

**Detailed California-Modified GREET
Pathway for Liquefied Natural Gas (LNG)
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 LNG from North American Natural Gas

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

One pathway not available in the original Argonne model is the dairy digester biogas to CNG fuel pathway. This was incorporated into the CA-GREET model with assistance from Life Cycle Associates. A variation of this pathway is to liquefy the gas (and not compress as in the CNG pathway) and this pathway document 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 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. This document presents all assumptions, and step by step calculations of energy consumption and GHG emissions for this LNG pathway. Most of the components of this pathway have been transferred from the dairy digester biogas pathway. Users are directed to this document as only summaries for these steps are provided in this document.

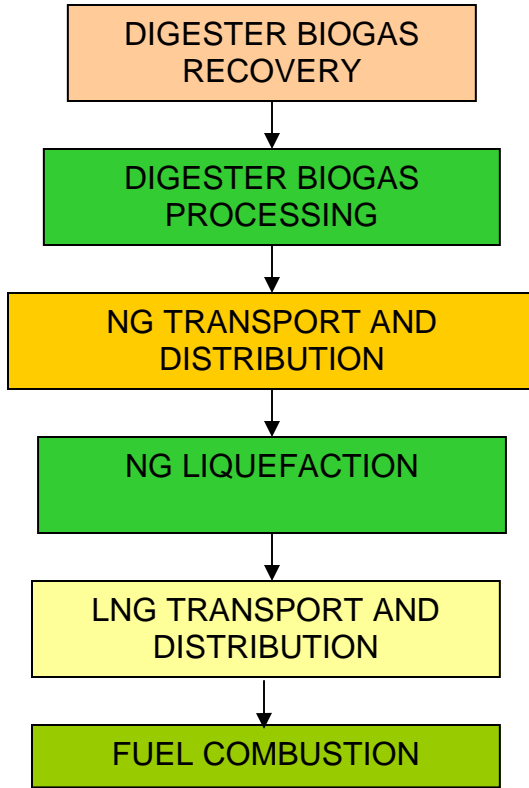


Figure 1. Discrete Components of the Dairy Digester BioGas to LNG Pathway.

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).
- 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.
- 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 included in the total.

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- 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:

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

Table A below provides a summary of the results for this LNG pathway. The WTW analysis for LNG indicates that **420,267** Btu of energy is required to produce 1 (one) mmBtu of available fuel energy. From a GHG perspective, **28.27** gCO₂e/MJ of GHG emissions are generated during the production and use of LNG (derived from dairy digester biogas) 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 GREET model to compare actual output values from the CA-modified model with values in this document.

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Table A. Summary of Energy Consumption and GHG Emissions per mmBtu of LNG Produced from Digester Biogas

	Energy Required (Btu/mmBtu)	GHG Emissions (gCO₂e/MJ)
Well-to-Tank		
Digester Gas Recovery and Transport	22,209	1.17
Digester Gas Processing to NG	-867,258	-48.02
NG Transport & Distribution	1,350	0.45
Liquefaction at LNG Plants	265,616	15.79
LNG Transport and Distribution	4,679	0.38
Total Well-to-Tank	-579,733	-30.23
Tank-to-Wheel		
Carbon in Fuel	1,000,000	56.00
Vehicle CH ₄ and N ₂ O		2.50
Total Tank-to-Wheel	1,000,000	58.50
Total Well-to-Wheel	420,267	28.27

Note: percentages may not add to 100 due to rounding

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. Expanded details are provided in Appendix A. A table of all input values is provided in Appendix B.

Digester Biogas Recovery

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

Table B. Total Energy Consumption for Dairy Digester Biogas Recovery

Fuel Type	Btu/mmBtu
Electricity	22,209

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

	GHG gCO₂e/mmBtu
VOC	0.176
CO	0.646
CH ₄	2.441
N ₂ O	0.029
CO ₂	1,163
Total	1,234
Total in g/MJ	1.17

Digester BioGas - Processing

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

Table D. Total Energy Consumption for Dairy Digester Biogas Processing

Fuel Type	Btu/mmBtu
Direct Biogas Use	145,100
Electricity	131,145
Biogas Credit	-1,143,504
Total Energy	-867,258

Table E. Total GHG Emissions from Processing Dairy Digester Biogas

	GHG gCO₂e/mmBtu
VOC	1.196
CO	7.30
CH ₄	17.708
N ₂ O	0.387
CO ₂	-51,237
Total	-50,663
Total in gCO₂e/MJ	-48.02

Natural Gas Transport

Tables F and G 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 F. Energy Use for NG Transport to a Liquefaction Plant

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

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

GHG gCO₂e/mmBtu	VOC	CO	CH₄	N₂O	CO₂	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 in g/MJ						0.45

Natural Gas Liquefaction to LNG

Tables H and I 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 H. Energy Use for NG Liquefaction

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

Table I. Total GHG Emissions Associated with Natural Gas Liquefaction

	CO₂	CH₄	N₂O	GHG gCO₂e/mmBtu	GHG gCO₂e/MJ
Total	15,717	32.9	0.389	16,655	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 J and K respectively.

