1.01)
B	120,830 Btu of energy used to recover and transport sufficient feedstock to generate 1 mmBtu electricity.
C	1,886,091 Btu used to produce 1 mmBtu electricity.

1.2 GHG Emissions from Landfill Gas Recovery

The emission calculation methodology is analogous to the energy calculations. First the direct emissions are calculated and then the upstream emissions (due to recovery and processing of each direct fuel used) are added. To calculate the direct emissions, direct energy by fuel type (provided in detail above) is multiplied by the technology share (% fired in turbine, boiler, engine etc) and then multiplied by the appropriate emission factor. Emissions of CO_2, N_2O and methane due to combustion are quantified. In addition, emissions of VOC and CO are quantified and assumed to convert to CO_2 in the atmosphere. The conversions are calculated as follows:

CO (g/MMBtu) * 44 gCO_2/gmole / 28 gCO/gmole

VOC (g/MMBtu) * 44 gCO_2/gmole / 12 gC/gmole * 0.85 gC/ gVOC

For LFG recovery, only electricity is utilized, so there are no direct emissions for this step. Similar to total energy, the total emissions include direct emissions plus the emissions associated with recovery and processing/refining the fuels used to recover LFG. Table 1.04 provides the upstream CO_2 emissions for landfill gas recovery. Table 1.05 details the values used in Table 1.04. The total emissions are presented in Table 1.06; the CO and VOC values are converted to CO_2.

Table 1.04 Calculation of Upstream CO_2 Emissions from Direct Energy Consumption for LFG Recovery

Fuel Type	**Formula**	**g/mmBtu**
Electricity	A (B + C)/ 10^6	489

Table 1.05 Values Used to Calculate Upstream CO_2 Emissions for LFG Recovery

Fuel Type	**Description**
A	4,651 Btu of direct electricity used to recover 1 mmBtu LFG.
B	8,773 g/mmBtu CO_2 to produce & transport feedstock.
C	96,314 gCO_2 to produce 1 mmBtu electricity.

Table 1.06 Total GHG Emissions from Landfill Gas Recovery, g/mmBtu

	VOC	**CO**	**CH_4**	**N_2O**	**CO_2**	**CO_2***	**Total GHG gCO_2e/ mmBtu**	**Total GHG gCO_2e/ MJ**
Electricity	0.054	0.134	1.104	0.012	488.8	489.2	518.2	0.491
Total	**0.054**	**0.134**	**1.104**	**0.012**	**488.8**	**489.2**	**518.2**	**0.491**

* Includes contributions from VOC and CO.

SECTION 2. LANDFILL GAS TRANSPORT TO PROCESSING

2.1 Energy Use For Landfill Gas Transport

Once the LFG has been recovered, it is transferred a short distance by pipeline to the processing plant. For this pathway it has been assumed that the processing plant is 1 mile from the landfill. For landfill gas transport, hermetically sealed blowers are utilized, so the leak rate is assumed to be zero. The pipeline energy consumption is the energy associated with moving the landfill gas through the pipeline. The main assumptions are:

- Fuel Shares (100% electricity)
- Energy Intensity (203 Btu/ton-mile, calculated from GREET defaults and LFG density)
- Distance (1 mile)
- Lower Heating Value (446 Btu/scf[5])
- Density (34.54 g/scf)

The T&D pipeline energy consumption is calculated as follows:

Pipeline Energy (Btu/mmBtu) = ((34.54 grams/scf)/ (446 Btu/scf))*(1 mile) * (203 Btu/ton-mile) * (1 pound/454 grams) * (1 ton/2,000 pound) *(100%*2.007) * 1,000,000 Btu/mmBtu
= 35 Btu/mmBtu

The value 2.007 in the calculation represents the upstream energy associated with electricity consumption. As illustrated in Table 3.01, the total T&D energy is the sum of the feedstock loss and pipeline energy consumption.

Table 2.01 Energy Use for LFG Transport to the Processing Plant

LFG Transport Energy Use = 35 Btu/mmBtu

[5] LHV and density calculated from average fuel properties at Bowerman Landfill, provided by Prometheus-Energy

2.2 GHG Emissions from LFG Transport to Processing

The pipeline transport emissions are composed of the emissions associated with pushing the LFG through the pipeline. The pipeline emissions are set by the energy intensity of 203 Btu/ton-mile, the assumption that electric blowers are utilized, and the assumed transport distance of 1 mile. As described above, the direct energy use is 35 Btu/mmBtu. Because only electric blowers are utilized, there are no direct emissions, only upstream emissions from electricity production. The emissions are calculated as follows:

Emissions = Miles * Energy Intensity * Fuel Density / Lower Heating Value * Upstream Emission Factor

The upstream emissions are those associated with electricity production and electricity feedstock recovery and transport. This pathway utilizes marginal electricity (natural gas and renewables). Table 2.02 provides the emission factors for electricity production utilized to calculate LFG transport emissions.

