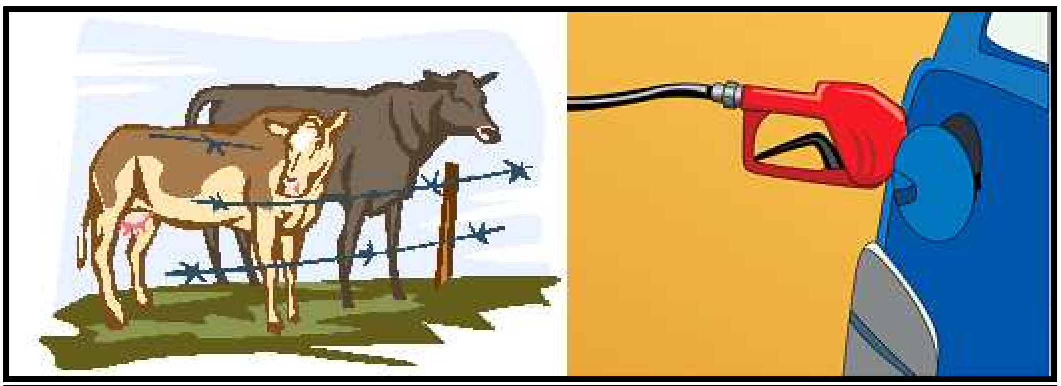
California Environmental Protection Agency

Air Resources Board

Detailed California-Modified GREET Pathway for Compressed Natural Gas (CNG) from Dairy Digester Biogas



Stationary Source Division

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

The ARB acknowledges contributions from the Life Cycle Associates (under contract with the California Energy Commission), and the California Integrated Waste Management Board 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 Digester 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 **Gr**eenhouse gases, **R**egulated **E**missions, and **E**nergy use in **T**ransportation (GREET)[1] developed by Argonne National Laboratory forms the core basis of the methodology used in this document. This model was modified with assistance from Life Cycle Associates to reflect California specific conditions and the modified model is referred to as the CA-GREET model. This CA-GREET model forms the basis for evaluating the WTW lifecycle emissions for the production and use of compressed natural (CNG) derived from manure digester (from dairy) biogas. This pathway is currently not available in the original Argonne GREET model but has been programmed into the CA-GREET model. The model is available for download from the LCFS website at http://www.arb.ca.gov/fuels/lcfs/lcfs.htm

This document describes the WTW analysis of the production and use of compressed natural gas (CNG) derived from digester biogas collected from dairy farms. For the pathway detailed here, biogas is produced from livestock manure generated through a process called anaerobic digestion. Anaerobic digestion is a biological process that produces a gas principally composed of methane (CH_4) and carbon dioxide (CO_2) otherwise known as biogas. For this document, the biogas is generated in a covered lagoon. The pathway modeled here includes digester gas recovery and processing, pipeline transport to the processing plant where it is upgraded to pipeline quality natural gas and compressed to pipeline pressures. The gas is then transported by pipeline to a CNG refueling station where it is compressed and delivered for use in an internal combustion engine (Heavy-duty vehicle). Figure 1 shows the discrete components that form the CNG from digester biogas pathway.

[1] http://www.transportation.anl.gov/modeling_simulation/GREET/index.html

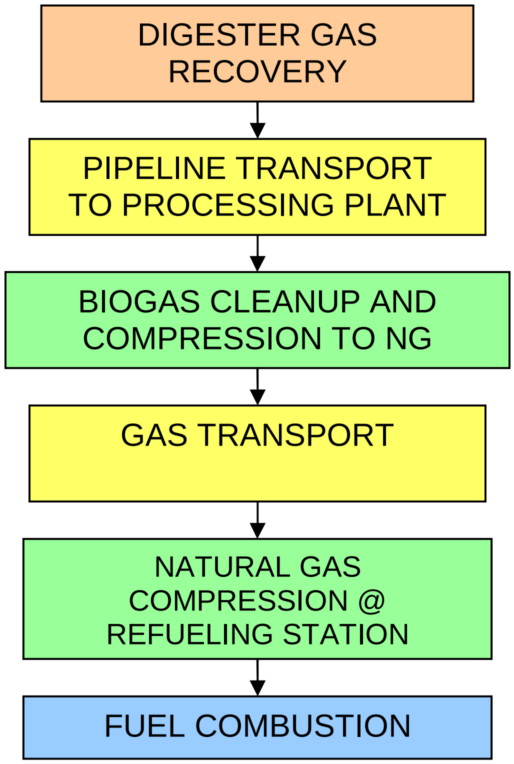

Figure 1. Discrete Components of the Dairy Digester BioGas to CNG Pathway

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:

