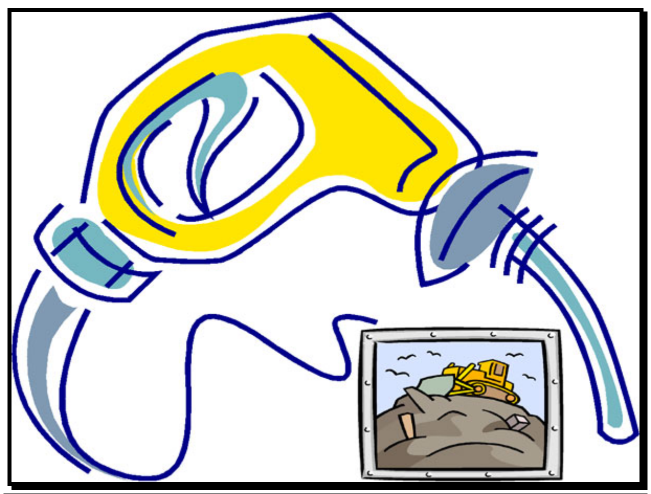
California Environmental Protection Agency

Air Resources Board

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



Stationary Source Division

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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.

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

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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]. Using this model, staff developed a pathway document for compressed natural gas (CNG) from Landfill Gas (Bio-Methane) which was made available in mid-2008 on the Low Carbon Fuel Standard (LCFS) website (http://www.arb.ca.gov/fuels/lcfs/lcfs.htm). Subsequent to this, the Argonne Model was updated in September 2008. To reflect the update and to incorporate other changes, staff contracted with Life Cycle Associates to update the CA-GREET model. This updated California modified GREET model (v1.8b) (released February 2009)[3] 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 and using compressed natural gas (CNG) from Landfill Gas in an internal combustion engine. Landfill gas to CNG pathway is not available in the original Argonne GREET model but has been coded into the CA-GREET model.

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. 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 GREET for all energy calculations. There are 1,055 MJ in one mmBtu of energy.

- 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)

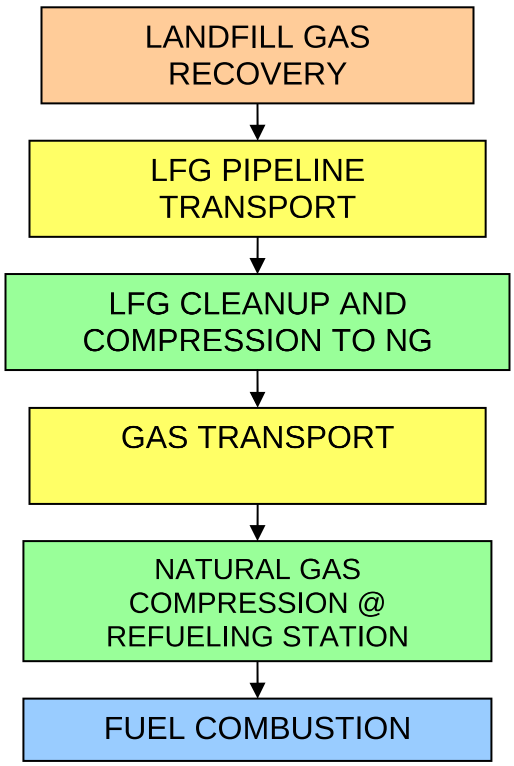

Figure 1. Discrete Components of the Landfill Gas to CNG Pathway

Table A below provides a summary of the results for this LFG to CNG pathway. The WTW analysis shows that **183,840** Btus of energy is required to produce 1 (one) mmBtu of available fuel energy. From a GHG perspective, **11.26** 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)	**GHG Emissions (gCO_2e/MJ)**
Landfill Gas Recovery and Transport	9,262	0.49
Landfill Gas Processing	-867,520*	-49.56*
Transport & Distribution	1,350	0.450
Compression at Station	40,748	2.15
Total WTT	**-816,160**	**-46.47**
Carbon in Fuel	1,000,000	55.20
Vehicle CH_4 and N_2O		2.53
Total TTW	**1,000,000**	**57.73**
Total WTW	**183,840**	**11.26**

*Credit for landfill gas processing

The following sections provide summaries of the 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 and transport. Calculation details are provided in Appendix A.