Table 2.02 Emission Factors for California Marginal Stationary Electricity Use, g/mmBtu

	VOC	**CO**	**CH_4**	**N_2O**	**CO_2**
Feedstock	11.567	14.849	230.235	0.117	8,773
Electricity Generation	0.000	14.062	7.150	2.495	96,314
Total	**11.567**	**28.911**	**237.385**	**2.612**	**105,086**

Table 2.03 provides the total emissions associated with transporting the LFG to the processing plant.

Table 2.03 Total GHG Emissions Associated with LFG Transport to Processing

	VOC	**CO**	**CH_4**	**N_2O**	**CO_2**	**CO_2***	**Total GHG gCO_2e/ mmBtu**	**Total GHG gCO_2e/ MJ**
Total	**0.000**	**0.001**	**0.004**	**0.000**	**1.820**	**1.821**	**1.929**	**0.002**

* Includes contributions from VOC and CO.

SECTION 3. LANDFILL GAS PROCESSING

3.1 Energy use for Landfill Gas Processing

The next step in the LFG to CNG pathway is cleaning the LFG to pipeline quality and compressing it to natural gas distribution pipeline pressures. The LFG processing data are based on an LFG to pipeline facility in Canada[6]. The facility draws 2,570 MMBtu/day of LFG from the landfill (~3,500 scfm) and requires 1.8 MW of grid electricity to run the compressors before the membrane to clean the gas. Currently the facility uses UOP membranes which can achieve 84% methane removal, but the new standard is the Air Liquide MEDAL membrane that can achieve 90% removal efficiency. The Air Liquide MEDAL membrane's 90% removal efficiency is used in this calculation. The remaining 10% is combusted in a thermal oxidizer to minimize emissions. The thermal oxidizer uses pre-membrane LFG as the fuel at a rate of 3 MMBtu/hr (72 MMBtu/day).

With 2,570 MMBtu/day drawn from the landfill and 72 being used as fuel in the thermal oxidizer, 2,498 MMBtu/day is fed to the membrane where 90% (2,248 MMBtu/day) is sent to the pipeline. The remaining 10% (250 MMBtu/day) is send to the thermal oxidizer. 1.8 MW (147.41 MMBtu/day) is used as the process energy. Therefore, the overall efficiency of the LFG gas cleaning process is 2,248/(2570+147.41) = 82.7%. The breakdown of the process energy used is 322 MMBtu/day total in the thermal oxidizer and 147.41 MMBtu/day from electricity, which is 68.6% and 31.4% respectively

The methodology to calculate direct and total energy for landfill gas processing is the same as that to calculate direct and total energy for LFG recovery. Table 3.01 provides details of direct energy consumption to process landfill gas. Note that this pathway includes a credit for the energy associated with all of the LFG that would have otherwise been flared.

Table 3.01 Calculation of Direct Energy Consumption for LFG Processing

Process Fuel Type	Fuel Shares	Relationship of Process Efficiency (0.827) and Fuel Shares	Direct Energy Consumption, Btu/mmBtu
Landfill Gas	91.1%	$(10^6)(1/0.827 – 1)(0.686)$	143,504
Electricity	2.8%	$(10^6)(1/0.827 – 1)(0.314)$	66,732
Flaring Credit		– (1,000,000 + 143,504)	– 1,143,504
Direct Energy Consumption for LFG Processing			**– 933,268**

The values provided in Table 3.01 are direct energy consumption per Btu for the LFG processing step. This is not the total energy required however, since GREET accounts for the "upstream" energy associated with each of the fuels utilized to process the LFG. Table 3.02 demonstrates how the direct energy consumption values shown in Table 3.01 and values in Table 3.03 are utilized to calculate total energy required.

[6] Emails and conversations between Renewable Solutions Group LLC, Pittsburgh, PA and TIAX LLC.

