California Environmental Protection Agency

Air Resources Board

Detailed California-Modified GREET Pathway for Liquefied Natural Gas (LNG) from Dairy Digester BioGas

Stationary Source Division

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Version 2.0

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 LNG from Dairy Digester Biogas

Well-To-Tank (WTT) Life Cycle Analysis of a fuel pathway includes all steps from feedstock recovery to final 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. This document presents a WTW energy use and greenhouse gas (GHG) emissions generated during the process of producing and using liquefied natural gas (LNG) from dairy digester biogas in a heavy-duty vehicle.

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 and updated to reflect California specific conditions and labeled the CA-GREET model. Using this model, staff developed several fuel pathway documents which are available on the Low Carbon Fuel Standard (LCFS) website at (http://www.arb.ca.gov/fuels/lcfs/lcfs.htm).

A pathway not available in the original Argonne model is the diary digester biogas to CNG fuel pathway. This was incorporated into the CA-GREET model with assistance from Life Cycle Associates and this document is available on the LCFS website. A variation of this pathway is to liquefy the gas (and not compress as in the CNG pathway) and the pathway document here includes additional steps such as the liquefaction, transport and use of Liquefied NG (LNG) derived from dairy digester biogas. For completeness, necessary components have been transferred from the dairy digester biogas to CNG pathway document published in July 2009.

The dairy digester biogas to LNG pathway includes gas recovery from digesters in California, transport and processing of the recovered biogas, transport and liquefaction in California LNG plants, and its use in a heavy-duty vehicle. For this document, dairy digester gas is modeled as being produced in lagoons. Figure 1 shows the discrete components of the LNG from dairy digester biogas pathway. Based on differences in liquefaction efficiencies, two separate pathways have been modeled in this document and they include:

- Dairy Digester Biogas to LNG liquefied in California using liquefaction with 80% efficiency (derived from combined cycle NG electricity)
- Dairy Digester Biogas to LNG liquefied in California using liquefaction with 90% efficiency (derived from California marginal electricity)

This document presents all assumptions, and step by step calculations of energy consumption and GHG emissions for the dairy digester biogas to LNG pathway. Details have been provided in Appendix A for the pathway with 80% liquefaction efficiency.

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

The pathway WTW emissions for the 90% liquefaction efficiency pathway can be generated by changing the energy inputs for liquefaction in the CA-GREET model. Complete details are provided in Appendix A.

Note:

Most of the components of this pathway have been transferred from the dairy digester biogas pathway to CNG[2]. Users are directed to the mentioned document as only summaries for these steps are provided in this document.

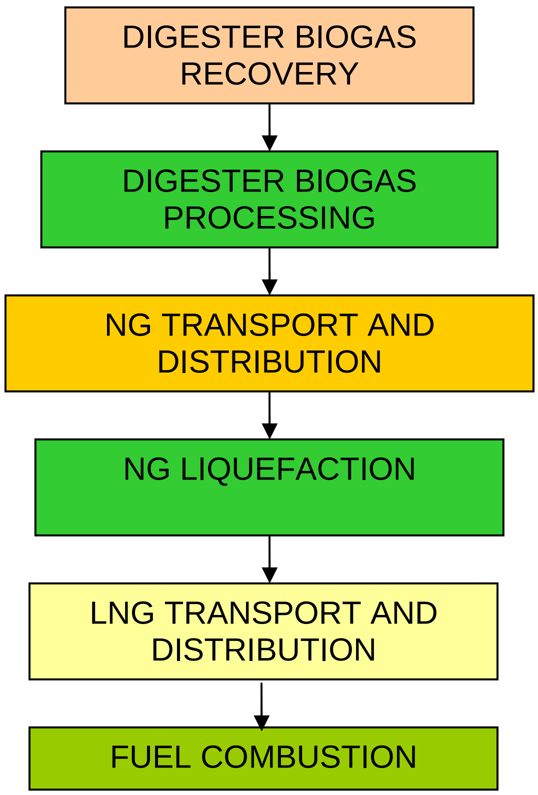

Figure 1. Discrete Components of the Dairy Digester BioGas to LNG Pathway.

Several general descriptions and clarification of terminology used throughout this document are:

- CA-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).

