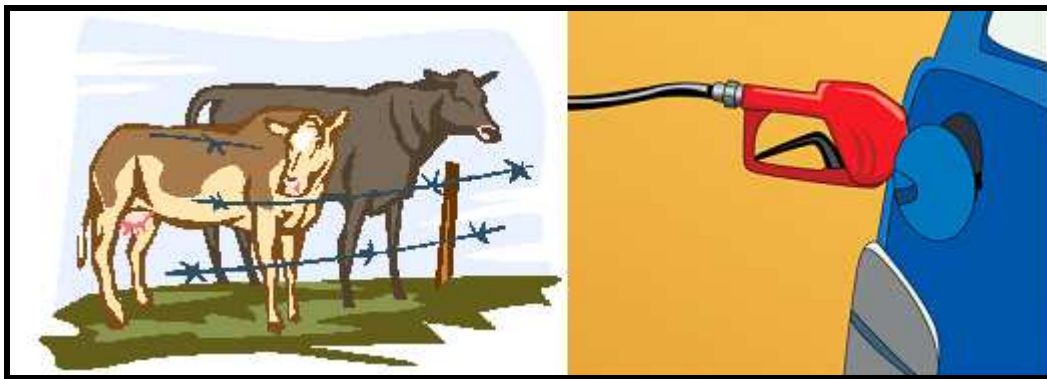


Detailed California-Modified GREET Pathway for Compressed Natural Gas (CNG) from Dairy Digester Biogas



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 **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. 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 (CH₄) and carbon dioxide (CO₂) 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

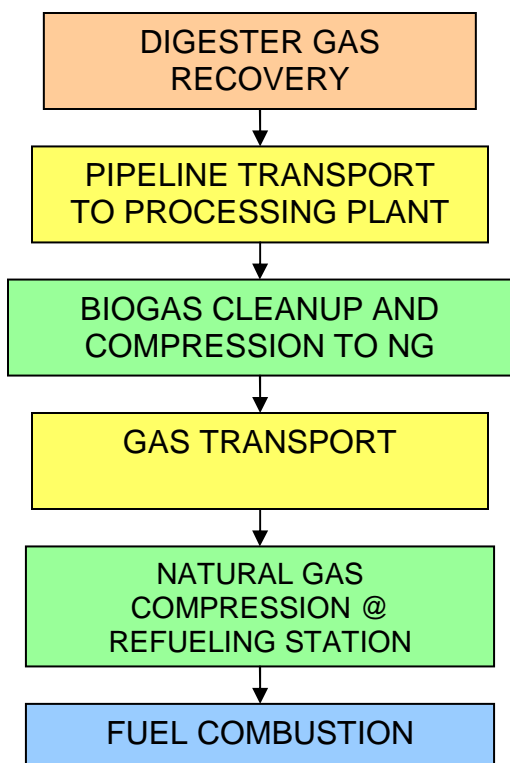


Figure 1. Discrete Components of the Dairy Digester BioGas to CNG Pathway

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.
- gCO₂e/MJ provides the total greenhouse gas emissions on a CO₂ equivalent basis per unit of energy (MJ) for a given fuel. Methane (CH₄) and nitrous oxide (N₂O) are converted to a CO₂ equivalent basis using IPCC global warming potential values and are included in the total.
- CA-GREET assumes that VOC and CO are converted to CO₂ in the atmosphere and includes these pollutants in the total CO₂ value using ratios of the appropriate molecular weights.
- Process Efficiency for any step in CA-GREET is defined as:

$$\text{Efficiency} = \text{energy output} / (\text{energy output} + \text{energy consumed})$$

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** gCO₂e/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 (gCO₂e/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 ₂ O | | 2.52 |
| Total TTW | 1,000,000 | 57.70 |
| Total WTW | 197,047 | 13.45 |

*Includes credit for biogenic uptake of CO₂

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 gCO₂e/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 gCO₂e/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 (gCO₂e/MJ) |
|-------------------|--------------------------------------------|
| Biogas processing | 15.03 |
| Total | 15.03 |

Table G. Total GHG Emissions Credit from Digester Gas Processing

| | Total GHG (gCO₂e/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 gCO₂e/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

| | CO₂ g/mmBtu | CH₄ g/mmBtu | N₂O g/mmBtu | Total GHG gCO₂e/mmBtu | Total GHG gCO₂e/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 ₂ e/MJ |
| CH ₄ and N ₂ O | 2.58 gCO ₂ /MJ |
| Total TTW | 57.70 gCO₂/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 Estimate²)
- 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.