Table 3.02 Total Energy Consumption from Direct Energy Consumption for LFG Processing

Fuel Type	Formula	Btu/mmBtu
Landfill Gas	$A(1 + B/10^6)* L1$	144,852.7
Electricity	$C (D + E)/ 10^6 * L1$	133,933.1
Flaring Credit	G	-1,143,574
Total Energy Consumption for NG Processing		**- 864,788**

Table 3.03 Values Used in Table 2.02

Fuel Type	Description
A	143,504 Btu of direct LFG fuel used per mmBtu LFG processed.
B	Total energy to recover LFG is 9,335 Btu/mmBtu.
C	66,732 Btu of direct electricity used to process 1 mmBtu LFG.
D	120,830 Btu of energy used to recover and transport sufficient feedstock to generate 1 mmBtu electricity.
E	1,886,091 Btu used to produce 1 mmBtu electricity.
L1	Loss factor for North American natural gas transmission, 1.0001 calculated from assumed leak fraction.

3.2 GHG Emissions from LFG Processing

As mentioned above, the only fuel directly combusted is LFG in a thermal oxidizer. A large industrial boiler has been used as a surrogate for the thermal oxidizer in GREET when calculating emissions. The exception is the CO_2 emission factor – LFG fuel properties were utilized for this emission factor. Because the LFG would otherwise have been flared, a credit is applied for the flare emissions. The emission factors are provided in Table 3.04. Note that LFG contains approximately 42% CO_2. Two emission factors are shown: the total CO_2 emitted and the CO_2 emitted due to the LFG methane. The emission factor utilized in the calculations is the one that only considers the methane content, since the CO_2 would have been emitted regardless.

Table 3.04 Direct LFG Emission Factors, g/mmBtu

	Large Boiler	**Flare**
VOC	0.000	2.500
CO	8.500	26.000
CH_4	1.133	49.000
N_2O	0.315	1.100
CO_2 (all LFG Carbon)	107,690	107,523
CO_2 (only LFG Methane)	58,054	57,887

These emission factors are combined with direct energy consumption to yield direct emissions, shown in Table 3.05 (electricity has no direct emissions). Similar to total energy, the total emissions include direct emissions plus the emissions associated with recovery and processing/refining the fuels used to process landfill gas. Table 3.06 provides the upstream CO_2 emission calculations and Table 3.07 provides the values for used in Table 3.06. Table 3.08 provides the total emissions associated with LFG processing.

Table 3.05 Direct GHG Emissions Associated with LFG Processing

	VOC	**CO**	**CH_4**	**N_2O**	**CO_2**	**CO_2***	**Total GHG gCO_2e/ mmBtu**	**Total GHG gCO_2e/MJ**
LFG	0.000	1.220	0.163	0.045	8,331	8,333	8,350	7.915
Electricity	0	0	0	0	0	0	0	0
Flare Credit	-2.859	-29.731	-56.032	-1.258	-66,194	-66,249	-67,910	-64.37
Total	**-2.86**	**-28.51**	**-55.87**	**-1.217**	**-57,863**	**-57,916**	**-59,560**	**-56.5**

* Includes contribution from VOC and CO.

Table 3.06 Calculation of Upstream CO_2 Emissions from Direct Energy Consumption for LFG Processing

Fuel Type	Formula	g/mmBtu
Landfill Gas	$A * B / 10^6 * L$	70.145
Electricity	$C (D + E) / 10^6 * L$	7012.56
Flare Credit	n/a	0

Table 3.07 Values Used in Table 2.06

Fuel Type	Description
A	143,504 Btu of direct LFG used per mmBtu LFG processed
B	489 g/mmBtu of CO_2 emissions to recover LFG
C	66,732 Btu of direct electricity used to process 1 mmBtu LFG
D	8,773 g/mmBtu CO_2 to produce & transport electricity feedstocks
E	96,314 g CO_2 to produce 1 mmBtu electricity.
L	Loss factor for transporting NG to the refueling station is 1.0001

Table 3.08 Total Direct and Upstream GHG Emissions for LFG Processing, g/mmBtu

	VOC	CO	CH_4	N_2O	CO_2	CO_2*	Total GHG gCO_2e/ mmBtu	Total GHG gCO_2e/ MJ
Landfill Gas	0.008	1.239	0.321	0.047	8,402	8,404	8,425	7.986
Electricity	0.772	1.929	15.842	0.174	7,013	7,018	7,434	7.047
Flare Credit	-2.859	-29.733	-56.035	-1.258	-66,198	-66,253	-67,914	-64.374
Total	**-2.079**	**-26.564**	**-39.872**	**-1.037**	**-50,783**	**-50,831**	**-52,055**	**-49.341**

* Includes contribution from VOC and CO.