[2] See Low Carbon Fuel Standard website (http://www.arb.ca.gov/fuels/lcfs/lcfs.htm) for complete details of the Dairy Digester Biogas to CNG

- 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, so in order to convert one million Btu into MJ, divide the million Btu by 1055.

- gCO_2e/MJ provides the total greenhouse gas emissions on a CO_2 equivalent basis per unit of energy (MJ) for a given fuel. Methane (CH_4) and nitrous oxide (N_2O) are converted to a CO_2 equivalent basis using IPCC global warming potential values and 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 provides a summary of the results for the dairy digester biogas LNG pathway which utilizes a 80% liquefaction efficiency. The WTW analysis indicates that **424,999** Btu of energy is required to produce 1 (one) mmBtu of available fuel energy. From a GHG perspective, **28.53** gCO_2e/MJ of GHG emissions are generated during the production and use of LNG (derived from dairy digester biogas) in a <u>heavy-duty vehicle</u>.

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 for the 80% Liquefaction Efficiency Dairy Digester Biogas to LNG Pathway

	Energy Required (Btu/mmBtu)	**GHG Emissions (gCO_2e/MJ)**
Well-to-Tank		
Digester Gas Recovery and Transport	22,209	1.17
Digester Gas Processing to NG	-868,855	-48.02
NG Transport & Distribution	1,350	0.45
Liquefaction at LNG Plants	265,616	15.79
LNG Transport, Distribution and Storage	4,679	0.64
Total Well-to-Tank	**-575,001**	**-29.97**
Tank-to-Wheel		
Carbon in Fuel	1,000,000	56.00
Vehicle CH_4 and N_2O		2.50
Total Tank-to-Wheel	**1,000,000**	**58.50**
Total Well-to-Wheel	**424,999**	**28.53**

The pathway GHG emissions shown above is when utilizing 80% liquefaction efficiency. When utilizing a 90% efficient process, GHG emissions for liquefaction is **5.04** gCO_2e/MJ (compared to the **15.79** gCO_2e/MJ when the liquefaction is 80% efficient). Table B provides a comparison of the WTW emissions for the two pathways modeled here. The only difference between the two pathways is that GHG emissions for liquefaction are different. Complete details of inputs, assumptions and calculations are provided in Appendix A.

Table B. Comparison of the Two Pathways for Dairy Biogas to LNG

	80% Liquefaction Efficiency	**90% Liquefaction Efficiency**
WTW Emissions (gCO_2e/MJ)	**28.53**	**17.78**

Values, assumptions, emission factors used in this document have been derived from other pathway documents published on the Low Carbon Fuel Standard website. They include pathway documents for electricity, NA NG to CNG, dairy digester biogas to CNG, NANG to LNG, and Landfill gas to CNG. Please refer to these documents for additional details.

The following sections provide summaries of each of the WTT components as well as the TTW values for the 80% liquefaction efficiency pathway. Expanded details are provided in Appendix A. A table of all input values is provided in Appendix B.

Digester Biogas Recovery

Tables C and D provide a summary of the energy consumption (mainly form electricity used in blowers) and associated GHG emissions from digester biogas recovery. Calculation details are provided in Appendix A.

Table C. Total Energy Consumption for Dairy Digester Biogas Recovery

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

Table D. Total GHG Emissions from Dairy Digester Bio Gas Recovery

	GHG $gCO_2e/mmBtu$
VOC	0.176
CO	0.646
CH4	2.441
N2O	0.029
CO2	1,163
Total	1,234
Total in gCO_2e/MJ	**1.17**

Digester BioGas - Processing

Tables E and F provide the energy consumption and associated GHG emissions from processing of dairy digester biogas. Calculation details are provided in Appendix A.

Table E. Total Energy Consumption for Dairy Digester Biogas Processing

Fuel Type	Energy Use
Direct Biogas Use (Btu/mmBtu)	145,100
Electricity (Btu/mmBtu)	131,145
Biogas Credit (Btu/mmBtu)	-1,145,100
Total Energy Use (Btu/mmBtu)	**-868,855**

Table F. Total GHG Emissions from Processing Dairy Digester Biogas

	GHG (gCO_2e/mmBtu)
VOC	1.196
CO	7.30
CH_4	17.708
N_2O	0.387
CO_2	-51,237
Total	**-50,663**
Total GHG Emissions (gCO_2e/MJ)	**-48.02**

Natural Gas Transport

Tables G and H summarize energy consumption and GHG emissions from natural gas transport via pipeline to a liquefaction plant in CA. Calculation details are provided in Appendix A.