- 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 CA-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.
- CA-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 CA-GREET is defined as:

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

Table A below provides a summary of the results for this digester gas to CNG pathway. The WTW analysis shows that **197,047** Btu of energy is required to produce 1 (one) mmBtu of available fuel energy. From a GHG perspective, **13.45** gCO_2e/MJ of GHG emissions are generated during the production and use of CNG from digester gas in a heavy-duty 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 CA-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 Digester Gas

	Energy Required (Btu/mmBtu)	**GHG Emissions (gCO_2e/MJ)**
Digester Gas Recovery	22,209	1.17
Digester Gas Processing*	-867,258	-48.02
Transport & Distribution	1,350	0.45
Compression at Station	40,746	2.15
Total WTT	**-802,953**	**-44.25**
Carbon in Fuel	1,000,000	55.18
Vehicle CH_4 and N_2O		2.52
Total TTW	**1,000,000**	**57.70**
Total WTW	**197,047**	**13.45**

*Includes credit for biogenic uptake of CO_2

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.

Digester Biogas Recovery

The first step in the CNG from dairy biogas pathway is biogas recovery and transport to the point of processing. Because it is assumed that the processing of the biogas into pipeline quality gas will occur at the dairy, these two steps are combined into one, without an additional step for transport to the point of processing. Tables B and C provide a summary of the energy consumption and associated GHG emissions from digester gas recovery and transport. Calculation details are provided in Appendix A.

Table B. Total Energy Consumption by Fuel Type for Digester Gas Recovery

Fuel Type	**Btu/mmBtu**
Electricity	22,209
Total	**22,209**

Table C. Total GHG Emissions from Digester Gas Recovery

	Total GHG gCO_2e/MJ
Digester Gas Recovery	1.17
Total GHG Emissions	**1.17**

Digester Gas Processing and Digester Gas Credit

Tables D and E provide details of energy consumption and energy credit associated with digester gas processing. Tables F and G provide details of associated GHG emissions corresponding to the energy consumption and energy credit analysis above. The net of these two values is -48.02 gCO_2e/MJ. Calculation details are provided in Appendix A.

Table D. Total Energy Consumption from Digester Gas Processing

Fuel Type	Btu/mmBtu
Bio Gas	145,100.3
Electricity	131,145.4
Total Energy	**276,246**

Table E. Total Energy Credit from Digester Gas Processing

Fuel Type	Btu/mmBtu
Bio Gas Credit	-1,143,504
Total Energy	**-1,143,504**

Table F. Total GHG Emissions from Digester Gas Processing

	Total GHG (gCO_2e/MJ)
Biogas processing	15.03
Total	**15.03**

Table G. Total GHG Emissions Credit from Digester Gas Processing

	Total GHG (gCO_2e/MJ)
Biogas Credit	-63.05
Total	**-63.05**

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 = 1,350 Btu/mmBtu

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

	Total GHG gCO_2e/MJ
Total	**0.45**

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 energy use for compression is 40,746 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	**2,136**	**4.5**	**0.05**	**2,264**	**2.15**

Natural Gas Tank to Wheel

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

Table L. Tank to Wheel GHG Emissions for NG

Carbon in Fuel	55.18 gCO_2e/MJ
CH_4 and N_2O	2.58 gCO_2/MJ
Total TTW	**57.70 gCO_2/MJ**

APPENDIX A

SECTION 1. DAIRY BIOGAS RECOVERY

1.1 Energy Use for Digester Gas (Biogas) Recovery

1.1.1 Energy Use for Biogas Recovery

Several types of biogas recovery systems exist for managing manure. In this case, it is assumed that the manure is managed in an unheated, covered lagoon. There are three key assumptions made to calculate direct energy consumption for the biogas recovery:

- Direct Energy Required (11,124 Btu/mmBtu, ARB Estimate[2])
- Fuel Shares (split of total energy consumed by fuel type)
- Leak Rate (0%[3])

An electric blower is used to capture the biogas that is produced in the lagoon and an electric mixer may be used to periodically mix the lagoon contents. Otherwise, there is no other energy consumption for the biogas recovery step. The assumed energy required to recover 1 mmBtu of biogas is 11,124 Btu, which represents a large, unmixed lagoon. The estimated energy consumption (3.26kWh/mmBtu) represents the energy used for the digestion process for a non-heated covered lagoon dairy digester using the processed biogas to run stationary IC engine/generators, milk trucks, and light-duty pick-up trucks. Energy consumption at dairy digester facilities may be higher if:

- the digester is heated.
- more or larger blowers are needed to transport the gas from the digester to the clean-up/processing system.
- the digester uses electric mixers.