SECTION 4. NATURAL GAS TRANSPORT & DISTRIBUTION

4.1 Energy Use for NG Transport and Distribution

The fourth step in the CNG from LFG pathway is transport and distribution of the natural gas by pipeline from the processing plant to the CNG refueling station. For this pathway, it is assumed that the refueling station is located 50 miles from the LFG processing plant. The energy consumption for T&D consists of:

- T&D Feedstock Loss
- T&D Pipeline Transport Energy Consumption

The feedstock loss factor is based on specification of a leak rate along the transmission & distribution pipelines. The GREET default value is 0.15% however in the AB1007 analysis, SoCal [7] gas provided a report documenting unaccounted for gas losses. This report indicates that pipeline leak rates are 0.08%. (871,900 MCF leakage over 1,052,280,216 MCF system throughput). Therefore the loss factor utilized is significantly lower than the GREET default. As discussed in the document describing the CNG from North American Natural Gas pathway, this assumption needs further investigation.

The leak rate is calculated as follows:

CH_4 Leak Rate = 0.0008 g CH_4/gNG * 20.4 g/930 Btu * 10^6 Btu/mmBtu / 600 * 50 mi - 0.125 g/mmBtu (CH_4 from combustion)
= 1.338 g/mmBtu

The leak rate is then used to calculate the Loss Factor (1.0001) as follows:
Loss Factor = 1.338 g/mmBtu * 930 Btu / 20.4 g / 10^6 Btu/mmBtu + 1 = 1.0001

Finally, the feedstock loss can be calculated:
T&D Feedstock Loss = (1.0001 – 1) * 10^6 = 61 Btu/mmBtu

The pipeline energy consumption is the energy associated with moving the natural gas through the pipeline. The main assumptions are:

- Fuel Shares (94% natural gas, 6% electricity)
- Energy Intensity (344 Btu/ton-mile, GREET default)
- Distance (1000 miles, GREET default is 750 miles)
- Heating value (930 Btu/scf)
- Density (20.4 g/scf)

[7] "A Study of the 1991 Unaccounted for Gas Volume At the Southern California Gas Company", Aug 1993.

The T&D pipeline energy consumption is calculated as follows:
Pipeline Energy (Btu/mmBtu) = ((20.4 grams/scf)/ (930 Btu/scf))*(50 miles) * (344 Btu/ton-mile) * (1 pound/454 grams) * (1 ton/2,000 pound) *(0.94*1.073+0.06*2.007) * 1,000,000
= 469 Btu/mmBtu

The values 1.073 and 2.007 are the upstream energy in Btu/mmBtu for natural gas and electricity, respectively. As illustrated in Table 4.01, the total T&D energy is the sum of the feedstock loss and pipeline energy consumption.

Table 4.01 Energy Use for NG Transport to Refueling Station

Total T&D Energy Use = 61 + 469 = 530 Btu/mmBtu

4.2 GHG Emissions from Natural Gas Transport to the Refueling Station

The pipeline transport emissions are composed of methane leaks and emissions associated with moving the natural gas through the pipeline. As discussed in the energy section, an assumed leak fraction dictates CH_4 leakage emissions of 1.338 g/mmBtu.

The pipeline combustion emissions are set by the GREET default energy intensity of 344 Btu/ton-mile and the assumed transport distance of 50 miles. The direct energy use is 469 Btu/mmBtu. The fuel split is 94% natural gas, 6% electricity. Table 4.02 provides the direct energy consumption and equipment shares. Direct emissions are calculated by multiplying the direct energy for each fuel type in Table 4.02 by the emission factors in Table 4.03. The direct emissions are shown in Table 4.04 and total emissions are shown in Table 4.05.