Table G. Energy Use for NG Transport to a Liquefaction Plant

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

Table H. GHG Emissions from Natural Gas Transport to a Liquefaction Plant

GHG gCO_2e/mmBtu	VOC	CO	CH_4	N_2O	CO_2	Total
Natural Gas	0.04	0.101	0.131	0.001	28.64	32.5
Electricity	0	0.002	0.006	0	3.07	3.257
Leakage	0	0	17.548	0	0	438.71
Total	0.04		17.69	0.001	32	474.47
Total GHG Emissions (gCO_2e/MJ)						**0.45**

Natural Gas Liquefaction to LNG

Tables I and J provide a summary of energy consumption and GHG emissions from natural gas liquefaction in California LNG plants. Calculation details are provided in Appendix A.

Table I. Energy Use for NG Liquefaction

Total Energy Use for Liquefaction is 265,616 Btu/mmBtu

Table J. Total GHG Emissions Associated with Natural Gas Liquefaction

	CO_2	CH_4	N_2O	GHG $gCO_2e/mmBtu$	GHG gCO_2e/MJ
Total	**15,717**	**32.9**	**0.389**	**16,517**	**15.79**

LNG Transport and Distribution

LNG is transported and distributed by trucks to the refueling stations. Summaries of the energy use and corresponding GHG emissions from transport and distribution are provided in Tables K and L respectively.

Table K. Energy Use for LNG Transport and Distribution

Total Energy Use for LNG T&D is 4,679 Btu/mmBtu

Table L. Total GHG Emissions Associated with LNG Transport, Distribution, and Storage in California

g/mmBtu	CO_2	CH_4	N_2O	GHG $gCO_2e/mmBtu$	GHG gCO_2e/MJ
Total	**378**	**11.98**	**0.009**	**681**	**0.64**

LNG Tank to Wheel

Table M provides a summary of TTW GHG emissions from combusting LNG in a heavy-duty vehicle. This includes CO_2, CH_4 and N_2O emissions generated during combustion. Details of calculations are provided in Appendix A.

Table M. Tank to Wheel GHG Emissions for LNG

TTW = Vehicle GHG = 58.5 gCO_2e/MJ

APPENDIX A

SECTION 1. DAIRY DIGESTER BIOGAS RECOVERY

1.1 Energy Use for Dairy Digester Biogas Recovery

The first step in the dairy digester 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.

An electric blower is used to capture the biogas that is produced in the lagoon. The assumed energy required to recover 1 mmBtu of biogas is 11,124 Btu, which represents a large, unmixed lagoon. It should be noted that this 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. This is not the total energy required however, since CA-GREET accounts for the “upstream” energy associated with each of the fuels utilized. The total energy associated with the 11,124 Btu of electricity includes the energy used to produce the electricity and the energy used to recover and deliver the feedstock to the electricity generating plants.

Table 1.01 provides a summary of the total energy consumption for biogas recovery and transport. Please refer to the dairy digester biogas to CNG pathway for complete details of the calculation.

Table 1.01 Total Energy Consumption from Direct Energy Consumption for Biogas Recovery and Transport

Fuel Type	Formula	Btu/mmBtu
Electricity	11,124 Btu/mmBtu (111,573 Btu/mmBtu+1,888,989 Btu/mmBtu) /10^6	22,209
Total energy for Biogas recovery		**22,209**

Note: See published Dairy Biogas to CNG pathway document for compete details[3]

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. Since the only fuel being used here is electricity which has no direct emissions, only the upstream emissions are accounted for in this step. Table 1.02 provides a summary of the total GHG emissions produced

[3] Dairy Biogas to CNG pathway: http://www.arb.ca.gov/fuels/lcfs/072009lcfs_biogas_cng.pdf

during biogas recovery and transport. Complete details are available in the dairy digester biogas to CNG pathway document[4].

