California Environmental Protection Agency

Air Resources Board

Detailed California-Modified GREET Pathway for Liquefied Natural Gas (LNG) from Landfill Gas

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 Landfill 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 presents a WTW energy use and greenhouse gas (GHG) emissions generated during the process of producing and using liquefied natural gas (LNG) from landfill gas 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).

Using this model, staff developed a pathway document for compressed natural gas (CNG) which was made available in mid-2008 on the Low Carbon Fuel Standard (LCFS) website (http://www.arb.ca.gov/fuels/lcfs/lcfs.htm). Subsequent to this, the Argonne Model was updated in September 2008. To reflect the update and to incorporate other changes, staff contracted with Life Cycle Associates to update the CA-GREET model. This updated California modified GREET model (v1.8b) (released February 2009) was used to calculate WTW emissions for the specific case of LNG derived from landfill gas.

The landfill gas (LFG) to CNG pathway was published in February 2009. In this document, additional steps such as the liquefaction, transport, and use of Liquefied NG (LNG) are included. For completeness, necessary components have been transferred from the NA NG pathway document. This document therefore presents the energy use and greenhouse gas (GHG) emissions generated during the process of producing and using liquefied natural gas (LNG) from landfill gas in a heavy-duty vehicle.

The pathway includes landfill gas collection in California landfills via pipeline, then routed to LNG processing plants, and transporting LNG to refueling station and finally for use in a heavy duty vehicle. In instances where LNG plants are located at the landfill site, no additional transport via pipeline will be required. Figure 1 shows the discrete components that form the LNG from LFG pathway. Based on differences in liquefaction efficiencies, two separate pathways have been modeled in this document and they include:

- LFG to LNG liquefied in California using liquefaction with 80% efficiency (derived from combined cycle NG electricity)

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

- LFG 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 this particular LNG pathway. Details have been provided in Appendix A for the pathway with 80% liquefaction efficiency. 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 North American (NA) NG pathway. Users are directed to the mentioned above document as only summaries for these steps are provided in this document.

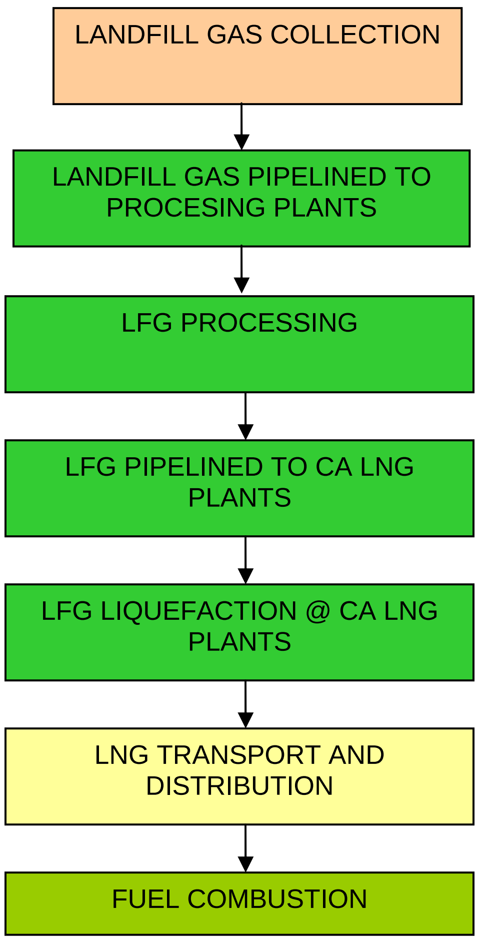

Figure 1. Discrete Components of the Landfill Gas to LNG Pathway.

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 1,055.

- 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 this LNG pathway which utilizes a 80% liquefaction efficiency. The WTW analysis for LNG results in **413,387** Btu of energy required to produce 1 (one) mmBtu of available fuel energy. From a GHG perspective, **26.31** gCO_2e/MJ of GHG emissions are generated during the production and use of LNG 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.