Table 4.02 NG Transport Direct Energy Consumption (Btu/mmBtu) and Equipment Shares

	Natural Gas
Direct Energy	441
Equipment Shares	
Turbine	55%
Engine	36%
Advanced Engine	9%
Direct Energy	
Turbine	242
Engine	159
Advanced Engine	40

Table 4.03 Emission Factors for NG Fired Equipment, g/mmBtu

	CO_2	**VOC**	**CO**	**CH_4 (comb.)**	**N_2O**
Turbine	58,196	0.00	15.07	4.32	1.51
Engine	56,013	230.4	379.8	328.4	2.00
Adv Eng	56,388	81.4	152.2	491.0	1.5

Table 4.04 Direct Emissions For NG Transport to Refueling (g/mmBtu)

	VOC	**CO**	**CH_4**	**N_2O**	**CO_2**	**CO_2***	**Total GHG gCO_2e/ mmBtu**	**Total GHG gCO_2e/ MJ**
Natural Gas	0.035	0.062	0.064	0.001	22.343	23	24.224	0.023
Electricity	0	0	0	0	0	0	0.000	0.000
Leakage	0	0	1.338	0	0	0	30.770	0.029
Total	**0.035**	**0.062**	**1.402**	**0.001**	**22.343**	**23**	**54.994**	**0.052**

* Includes contribution from VOC and CO

Table 4.05 Direct and Upstream Emissions for NG Transport to Refueling (g/mmBtu)

	VOC	**CO**	**CH_4**	**N_2O**	**CO_2**	**CO_2***	**Total GHG gCO_2e/ mmBtu**	**Total GHG gCO_2e/ MJ**
Natural Gas	0.038	0.065	0.119	0.001	24.399	24.620	27.551	0.026
Electricity	0.000	0.001	0.006	0.000	2.618	2.620	2.775	0.003
Leakage	0.000	0.000	1.368	0.000	0.000	0.000	31.474	0.030
Total	**0.038**	**0.066**	**1.493**	**0.001**	**27.017**	**27.240**	**61.800**	**0.059**

* Includes contribution from VOC and CO

SECTION 5. NATURAL GAS COMPRESSION TO CNG

5.1 CNG Compression Energy Use

The final step in CNG production is compression at the refueling station. The two assumptions for this part of the analysis are:

- Compression Efficiency (98%)
- Compression Fuel (electric)
- Electricity mix is marginal California mix (NG + renewable)

The GREET default value for compression efficiency is 97%. For the AB1007 analysis, Clean Energy Fuels provided data indicating that compressor efficiency in California is 98.046%. Using this:

Direct electricity use = 106 * (1/98.046% -1) * 100% = 19,927 Btu/mmBtu

Total electricity use = 19,927 * (120,830 + 1,886,091)/106 = 39,992 Btu/mmBtu
(see table 1.04 for energy required for electricity).

The direct and total electricity uses for compression are therefore 19,927 Btu/mmBtu and 39,992 Btu/mmBtu, respectively.

5.2 GHG Emissions from Natural Gas Compression to CNG

As stated above, this pathway assumes that only electric compressors are used to compress the natural gas. The direct energy use is 19,927 Btu/mmBtu CNG (see section 5.1 above). There are no direct emissions from electricity, only upstream emissions. The upstream emissions associated with electricity production are provided in Table 5.01. These emissions are calculated by multiplying direct energy use in NG compression by CO_2 (shown in table 2.07), VOC, CO, CH_4 and N_2O emission factors. Table 5.02 provides final values (CO and VOC converted to CO_2).

Table 5.01 Upstream Emissions From Electricity Production for Compression, g/mmBtu

	CO_2*	**VOC**	**CO**	**CH_4 (comb.)**	**N_2O**
Total	**2,094.059**	**0.231**	**0.576**	**4.730**	**0.052**

* CO_2 calculation: ((19,927 Btu/MmmBtu)*(8,773 + 96,314) g/mmBtu)/106 = 2,094 CO_2 g/mmBtu
Where:
CO_2 emission factor of electricity as feedstock is 8,773 g/mmBtu and as fuels is 96,314 g/mmBtu (see table 2.07 CO_2 emission factor)

Table 5.02 Total GHG Emissions Associated with Natural Gas Compression

	CO_2* g/mmBtu	**CH_4 g/mmBtu**	**N_2O g/mmBtu**	**Total GHG gCO_2e/mmBtu**	**Total GHG gCO_2e/MJ**
Total	**2,095.682**	**4.73**	**0.052**	**2220**	**2.10**

*CO_2 includes contribution from VOC and CO.

SECTION 6. GHG EMISSIONS FROM VEHICLE

6.1 GHG Emissions from Vehicles

The vehicle GHG emissions consist of:

- Tailpipe CO_2 (100% of carbon in fuel goes to CO_2)
- Tailpipe N_2O (combustion product)
- Tailpipe CH_4 (product of incomplete combustion, evaporative losses)

The CO_2 may be directly calculated from finished fuel properties as follows:

Vehicle CO_2 (g/MJ) = (20.4 g NG/scf) * (0.72 g C/g NG) * (1/930 Btu/scf)
* (44 g CO_2 / 12 g C) * (Btu/1.055kJ) * (1000kJ/MJ)
= 54.9 g/MJ

Here, 20.4 g/scf is the density of NG (GREET default), 0.72 is the Carbon in NG (GREET default) and the LHV of NG is 930 Btu/scf. 1.055 is a factor to convert from Btu to kJ.