Table 1.02 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**

[4] Dairy Biogas to CNG pathway: http://www.arb.ca.gov/fuels/lcfs/072009lcfs_biogas_cng.pdf

SECTION 2. DIGESTER BIOGAS PROCESSING

2.1 Energy Use for Digester Biogas Processing

The next step in the digester biogas to LNG pathway is cleaning the biogas to pipeline quality and compressing it to natural gas distribution pipeline pressures. 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 the total energy consumption to process dairy digester biogas. Complete details ate available from the dairy digester biogas to CNG pathway.

Table 2.01 Total Energy Consumption for Digester Biogas Processing

Fuel Type	Formula	Btu/mmBtu
Biogas	143,504 Btu/mmBtu*(1 + 11124 Btu/mmBtu/10^6)* 1.000	145,100.3
Electricity	65,686 Btu/mmBtu*(111,573 + 1,884,989) Btu/mmBtu / 10^6	131,145.4
Biogas Credit	-(1,000,000 + 145,100.3)	-1,145,100.3
Total Energy Consumption for Biogas Processing		**-868,854.6**

2.2 GHG Emissions from Digester Biogas Processing

As mentioned above, the only fuel directly combusted during processing is biogas 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–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.

Table 2.02 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. Complete details are available from the dairy digester to CNG pathway.

Table 2.02 Total Direct and Upstream GHG Emissions for Biogas Processing, g/mmBtu

	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**

SECTION 3. NATURAL GAS TRANSPORT & DISTRIBUTION

3.1 Energy Use for NG Transport to a LNG Station

In this step, we assume the same calculation as detailed in the dairy digester biogas to CNG pathway. It involves transport and distribution of the natural gas by pipeline from the processing plant to a LNG liquefaction facility. For this pathway, it is assumed that the LNG facility is located 50 miles from the biogas processing plant. Complete details are available from the LFG to LNG pathway document.

As illustrated in Table 3.01, the total transport energy is 1,350 Btu/mmBtu

Table 3.01 Energy Use for NG Transport to a LNG Station

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

3.2 GHG Emissions from Natural Gas Transport to a LNG Station

The pipeline transport emissions are composed of methane leaks and emissions associated with transporting the natural gas through the pipeline. 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. Total emissions are shown in Table 3.02. For complete details, refer to the LFG to LNG pathway document.

Table 3.02 Direct and Upstream Emissions for NG Transport to a LNG Station

	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**

SECTION 4. NATURAL GAS LIQUEFACTION TO LNG

4.1 LNG Liquefaction Energy Use

Complete details for liquefaction are provided in the pathway document for LNG from NA NG and Remote NG sources. Total energy is shown in Table 4.01.

Table 4.01 Total Energy Use for Liquefaction.

Fuel	Direct Energy	Upstream Energy	Total Energy
Natural Gas	10^6*(1/80%)*100% =	250,000*(31,144 + 31,321)/10^6	265,616
Total (Btu/mmBtu)	**250,000**	**15,616**	**265,616**

Note: 31,144 Btu/mmBtu and 31,321 Btu/mmBtu are NG recovery and processing for LNG (cells F93 and G93) of NG sheet – CA-GREET model

4.2 GHG Emissions from Natural Gas Liquefaction to LNG

For this document, liquefaction energy for the 80% efficient case comes from co-generated electricity. Results for GHG emissions are similar to the energy calculations in the previous section. Table 4.02 summarizes the results for liquefying dairy digester derived gas.

Table 4.02 Total GHG Emission Summary for NG Liquefaction

Natural Gas	**CO_2**	**CH_4**	**N_2O**	**GHG**	**GHG**
	g/mmBtu				g/MJ
Total	**15,717**	**32.906**	**0.389**	**16,655**	**15.79**

Example calculation of CO_2 from natural gas combustion:

Direct CO_2 from NG combustion in NG turbine

$$\frac{250{,}000 Btu/mmBtu \times 100\% \times 58{,}179 gCO2/mmBtu}{10^6}$$ = **14,545 g/mmBtu**

Upstream CO_2 of NG

$$\frac{250{,}000 Btu/mmBtu \times (1691+1761+1237) Btu/mmBtu}{10^6} =$$ **1,172 gCO_2/mmBtu**