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

Fuel Type	**Btu/mmBtu**
Electricity	9,262
Total	**9,262**

Table C. Total GHG Emissions from LFG Recovery

	Total GHG gCO_2e/MJ
LFG Recovery	0.49
Total GHG Emissions	**0.49**

Landfill Gas Processing

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

Table D. Total Energy Consumption for the LFG Processing Step

Fuel Type	Btu/mmBtu
Landfill Gas	144,833.1
Electricity	131,151.2
Avoided Flaring Credit	-1,143,504
Total Energy	**-867,520**

See table 2.02

Table E. Total GHG Emissions from LFG Processing

	Total GHG (gCO_2e/MJ)
Landfill Gas	8.431
Electricity	6.878
Flaring Credit	-64.650
Total	**-49.56**

Natural Gas Transport

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

Table F. Energy Use for NG Transport

Total T&D Energy Use = 1,350 Btu/mmBtu

See table 3.01

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

	Total GHG gCO_2e/MJ
Total	**0.45**

Natural Gas Compression

Tables H and I 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 H. Energy Use for NG Compression, Btu/mmBtu

Total energy use for compression is 40,748 Btu/mmBtu

Table I. 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	**2,136**	**4.5**	**0.05**	**2,264**	**2.15**

Natural Gas Tank to Wheel

Table K provides details of WTT GHG emissions from combusting NG in a heavy duty vehicle. Details of calculations are provided in Appendix A.

Table K. Tank to Wheel GHG Emissions for NG

TTW = Vehicle = 57.73g CO_2e/MJ

APPENDIX A

SECTION 1. LANDFILL GAS RECOVERY AND TRANSPORT

1.1 Energy Use for Landfill Gas Recovery and Transport to Processing

The first step in the CNG from LFG pathway is LFG recovery and transport to the point of processing. Because the location of processing is typically very close to the landfill and the energy consumed in this transport is very small, these two steps are combined into one.

1.1.1 Energy Use for Landfill Gas Recovery

There are three key assumptions made to calculate direct energy consumption for landfill gas recovery:

- Direct Energy Required (4,621.25 Btu/mmBtu, TIAX Estimate[1])
- Fuel Shares (split of total energy consumed by fuel type)
- Leak Rate (0%, TIAX Estimate[2])

To recover the LFG, a hermetically sealed electric blower is utilized. The assumed energy required to recover 1 mmBtu of LFG is 4621.25 Btu. 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 figure of 4621.25 Btu/mmBtu is the 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. The total energy associated with the 4,621.25 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.

1.1.2 Energy Use for Landfill Gas Transport to Processing

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 CA-GREET defaults and LFG density)
- Distance (1 mile)

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[1] 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.
[2] 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.

- Lower Heating Value (446 Btu/scf[3])
- Density (34.54 g/scf)

The transport pipeline direct 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) *1,000,000 Btu/mmBtu
= 17.31 Btu/mmBtu

1.1.3 Total Direct Energy Consumption and Efficiency for Landfill Gas Recovery and Transport

The total direct energy consumption for LFG recovery and transport of one mile to processing is **4,638.56** Btu/mmBtu. The relationship between figure and the combined recovery and transport efficiency is shown in Table 1.01.

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

Process Fuel Type	**Fuel Shares**	**Relationship of Recovery Efficiency (0.9954) and Fuel Shares**	**Direct Energy Consumption, Btu/mmBtu**
Electricity	100%	$(10^6)(1/0.9954 – 1) * 100\%$	4,638.56
Total Direct Energy Consumption for LFG recovery and transport			**4,638.56**

Table 1.02 details how total energy is calculated from direct energy shown in Table 1.01. Table 1.03 provides values for factors used in Table 1.02.