Table J. Energy Use for LNG Transport and Distribution

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

Table K. Total GHG Emissions Associated with LNG Transport and Distribution in California

	CO₂	CH₄	N₂O	GHG gCO₂e/mmBtu	GHG gCO₂e/MJ
Total	378	0.879	0.009	403	0.38

LNG Tank to Wheel

This section provides a summary of TTW GHG emissions from combusting LNG in a heavy-duty vehicle. This includes CO₂, CH₄ and N₂O emissions generated during combustion. Details of calculations are provided in Appendix A.

Table L. Tank to Wheel GHG Emissions for LNG

TTW = Vehicle GHG = 58.5 gCO₂e/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	$A (B + C) / 10^6$	22,209
Total energy for Biogas recovery		22,209

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

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Table 1.02 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

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. 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 are 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	$143,504 \text{ Btu/mmBtu} * (1 + 11124 \text{ Btu/mmBtu} / 10^6) * 1.000$	145,100.3
Electricity	$65,686 \text{ Btu/mmBtu} * (111,573 + 1,884,989) \text{ Btu/mmBtu} / 10^6$	131,145.4
Biogas Credit		-1,143,504
Total Energy Consumption for Biogas Processing		-867,258

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 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.

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 CO₂. Complete details are available from the dairy digester to CNG pathway.

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

	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

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 ₂ O	CO ₂	CO ₂ *	Total GHG gCO ₂ e/mmBtu	Total GHG gCO ₂ e/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 RNG 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	$10^6 \times (1/80\%) \times 100\% = 250,000$	$250,000 \times (31,144 + 31,321) / 10^6 = 15,616$	265,616
Total (Btu/mmBtu)			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 comes from a mix of NG and electricity, with 100% from NG. The liquefaction efficiency is assumed to be 80%. 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 GHG Emission Summary for Liquefaction

Natural Gas	CO ₂	CH ₄	N ₂ O	GHG	GHG
	g/mmBtu				g/MJ
Total	15,717	32.906	0.389	16,655	15.79

Example calculation of CO₂ from natural gas combustion:

Direct CO₂ from NG combustion in NG turbine

$$\frac{250,000 \text{ Btu} / \text{mmBtu} \times 100\% \times 58,179 \text{ gCO}_2 / \text{mmBtu}}{10^6} = 14,545 \text{ g/mmBtu}$$

Upstream CO₂ of NG

$$\frac{250,000 \text{ Btu} / \text{mmBtu} \times (1691 + 1761 + 1237) \text{ Btu} / \text{mmBtu}}{10^6} = 1,172 \text{ gCO}_2 / \text{mmBtu}$$

Where all are GREET defaults):

58,179 g CO₂/mmBtu: emission factor of NG turbine

1,691g CO₂/mmBtu: NG recovery

1,761 g CO₂/mmBtu: NG processing

1,237 g CO₂/mmBtu: NG T&D

SECTION 5. LNG TRANSPORT AND DISTRIBUTION

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

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

Upstream Diesel Energy

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

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 ₂ O	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 CO₂ shown above:

Upstream Diesel CO₂:

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

64 g/mmBtu

where 15,813 g/mmBtu is the upstream CO₂ emissions associated with diesel production (calculated in the *Petroleum* sheet of the CA-GREET model)

Direct Diesel CO₂

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

= 313 g/mmBtu CO₂

Total: **378 g/mmBtu CO₂**

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

SECTION 6. GHG EMISSIONS FROM VEHICLES

6.1 GHG Emissions from Vehicles

Vehicle GHG emissions consist of:

- Tailpipe CO₂
- Tailpipe N₂O
- Tailpipe CH₄

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	CO₂	CH₄ and N₂O	Total
gCO ₂ e/MJ	56.0	2.5	58.5

APPENDIX B

LIQUEFIED NATURAL GAS (LNG) FROM DAIRY DIGESTER BIOGAS PATHWAY INPUT VALUES

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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%	CA-GREET Default
Natural Gas Leak Rate		0.0%	TIAX Assumption
Fuel Shares			
<i>Natural Gas</i>		0%	ARB Assumption
<i>Electricity</i>		100%	ARB Assumption
<i>Feed Loss (Leak)</i>		0%	ARB Assumption
Equipment Shares			
<i>Electric Blower</i>		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			
<i>Bio Gas</i>		68.6%	Assumed the same as LFG
<i>Electricity</i>		31.4%	Assumed the same as LFG
Equipment Shares			
Large Boiler - NG		100%	CA-GREET Default
<i>CO₂ Emission Factor</i>	gCO ₂ /mmBtu	58,198	CA-GREET Default
NG Liquefaction			
NG Liquefaction Efficiency in CA		80%	CA-GREET Default
Process Fuels Shares			
<i>Natural Gas</i>		98%	CA-GREET Default
<i>Electricity</i>		2%	CA-GREET Default
Remote NG Processing Efficiency		80%	Excluding gas processing
Process Fuels Shares			Assumed the same as LFG
LNG Truck Transport			
<i>Tanker Truck Size</i>	ton	15	fueled by diesel or LNG
<i>Distance travel</i>	Miles	50	from LNG plants in CA to CA filling stations
		250	from LNG plants in Baja to CA filling stations
<i>Fuel Economy</i>	Mi/gal	5	
<i>Fugitive Emissions During Storage</i>	%/day	0.1%/day	CA-GREET default
<i>Fugitive Emissions Recovery Rate</i>		80%	Industry Practice

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