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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:

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

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 CO₂, N₂O, and CH₄ due to combustion are quantified. In addition, emissions of VOC and CO are quantified and assumed to convert to CO₂ in the atmosphere. The conversions are calculated as follows:

$$\text{CO (g/mmBtu)} * 44 \text{ gCO}_2/\text{gmole} / 28 \text{ gCO/gmole}$$

$$\text{VOC (g/mmBtu)} * 44 \text{ gCO}_2/\text{gmole} / 12 \text{ gC/gmole} * 0.85 \text{ gC/ gVOC}$$

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:

$$\text{Emissions} = \text{Energy Intensity} * \text{Upstream Emission Factor}$$

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 ₂ O | 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).

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Table 1.05 provides the upstream CO₂ 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 CO₂.

Table 1.05 Calculation of Upstream CO₂ Emissions from Direct Energy Consumption for Biogas Recovery

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

Similar calculations for CH₄ and N₂O 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 CO₂ 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 ₂ O | CO ₂ | CO ₂ * | Total GHG gCO ₂ e/mmBtu | Total GHG gCO ₂ e/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 CO₂, 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.

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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 CO₂ 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 CO₂. 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 CO₂ 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 ₂ O | 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 CO₂.

Table 2.05 Total Direct and Upstream GHG Emissions for Biogas Processing

| | VOC | CO | CH ₄ | N ₂ O | CO ₂ | CO ₂ * | Total GHG gCO ₂ e/ mmBtu | Total GHG gCO ₂ e/ 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:

$$\text{CH}_4 \text{ Leak Rate} = 0.0008 \text{ g CH}_4/\text{gNG} * 20.4 \text{ g}/930 \text{ Btu} * 10^6 \text{ Btu}/\text{mmBtu} \\ = 17.548 \text{ g}/\text{mmBtu}$$

The leak rate is then used to calculate the Loss Factor (1.001) as follows:

$$\text{Loss Factor} = 17.548 \text{ g}/\text{mmBtu} * 930 \text{ Btu} / 20.4 \text{ g} / 10^6 \text{ Btu}/\text{mmBtu} + 1 = 1.0008$$

Finally, the feedstock loss can be calculated:

$$\text{T\&D Feedstock Loss} = (1.0008 - 1) * 10^6 = \mathbf{800} \text{ Btu}/\text{mmBtu}$$

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 CH₄ 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 |

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

| | CO₂ | VOC | CO | CH₄ (comb.) | N₂O |
|---------|-----------------------|------------|-----------|-------------------------------|-----------------------|
| 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 | CH₄ | N₂O | CO₂ | CO₂* | Total GHG gCO₂e/ mmBtu | Total GHG gCO₂e/ 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 = $10^6 * (1/98.000\% - 1) * 100\% = 20,408 \text{ Btu/mmBtu}$

Total electricity use = $20,408.143 * (111,573 + 1,884,989)/10^6 = 40,746 \text{ Btu/mmBtu}$
(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 CO₂ (shown in table 1.04), VOC, CO, CH₄ and N₂O emission factors. Table 5.02 provides final values (CO and VOC converted to CO₂).

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

| | CO ₂ * | VOC | CO | CH ₄ (comb.) | N ₂ O |
|--------------|-------------------|--------------|-------------|----------------------------|------------------|
| Total | 2,133.18 | 0.324 | 1.19 | 4.48 | 0.053 |

* CO₂ calculation: $((20,408 \text{ Btu/MmmBtu}) * (8,277 + 96,250) \text{ g/mmBtu}) / 10^6 = 2,133.26 \text{ CO}_2 \text{ g/mmBtu}$

Where:

CO₂ emission factor of electricity as feedstock is 8,281 g/mmBtu and as fuels is 96,250 g/mmBtu (see table 1.04 CO₂ emission factor)