Note: The energy consumption figure is per million Btu of biogas captured by the collection system, not per million Btu of biogas produced, as lagoon capture systems do not have 100 % capture efficiency.

The figure of 11,124 Btu/mmBtu is the direct energy consumption for the biogas recovery step. However, this is not the total energy required because CA-GREET accounts for the “upstream” energy associated with each of the fuels utilized. The total energy associated with the 11,124 Btu of California marginal electricity includes the energy used to produce the electricity and the energy used to recover and deliver the fuels to the power plants.

[2] Based on data provided by the California Air Resources Board, 3.26 kilowatt-hours of electricity are required to recovery one million Btus of biogas.
[3] While the capture efficiency of the collection system is less than 100 percent, once the biogas has been captured, it is assumed that no additional leakage occurs to the point of processing.

1.1.2 Total Direct Energy Consumption and Efficiency for Biogas Recovery and Transport

Because it is assumed that the biogas is treated at the dairy and is transported to the point of treatment by the same blower that captures the gas, the total direct energy consumption for biogas recovery and transport to processing is also 11,124 Btu/mmBtu. The recovery process efficiency is calculated from the energy consumption as flowing:

$$\frac{1}{\left[(3{,}412 Btu / KW \times 3.26 kWh)\frac{1}{10^6}+1\right]} = 0.989 = 98.9\%$$

The relationship between the energy consumption figure and the recovery efficiency is shown in Table 1.01.

Table 1.01 Relationship of Direct Energy Consumption (Btu/mmBtu)for Biogas to Recovery Efficiency and Assumed Values for Fuel Shares

Process Fuel Type	Fuel Shares	Relationship of Recovery Efficiency (0.989) and Fuel Shares	Direct Energy Consumption, Btu/mmBtu
Electricity	100%	$(10^6)(1/0.989 – 1) * 100\%$	11,124
Total Direct Energy Consumption for Biogas Recovery			**11,124**

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.

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

Fuel Type	Formula	Btu/mmBtu
Electricity	$A (B + C)/ 10^6$	22,209
Total energy for Biogas recovery		**22,209**

Details of values used in Table 1.03 are available in the electricity pathway document available on the Low Carbon Fuel Standard website.

Table 1.03 Values Used in Table 1.02

Fuel Type	Description
A	11,124 Btu of direct electricity used to recover 1 mmBtu of biogas. (See Table 1.01)
B	111,573 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 Dairy Biogas 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 (% of energy consumed in turbine, boiler, engine, etc.) and then multiplied by the appropriate emission factor. Emissions of CO_2, N_2O, and CH_4 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 biogas modeled here, only electric blowers have been utilized. Therefore, there are no direct emissions, only upstream emissions from electricity production. The emissions are calculated as follows:

Emissions = Energy Intensity * Upstream Emission Factor

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

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

	VOC	**CO**	**CH_4**	**N_2O**	**CO_2**
Feedstock	10.194	18.440	212.375	0.105	8,277
Electricity Generation	5.669	39.677	7.043	2.480	96,250
Total	**15.86**	**58.12**	**219.42**	**2.585**	**104,527**

The upstream emissions are those associated with electricity production and electricity feedstock recovery and transport. This pathway utilizes marginal electricity (79 % natural gas combined cycle and 21 % renewable energy projected for 2010).

Table 1.05 provides the upstream CO_2 emissions for biogas recovery. Table 1.06 details the values used in Table 1.05. 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 Biogas Recovery

Fuel Type	Formula	g/mmBtu
Electricity	$A (B + C)/ 10^6$	1,163

Similar calculations for CH_4 and N_2O are performed to obtain the results in table 1.07. Values used in Table 1.06 are detailed in the electricity document published on the Low Carbon Fuel Standard website.