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

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

Fuel Type	Formula	Btu/mmBtu
Electricity	$A (B + C)/ 10^6$	9,262
Total energy for LFG recovery		**9,262**

Table 1.03 Values Used in Table 1.02

Fuel Type	Description
A	4,638.56 Btu of direct electricity used to recover and transport 1 mmBtu LFG one mile. (see Table 1.01)
B	111,649 Btu of energy used to recover and transport sufficient feedstock to generate 1 mmBtu electricity.
C	1,884,989 Btu used to produce 1 mmBtu electricity.

1.2 GHG Emissions from Landfill Gas Recovery and Transport to Processing

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 and transport, only electric blowers are utilized. Therefore, 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

Table 1.04 provides all of the emission factors for electricity production utilized to calculate LFG recovery and transport GHG emissions.

Table 1.04 Emission Factors for California Marginal Stationary Electricity Use, g/mmBtu

	VOC	**CO**	**CH_4**	**N_2O**	**CO_2**
Feedstock	10.201	18.484	212.375	0.105	8,281
Electricity Generation	5.67	39.677	7.043	2.48	96,250
Total	**15.87**	**58.16**	**219.42**	**2.585**	**104,531**

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 1.05 provides the upstream CO_2 emissions for landfill gas recovery and transport. Table 1.06 details the values used in Table 1.04. The total emissions are presented in Table 1.07 along with the other GHGs; the CO and VOC values are converted to CO_2.

Table 1.05 Calculation of Upstream CO_2 Emissions from Direct Energy Consumption for LFG Recovery and Transport

Fuel Type	Formula	g/mmBtu
Electricity	A (B + C)/ 10^6	485

Table 1.06 Values Used to Calculate Upstream CO_2 Emissions for LFG Recovery

Fuel Type	Description
A	4,638.56 Btu of direct electricity used to recover 1 mmBtu LFG.
B	8,281 g/mmBtu CO_2 to produce & transport feedstock.
C	96,250 gCO_2 to produce 1 mmBtu electricity.

Table 1.07 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	0.074	0.270	1.018	0.012	484.8	485.5	514.5	0.488
Total	**0.074**	**0.270**	**1.018**	**0.012**	**484.8**	**485.5**	**514.5**	**0.49**

* Includes contributions from VOC and CO.

SECTION 2. LANDFILL GAS PROCESSING

2.1 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[4]. 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[4] 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 2.01 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 2.01 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	68.6%	$(10^6)(1/0.827 – 1)(0.686)$	143,504
Electricity	31.4%	$(10^6)(1/0.827 – 1)(0.314)$	65,686
Flaring Credit		– (1,000,000 + 143,504)	– 1,143,504
Direct Energy Consumption for LFG Processing			**– 934,314**

The values provided in Table 2.01 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 2.02 demonstrates how the direct energy consumption values shown in Table 2.01 and values in Table 2.03 are utilized to calculate total energy required.

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

Table 2.02 Total Energy Consumption from Direct Energy Consumption for LFG Processing

Fuel Type	Formula	Btu/mmBtu
Landfill Gas	$A(1 + B/10^6)* L1$	144,833.1
Electricity	$C (D + E)/ 10^6$	131,151.2
Flaring Credit	G	-1,143,504
Total Energy Consumption for NG Processing		**- 867,520**

Table 2.03 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 9,262 Btu/mmBtu.
C	65,686 Btu of direct electricity used to process 1 mmBtu LFG.
D	111,649 Btu of energy used to recover and transport sufficient feedstock to generate 1 mmBtu electricity.
E	1,884,989 Btu used to produce 1 mmBtu electricity.
L1	Loss factor for LFG transport to processing, 1.000 calculated based on assumption of no leakage.