For CH_4 and N_2O emissions, California Climate Action Registry (CCAR)8 g/mile values are used. The CCAR emission factors for CH_4 and N_2O for CNG vehicles are both set at 0.04 g/mi.

To convert this to a g/MJ basis, we need to assume a vehicle fuel economy. For the AB1007 analysis, CNG vehicles were assumed to have a fuel economy of 4.728 MJ/mi. Using this value, the vehicle emissions would are:

Vehicle GHG = 54.9 gCO_2/MJ + (0.04 gN_2O/mi * 296 + 0.04 gCH_4/mi * 23)/4.728 MJ/mi
= 57.7 gCO_2e/MJ

[8] http://www.climateregistry.org/PROTOCOLS/

APPENDIX B

Compressed Natural Gas from Landfill Gas Pathway Input Values

Parameters	Units	Values	Note
GHG Equivalent			
CO_2		1	GREET Default
CH_4		23	GREET Default
N_2O		296	GREET Default
VOC		3.1	GREET Default
CO		1.6	GREET Default
Landfill Gas Recovery			
Process Efficiency		99.5%	TIAX Calculation from Data Supplied by Prometheus-Energy
Natural Gas Leak Rate		0%	TIAX Assumption, Communication with Spencer Turbine Company.
Fuel Shares			
Residual Oil		0%	GREET Default
Conventional Diesel		0%	GREET Default
Conventional Gasoline		0%	GREET Default
Natural Gas		0%	GREET Default
Electricity		100%	TIAX Assumption
Feed Loss (Leak)		0%	Calculated from Leak Rate Assumption
Landfill Gas Processing			
Process Efficiency		82.7%	TIAX Calculation from data provided by Renewable Solutions Group LLC for their facility in Canada
Natural Gas Leak Rate		0 %	TIAX Assumption based on email exchange with Prometheus-Energy
Fuel Shares			
Natural Gas		68.6%	TIAX Calculation from data provided by Renewable Solutions Group LLC
Electricity		31.4%	TIAX Calculation from data provided by Renewable Solutions Group LLC
Equipment Shares			
CO_2 Emission Factor	gCO_2/mmBtu	58,054	TIAX calculation for avg LFG at Bowerman landfill in Southern California. Only includes CO_2 produced by combusting the CH_4, not the CO_2 present in LFG since this would be emitted anyway.
Large Boiler - NG		100%	TIAX Assumption
CNG Compression			
Efficiency		98.0%	Based on Data Provided by Clean Energy Fuels
Process Shares			
Electricity		100%	AB 1007 Assumption
CNG Transportation and Distribution			
Leak Rate		0.08%	Based on Data Provided by SoCal Gas Ab1007
Transportation by pipeline		100%	GREET Default
Distance	miles	50	TIAX Assumption
Energy Intensity	Btu/ton-mile	344	GREET Default
Fuel Shares			
Natural Gas		94%	GREET Default
Electricity		6%	GREET Default
Equipment Shares			
Turbine - NG		55%	GREET Default
CO_2 Emission Factor	gCO_2/mmBtu	58,196	GREET Default
Engine - NG		36%	GREET Default
CO_2 Emission Factor	gCO_2/mmBtu	56,013	GREET Default
Advanced Engine - NG		9%	GREET Default

Parameters	Units	Values	Note
CO_2 Emission Factor	gCO_2/mmBtu	56,388	GREET Default
Loss Factor of CNG by T&D		1.00122	GREET Default
Fuels Specifications	**LHV (Btu/gal)**	**Density (g/gal)**	
Crude	129,670	3,205	GREET Default
Residual Oil	140,353	3,752	GREET Default
Conventional Diesel	128,450	3,167	GREET Default
Conventional Gasoline	116,090	2,819	GREET Default
Natural Gas	83,686	2,651	as liquid - for gaseous LHV: 930 Btu/SCF, 20.4 g/SCF
Landfill Gas	446 Btu/scf	34.54 g/scf	TIAX calculation from avg fuel composition at Bowerman Landfill in Southern California