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

Fuel Type	Description
A	11,124 Btu of direct electricity used to recover 1 mmBtu biogas.
B	8,277 gCO_2/mmBtu to produce & transport feedstock.
C	96,250 gCO_2 to produce 1 mmBtu electricity.

Table 1.07 Total GHG Emissions from Biogas Recovery

	VOC	CO	CH_4	N_2O	CO_2	CO_2*	Total GHG gCO_2e/ mmBtu	Total GHG gCO_2e/ MJ
Electricity	0.176	0.646	2.441	0.029	1,163	1,164	1,234	1.17
Total	0.176	0.646	2.441	0.029	1,163	1,164	1,234	**1.17**

* Includes contributions from VOC and CO.

SECTION 2. DIGESTER BIOGAS PROCESSING

2.1 Energy Use for Digester Biogas Processing

The next step in the digester biogas to CNG pathway is cleaning the biogas to pipeline quality and compressing it to natural gas distribution pipeline pressures. Similar to the landfill gas to CNG pathway (as presented in the landfill gas to CNG pathway document published in Feb 2009 by ARB http://www.arb.ca.gov/fuels/lcfs/022709lcfs_cng.pdf), the biogas processing data are based on a landfill gas (LFG). Details of this are available in the Landfill Gas to CNG pathway document published on the Low Carbon Fuel Standard website. The results are summarized in Table 2.01 below.

The methodology to calculate direct and total energy for biogas processing is the same as that to calculate direct and total energy for biogas recovery. Table 2.01 provides details of direct energy consumption to process biogas. Note that this pathway includes a credit for the energy associated with the biogas used during processing that would have otherwise been released to the atmosphere at the dairy. This credit is based on the carbon content of the consumed biogas. It is treated as biogenic carbon that would otherwise have been emitted as CO_2, as this would be the ultimate fate of the carbon in the dairy gas emitted to the atmosphere.

Table 2.01 Calculation of Direct Energy Consumption for Digester Biogas Processing

Process Fuel Type	Fuel Shares	Relationship of Process Efficiency (0.827) and Fuel Shares	Direct Energy Consumption, Btu/mmBtu
Biogas	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
Biogas Credit		– (1,000,000 + 143,504)	– 1,143,504
Direct Energy Consumption for Biogas Processing			**– 1,065,686**

The values provided in Table 2.01 are direct energy consumption per Btu for the biogas processing step. However, this is not the total energy required because CA-GREET accounts for the “upstream” energy associated with each of the fuels utilized to process the biogas. 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.

Table 2.02 Total Energy Consumption from Direct Energy Consumption for Digester Biogas Processing

Fuel Type	Formula	Btu/mmBtu
Biogas	$A*(1 + B/10^6)* L1$	145,100.3
Electricity	$C*(D + E)/ 10^6$	131,145.4
Biogas Credit		-1,143,504
Total Energy Consumption for Biogas Processing		**-867,258**

Table 2.03 Values Used in Table 2.02

Fuel Type	Description
A	143,504 Btu of direct biogas fuel used per mmBtu biogas processed.
B	Total energy to recover biogas is 11,124 Btu/mmBtu.
C	65,686 Btu of direct electricity used to process 1 mmBtu biogas.
D	111,573 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 biogas transport to processing, 1.000 calculated based on assumption of no leakage.

2.2 GHG Emissions from Digester Biogas Processing

As mentioned above, the only fuel directly combusted during processing is biogas in a thermal oxidizer. The oxidation is assumed to occur in a large industrial boiler with CA-GREET default parameters. The only change is the fuel properties of NG have been replaced by with those for biogas. The exception is the CO_2 emission factor–biogas fuel properties were utilized for this emission factor. Because the biogas would otherwise have been emitted, a credit is applied as if the emissions occurred as biogenic CO_2. The emission factors are provided in Table 2.04. The emission factor utilized in the calculations only considers the methane content of the biogas, since any CO_2 in the gas would have been emitted regardless.

Table 2.04 Direct Biogas Emission Factors, g/mmBtu

	Large Boiler
VOC	1.1557
CO	16.419
CH_4	1.100
N_2O	0.315
CO_2 (Biogas Methane)	58,198

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 biogas. Table 2.05 provides the total emissions associated with biogas processing, including the full credit for the biogas that would have otherwise been emitted, based on the carbon content of the emitted biogas as CO_2.