2.2 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 2.04. 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 2.04 Direct LFG Emission Factors, g/mmBtu

	Large Boiler	**Flare**
VOC	1.1557	2.5
CO	16.419	26.
CH_4	1.100	49.
N_2O	0.315	1.1
CO_2 (all LFG Carbon)	107,690	107,523
CO_2 (only LFG Methane)	58,198	58,048

These emission factors are combined with direct energy consumption to yield 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 2.05 provides the total emissions associated with LFG processing.

Table 2.05 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	0.154	3.483	16.257	0.217	8,418	8,424	8,896	8.431
Electricity	1.042	3.820	4.033	0.170	6,866	6,875	7,027	6.878
Flare Credit	-2.859	-29.731	-56.032	-1.258	-66,378	-66,434	-68,209	-64.650
Total	**-1.662**	**-22.43**	**-35.74**	**-0.87**	**-51,093**	**-51,134**	**-52,287**	**-49.56**

* Includes contribution from VOC and CO.

SECTION 3. NATURAL GAS TRANSPORT & DISTRIBUTION

3.1 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 the specification of a leak rate along the transmission & distribution pipelines. The GREET default value is 0.15% however in the AB1007 analysis, Southern California Gas Company (SoCal)[5] 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. Because almost all of this loss occurs in the distribution system, the leak rate does not vary with distance. 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
= 17.548 g/mmBtu

The leak rate is then used to calculate the Loss Factor (1.001) as follows:
Loss Factor = 17.548 g/mmBtu * 930 Btu / 20.4 g / 10^6 Btu/mmBtu + 1 = 1.0008

Finally, the feedstock loss can be calculated:
T&D Feedstock Loss = (1.0008 – 1) * 10^6 = **800** 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 (405 Btu/ton-mile, current GREET default)
- Distance (50 miles, GREET default is 750 miles)
- Heating value (930 Btu/scf)
- Density (20.4 g/scf)

The T&D pipeline energy consumption is calculated as follows:
Pipeline Energy (Btu/mmBtu) = ((20.4 grams/scf)/ (930 Btu/scf))*(50 miles)

* (405 Btu/ton-mile) * (1 pound/454 grams) * (1 ton/2,000 pound)
*(0.94*1.069+0.06*1.9966) * 1,000,000 = **550** Btu/mmBtu

The values 1.069 and 1.9966 are the upstream energy in Btu/mmBtu for natural gas and electricity, respectively. As illustrated in Table 3.01, the total T&D energy is the sum of the feedstock loss and pipeline energy consumption.

Table 3.01 Energy Use for NG Transport to Refueling Station

Total T&D Energy Use = 800 + 550 = 1,350 Btu/mmBtu

3.2 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 17.548 g/mmBtu.

The pipeline combustion emissions are set by the GREET default energy intensity of 405 Btu/ton-mile and the assumed transport distance of 50 miles. The direct energy use is 550 Btu/mmBtu. The fuel split is 94% natural gas, 6% electricity. Table 3.02 provides the direct energy consumption and equipment shares. Direct emissions are calculated by multiplying the direct energy for each fuel type in Table 3.02 by the emission factors in Table 3.03. Total emissions are shown in Table 3.04.

Table 3.02 NG Transport Direct Energy Consumption (Btu/mmBtu) and Equipment Shares

	Natural Gas
Direct Energy	517
Equipment Shares	
Turbine	55%
Engine	36%
Advanced Engine	9%
Direct Energy	
Turbine	284
Engine	186
Advanced Engine	47

Table 3.03 Emission Factors for NG Fired Equipment, g/mmBtu

	CO_2	**VOC**	**CO**	**CH_4 (comb.)**	**N_2O**
Turbine	58,044	0.91	77.18	23.15	2.00
Engine	56,013	230.4	379.8	328.4	2.00
Adv Eng	56,725	61.3	331.4	289.0	2.00

Table 3.04 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	0.044	0.101	0.131	0.001	28.635	28.931	32.501	0.0308
Electricity	0.000	0.002	0.006	0.000	3.069	3.073	3.257	0.0031
Leakage	0.000	0.000	17.548	0.000	0.000	0.000	438.71	0.4158
Total	**0.04**	**0.10**	**17.69**	**0.001**	**31.70**	**32.00**	**474.47**	**0.45**