Where all are GREET defaults:
58,179 gCO_2/mmBtu: emission factor of NG turbine
1,691gCO_2/mmBtu: NG recovery
1,761 gCO_2/mmBtu: NG processing
1,237 gCO_2/mmBtu: NG T&D
Total gCO_2/mmBtu: 14,454 + 1,172 gCO_2/mmBtu = **17,717 gCO_2/mmBtu**

When using the 90% liquefaction case, the energy inputs translate to 1.14 kWh/gal of energy use where all the electricity is derived from grid based marginal California electricity. Based on this input, the GHG emissions are calculated to be 5.04 gCO_2e/MJ. Therefore the only change for the two pathways modeled here is that for the 80% efficiency one, the liquefaction GHG emissions are **15.79 gCO_2e/MJ**. For the 90% efficiency one, the corresponding emissions are **5.04 gCO_2e/MJ**.

SECTION 5. LNG TRANSPORT, DISTRIBUTION, AND STORAGE

5.1 Energy Consumption for transport of LNG to a Refueling Station

Heavy duty trucks distribute the LNG from the liquefaction facility to LNG refueling stations. The energy results are calculated using a 50 mile transport distance from a LNG plant in CA. The main transport inputs are shown below.

- Region: CA region (CA marginal electricity)
- Capacity (15 tons)
- Fuel economy (5 mi/gal)
- Fuel used (diesel)
- Fugitive emissions during storage (0.1% loss/day, CA-GREET default)
- Fugitive emission recovery rate (80% industry practice)
- Distance (50 mi, CA-GREET default)

Table 5.01 summarizes the total energy use for transporting LNG to LNG refueling stations. Complete details are available from the LFG to LNG pathway and the NA NG to LNG pathway.

Table 5.01 Direct, Upstream and Total Energy Use for Heavy Duty Diesel Truck Delivering LNG from LNG Plants to Refueling Stations

Direct Energy	Upstream Energy	Total Energy
Btu/mmBtu		
4,016	663	4,679

Energy Intensity for Trip to Destination and Return Trip:
(128,450 Btu/gal)/(5 mi/gal)/15 tons = 1,713 Btu/ton-mi
Direct Diesel Energy

$$\left[\frac{10^6 \times 1{,}724 g/gal}{80{,}968 Btu/gal \times 454 g/lb \times 2{,}000 lbs/ton}\right] \times 50 miles \times 1713 \times 2 \frac{Btu}{ton-mile}$$ = 4,016 Btu/mmBtu

Upstream Diesel Energy

$$\left[\frac{10^6 \times 1{,}724 g/gal}{80{,}968 Btu/gal \times 454 g/lb \times 2{,}000 lbs/ton}\right] \times 50 miles \times 1713 \times 2 \frac{Btu}{ton-mile} \times 0.165 Btu/Btu =$$ 663 Btu/mmBtu

(where 0.165 Btu/Btu is Btu energy of diesel consumption per Btu of Btu diesel transported - upstream)

5.2 GHG Emissions from Truck Transport of LNG

Total emissions for LNG transport by truck from the LNG plants is shown in Table 5.02 below.

Table 5.02 Total GHG for LNG Truck Transport from LNG Plants to Stations

Fuels	CO_2	CH_4	N_2O	GHG	GHG
	g/mmBtu				g/MJ
Diesel	378	0.453	0.009	392	0.372
Methane Losses		0.426		11	0.01
Total	**378**	**0.879**	**0.009**	**403**	**0.38**

Example of calculation 378 g/mmBtu CO_2 shown above:

Upstream Diesel CO_2:

$$\left[\frac{1{,}724 g/gal}{80{,}968 Btu/gal \times 454 g/lb \times 2{,}000 lbs/ton}\right] \times 50 miles \times 15{,}813 g/mmBtu \times 1{,}713 \times 2 \frac{Btu}{ton-mile} =$$

64 g/mmBtu

where 15,813 g/mmBtu is the upstream CO_2 emissions associated with diesel production (calculated in the "*Petroleum"* sheet of the CA-GREET model)

Direct Diesel CO_2

$$\left[\frac{1{,}724 g/gal}{80{,}968 Btu/gal \times 454 g/lb \times 2{,}000 lbs/ton}\right] \times 50 miles \times (77{,}809 + 77{,}912) g/mmBtu \times 1{,}713 \frac{Btu}{ton-mile}$$

= **313 g/mmBtu CO_2**

Total: **378 g/mmBtu CO_2** where 77,809 g/mmBtu and 77,912 g/mmBtu are the emission factors from the *EF* sheet of CA-GREET.