Table 2.05 Total Direct and Upstream GHG Emissions for Biogas Processing

	VOC	**CO**	**CH_4**	**N_2O**	**CO_2**	**CO_2***	**Total GHG gCO_2e/ mmBtu**	**Total GHG gCO_2e/ MJ**
Biogas Processing	1.196	7.300	17.708	0.387	15,284	15,300	15,858	15.03
Biogas Credit	0.000	0.000	0.000	0.000	-66,521	-66,521	-66,521	-63.05
Total	**1.196**	**7.300**	**17.708**	**0.387**	**-51,237**	**-51,221**	**-50,663**	**-48.02**

* Includes contribution from VOC and CO.

SECTION 3. NATURAL GAS TRANSPORT & DISTRIBUTION

3.1 Energy Use for NG Transport and Distribution

In this step, we assume the same calculation as the LFG to CNG pathway. It involves 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 biogas 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)[4] 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 here is 0.08%.

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 CA-GREET default)
- Distance (50 miles)
- Heating value (930 Btu/scf)
- Density (20.4 g/scf)

[4] *"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) * (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 transporting 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 CA-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

	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

	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)

Direct electricity use = 10^6 * (1/98.000% -1) * 100% = 20,408 Btu/mmBtu

Total electricity use = 20,408.143 * (111,573 + 1,884,989)/10^6 = 40,746 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 **40,746** 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	**2,133.18**	**0.324**	**1.19**	**4.48**	**0.053**

* CO_2 calculation: ((20,408 Btu/MmmBtu)*(8,277 + 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 VEHICLES

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) = **55.20** g/MJ

Here, 20.4 g/scf is the density of NG (CA-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. The calculation above is based on the assumption of complete combustion of the carbon in the fuel.

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 that 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. (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 = 55.18 gCO_2/MJ + (0.0375 gN_2O/mi * 298 + 0.0375 gCH_4/mi * 25)/4.8 MJ/mi = 55.18 + 2.52 = **57.70** 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 Digester BioGas from Dairy Pathway Input Values

Parameters	Units	Values	Note
GHG Equivalent			
CO_2		1	CA-GREET Default
CH_4		25	CA-GREET Default
N_2O		298	CA-GREET Default
VOC		3.1	CA-GREET Default
CO		1.6	CA-GREET Default
Digester Gas Recovery			
Process Efficiency		98.9%	Calculated from energy consumption
Fuel Shares			
Natural Gas		0%	Assumed for this pathway
Electricity		100%	Assumed for this pathway
Feed Loss (Leak)		0%	Assumed for this pathway
Equipment shares			
Electric Blowers		100%	Assumed for this pathway
Digester Gas Processing			
Process Efficiency		82.7%	Assumed same as Landfill Gas
Fuel Shares			
Bio Gas		68.6%	Assumed same as Landfill Gas
Electricity		31.4%	Assumed same as Landfill Gas
Equipment Shares			
Boiler CO_2 Emission Factor	gCO_2/mmBtu	58,198	Calculation same as LFG
Large Boiler - NG		100%	Assumed same as Landfill Gas
CNG Compression, Transportation and Distribution			
Efficiency		98.0%	Assumed the same as LFG
Process Shares			
Electricity		100%	Assumed for this pathway
Leak Rate		0.08%	see Landfill Gas Pathway
Transportation by pipeline		100%	CA-GREET Default
Distance	miles	50	Assumed for this pathway
Energy Intensity	Btu/ton-mile	344	CA-GREET Default
Fuel Shares			
Natural Gas		94%	CA-GREET Default
Electricity		6%	CA-GREET Default
Equipment Shares			
Turbine - NG		55%	CA-GREET Default
CO_2 Emission Factor	gCO_2/mmBtu	58,196	CA-GREET Default
Engine - NG		36%	CA-GREET Default
CO_2 Emission Factor	gCO_2/mmBtu	56,013	CA-GREET Default
Advanced Engine - NG		9%	CA-GREET Default
CO_2 Emission Factor	gCO_2/mmBtu	56,388	CA-GREET Default
Loss Factor of CNG by T&D		1.00122	CA-GREET Default
Fuels Specifications	**LHV (Btu/gal)**	**Density (g/gal)**	
Natural Gas	83,686	2,651	as liquid - for gaseous LHV: 930 Btu/SCF, 20.4 g/SCF
Digester Biogas	446 Btu/scf	34.54 g/scf	Assumed to be the same as LFG