* Includes contribution from VOC and CO

SECTION 4. NATURAL GAS COMPRESSION TO CNG

4.1 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 + renewables)

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 98.00%. Using this:

Direct electricity use = 10^6 * (1/98.000% -1) * 100% = 20,408.14 Btu/mmBtu

Total electricity use = 20,408.143 * (111,649 + 1,884,989)/10^6 = 40,748 Btu/mmBtu (see table 1.03 for energy required for electricity).

The direct and total electricity uses for compression are therefore **20,408** Btu/mmBtu and **40,748** Btu/mmBtu, respectively.

4.2 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 20,408 Btu/mmBtu CNG (see section 4.1 above). There are no direct emissions from electricity, only upstream emissions. The upstream emissions associated with electricity production are provided in Table 4.01. These emissions are calculated by multiplying direct energy use in NG compression by CO_2 (shown in table 1.04), VOC, CO, CH_4 and N_2O emission factors. Table 5.02 provides final values (CO and VOC converted to CO_2).

Table 4.01 Upstream Emissions From Electricity Production for Compression, g/mmBtu

	CO_2*	VOC	CO	CH_4 (comb.)	N_2O
Total	**2,133.26**	**0.324**	**1.19**	**4.48**	**0.053**

* CO_2 calculation: ((20,408 Btu/MmmBtu)*(8,281 + 96,250) g/mmBtu)/10^6 = 2,133.26 CO_2 g/mmBtu
Where:
CO_2 emission factor of electricity as feedstock is 8,281 g/mmBtu and as fuels is 96,250 g/mmBtu (see table 1.04 CO_2 emission factor)

Table 4.02 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	**2,136.15**	**4.478**	**0.053**	**2,263.82**	**2.15**

*CO_2 includes contribution from VOC and CO.

SECTION 5. GHG EMISSIONS FROM VEHICLE

5.1 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) * (0.724 g C/g NG) * (1/930 Btu/scf)
 * (44 g CO_2 / 12 g C) * (Btu/1.055kJ) * (1000kJ/MJ) = **55.2** g/MJ

Here, 20.4 g/scf is the density of NG (GREET default), 0.724 is the Carbon in NG (CA-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)[5] g/mile values are used. The CCAR emission factors for CH_4 and N_2O for CNG vehicles are both set at 0.0375 g/mi.

Note: CH_4 and N_2O emission factors for tailpipe emissions have been used as place holder since staff is investigating the availability of appropriate tailpipe emissions data for heavy duty CNG vehicles. When available, staff will adjust contributions from tailpipe emissions CH_4 and N_2O appropriately.

(Note: In a study on CNG use in urban buses[6], calculations for tailpipe CH_4 and N_2O emissions were approximately 2.82 g/MJ, close to the value shown below).

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 4.8 MJ/mi. Using this value, the vehicle emissions are:

Vehicle GHG = 55.2 gCO_2/MJ + (0.0375 gN_2O/mi * 298 + 0.0375 gCH_4/mi * 25)/4.8 MJ/mi = 55.2 + 2.53 = 57.73 gCO_2e/MJ

[5] http://www.climateregistry.org/PROTOCOLS/
[6] http://www.cleanairnet.org/infopool/1411/articles-59987_resource_1.pdf

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

[1] GREET Model: Argonne National Laboratory:
http://www.transportation.anl.gov/modeling_simulation/GREET/index.html

[2] California Assembly Bill AB 1007 Study: http://www.energy.ca.gov/ab1007

[3] CA_GREET Model (modified by Lifecycle Associates) released February 2009
http://www.arb.ca.gov/fuels/lcfs/lcfs.htm

[4] CO_2 Membrane Technology by Air Liquide MEDAL:
http://www.medal.airliquide.com/en/co-membrane/co-membrane-technology.html

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