Table 4.02 Total GHG Emissions Associated with Natural Gas Compression

| | CO ₂ * g/mmBtu | CH ₄ g/mmBtu | N ₂ O g/mmBtu | Total GHG gCO ₂ e/mmBtu | Total GHG gCO ₂ e/MJ |
|--------------|------------------------------|----------------------------|-----------------------------|---------------------------------------|------------------------------------|
| Total | 2,136.15 | 4.478 | 0.053 | 2,263.82 | 2.15 |

*CO₂ 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 CO₂ (100% of carbon in fuel goes to CO₂)
- Tailpipe N₂O (combustion product)
- Tailpipe CH₄ (product of incomplete combustion, evaporative losses)

The CO₂ may be directly calculated from finished fuel properties as follows:

$$\text{Vehicle CO}_2 \text{ (g/MJ)} = (20.4 \text{ g NG/scf}) * (0.724 \text{ g C/g NG}) * (1/930 \text{ Btu/scf}) \\ * (44 \text{ g CO}_2 / 12 \text{ g C}) * (\text{Btu}/1.055\text{kJ}) * (1000\text{kJ}/\text{MJ}) = \mathbf{55.20 \text{ g/MJ}}$$

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 CH₄ and N₂O emissions, California Climate Action Registry (CCAR)⁵ g/mile values are used. The CCAR emission factors for CH₄ and N₂O for CNG vehicles are both set at 0.0375 g/mi.

Note that CH₄ and N₂O 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 CH₄ and N₂O appropriately. (In a study on CNG use in urban buses⁶, calculations for tailpipe CH₄ and N₂O 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:

$$\text{Vehicle GHG} = 55.18 \text{ gCO}_2/\text{MJ} + (0.0375 \text{ gN}_2\text{O}/\text{mi} * 298 + 0.0375 \text{ gCH}_4/\text{mi} * 25)/4.8 \\ \text{MJ}/\text{mi} = 55.18 + 2.52 = \mathbf{57.70 \text{ gCO}_2\text{e}/\text{MJ}}$$

⁵ <http://www.climateregistry.org/PROTOCOLS/>

⁶ http://www.cleanairnet.org/infopool/1411/articles-59987_resource_1.pdf

APPENDIX B

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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 ₂ O | | 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 | | | |
| <i>Natural Gas</i> | | 0% | Assumed for this pathway |
| <i>Electricity</i> | | 100% | Assumed for this pathway |
| <i>Feed Loss (Leak)</i> | | 0% | Assumed for this pathway |
| Equipment shares | | | |
| <i>Electric Blowers</i> | | 100% | Assumed for this pathway |
| Digester Gas Processing | | | |
| Process Efficiency | | 82.7% | Assumed same as Landfill Gas |
| Fuel Shares | | | |
| <i>Bio Gas</i> | | 68.6% | Assumed same as Landfill Gas |
| <i>Electricity</i> | | 31.4% | Assumed same as Landfill Gas |
| Equipment Shares | | | |
| <i>Boiler CO₂ Emission Factor</i> | 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 | | | |
| <i>Electricity</i> | | 100% | Assumed for this pathway |
| Leak Rate | | 0.08% | see Landfill Gas Pathway |
| Transportation by pipeline | | 100% | CA-GREET Default |
| <i>Distance</i> | miles | 50 | Assumed for this pathway |
| <i>Energy Intensity</i> | Btu/ton-mile | 344 | CA-GREET Default |
| Fuel Shares | | | |
| <i>Natural Gas</i> | | 94% | CA-GREET Default |
| <i>Electricity</i> | | 6% | CA-GREET Default |
| Equipment Shares | | | |
| <i>Turbine - NG</i> | | 55% | CA-GREET Default |
| <i>CO₂ Emission Factor</i> | gCO ₂ /mmBtu | 58,196 | CA-GREET Default |
| <i>Engine - NG</i> | | 36% | CA-GREET Default |
| <i>CO₂ Emission Factor</i> | gCO ₂ /mmBtu | 56,013 | CA-GREET Default |
| <i>Advanced Engine - NG</i> | | 9% | CA-GREET Default |
| <i>CO₂ Emission Factor</i> | 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) | |
| <i>Natural Gas</i> | 83,686 | 2,651 | as liquid - for gaseous LHV: 930 Btu/SCF, 20.4 g/SCF |
| <i>Digester Biogas</i> | 446 Btu/scf | 34.54 g/scf | Assumed to be the same as LFG |