5.3 GHG Emissions from Storage of LNG

Fugitive methane emissions occur during LNG storage. The net emissions are a function of the methane boil-off and recovery rates. There are 6 key inputs determining the fugitive methane emissions, shown below in Table 5.03.

Table 5.03. LNG Storage Emissions

Description	Bulk Terminal	Distribution
Daily Boil-Off Rate (%)	0.05%	0.1%
Duration (Days)	5	0.1
Boil-Off Recovery Rate (%)	80%	80%
Net Methane Emissions (g/mmBtu)	10.7	0.4
Net Methane Emissions (gCO_2e/mmBtu)	267	10.6
Net Methane Emissions (gCO_2e/MJ)	0.25	0.01
Total GHG Emissions (gCO_2e/MJ)	**0.26**	

Net Boil-Off Emissions:
[(0.05% bulk terminal boil-off/day)*(5 days)/(1-(0.05% bulk terminal boil-off/day)*(5 days))*(1-80% recovery) + [(0.1% distribution boil-off/day)*(0.1 days)/(1-(0.1% distribution boil-off/day)*(5 days))*(1-80% recovery)]*10^6/(80,968 Btu/gal)*(1,724 g/gal) = **11.1** g CH_4/mmBtu

Converting to gCO_2e/MJ: (11.1 g CH_4/mmBtu)*25/(1055 MJ/mmBtu) = **0.26** gCO_2e/MJ

From Tables 5.02 and 5.03, total GHG for LNG transport, distribution, and storage is (0.38+0.26) g/MJ = **0.64 gCO_2e/MJ**

SECTION 6. GHG EMISSIONS FROM VEHICLES

6.1 GHG Emissions from Vehicles

Vehicle GHG emissions consist of:

- Tailpipe CO_2
- Tailpipe N_2O
- Tailpipe CH_4

In this analysis, heavy duty trucks use LNG. Table 6.01 summarizes the TTW emissions. Complete details are available from the NA NG to LNG pathway.

Table 6.01 TTW Emissions for LNG Derived from Dairy Digester Biogas

Tailpipe Emissions	**CO_2**	**CH_4 and N_2O**	**Total**
gCO_2e/MJ	56.0	2.5	**58.5**

APPENDIX B

LIQUEFIED NATURAL GAS (LNG) FROM DAIRY DIGESTER BIOGAS 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%	CA-GREET Default
Natural Gas Leak Rate		0.0%	TIAX Assumption
Fuel Shares			
Natural Gas		0%	ARB Assumption
Electricity		100%	ARB Assumption
Feed Loss (Leak)		0%	ARB Assumption
Equipment Shares			
Electric Blower		100%	
Digester Gas Processing			
Process Efficiency		82.7%	Assumed the same as LFG
Natural Gas Leak Rate		0%	Assumed the same as LFG
Fuel Shares			
Bio Gas		68.6%	Assumed the same as LFG
Electricity		31.4%	Assumed the same as LFG
Equipment Shares			
Large Boiler - NG		100%	CA-GREET Default
CO_2 Emission Factor	gCO_2/mmBtu	58,198	CA-GREET Default
NG Liquefaction			
NG Liquefaction Efficiency in CA		80%	Assumed
Process Fuels Shares			
Electricity		100%	CA-GREET Default
Remote NG Processing Efficiency		80%	Excluding gas processing
Process Fuels Shares			Assumed the same as LFG
LNG Truck Transport			
Tanker Truck Size	ton	15	fueled by diesel or LNG
Distance travel	Miles	50	from LNG plants in CA to CA filling stations
		250	from LNG plants in Baja to CA filling stations
Fuel Economy	Mi/gal	5	
Fugitive Emissions During Storage	%/day	0.1%/day	CA-GREET default
Fugitive Emissions Recovery Rate		80%	Industry Practice