Table A. Summary of Energy Consumption and GHG Emissions for the 80% Liquefaction Efficiency LFG to LNG

	Energy Required (Btu/mmBtu)	**GHG Emissions (gCO_2e/MJ)**
Well-to-Tank		
LFG Collection and Pipeline Transport	9,262	0.49
LFG Processing	-867,520	-49.56
Cleaned LFG Transport via Pipeline	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	**-586,613**	**-32.19**
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	**413,387**	**26.31**

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 LFG to LNG

	80% Liquefaction Efficiency	**90% Liquefaction Efficiency**
WTW Emissions (gCO_2e/MJ)	**26.31**	**15.56**

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

From an energy viewpoint, energy is credit for collection of LFG of the WTW analysis. Similarly, from a GHG perspective, a large amount of GHG is credited for not using fossil fuel for this pathway.

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.

Landfill Gas Collection and Transport

Tables C and D provide a summary of the energy consumption and associated GHG emissions from landfill gas collection. Calculation details are provided in Appendix A.

Table C. Total Energy Consumption by Fuel Type for Landfill Gas Collection and Transport

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

Table D. Total GHG Emissions from Landfill Gas and Transport

	GHG (gCO_2e/MJ)
Electricity	0.49
Total	**0.49**

Landfill Gas Processing

Tables E and F provide the energy consumption and associated GHG emissions from landfill gas cleanup and processing. Calculation details are provided in Appendix A.

Table E. Total Energy Consumption for the Landfill Gas Processing

Fuel Type	Energy Use (Btu/mmBtu)
Landfill gas	144,833
Electricity	131,151
Avoided Flaring Credit	-1,143,504
Total Energy Use	**-867,520**

Table F. Total GHG Emissions from Landfill Gas Processing

	GHG (gCO_2e/MJ)
Landfill Gas	8.43
Electricity	6.88
Flaring Credit	-64.65
Total	**-49.56**

Natural Gas Transport

Tables G and H summarize energy consumption and GHG emissions from natural gas (cleaned LFG) transport to liquefaction plant in CA. Calculation details are provided in Appendix A.

Table G. Energy Use for NG Transport to Liquefaction Plant

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

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

	CO_2	**CH_4**	**N_2O**	**GHG $gCO_2e/mmBtu$**	**GHG gCO_2e/MJ**
Total	**31.7**	**17.49**	**0.001**	**1,028**	**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, Btu/mmBtu

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, Btu/mmBtu

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

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

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

This section 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. LANDFILL GAS COLLECTION

1.1 Energy Use for Natural Gas Recovery

The first step in the LFG pathway is landfill gas collection at the landfills. Currently, there are 218 landfills in California that are subjected to the proposed ARB's methane emissions reduction regulation[2]. A collection and control system is required in the landfills that have 450,000 tons of water-in-place or greater. These systems consist most commonly of vertical wells and in some cases horizontal trenches that are buried within the waste and connected to header pipes which route the gas to a pump or blower station. Vacuum applied to the wells by a pump or blower draws the gas to a control device, such as a flare, internal combustion engine, boiler, gas turbine, or microturbine. The collected gas can either be combusted, used to produce energy, or purified for offsite use. Complete details are provided in the LFG to CNG pathway published in February 2009 (http://www.arb.ca.gov/fuels/lcfs/022709lcfs_lfg.pdf).

In this document, the LFG is assumed to be collected via an electric blower and pipelined to a processing plant. Because the location of the plant is typically very close to the landfill, the energy consumed in this transport is very small. Based on the LFG to CNG pathway document published in February 2009, there are three key assumptions made to calculate direct energy consumption for landfill gas recovery:

- Direct Energy Required (4,621.25 Btu/mmBtu, TIAX Estimate[3])
- Fuel Shares (split of total energy consumed by fuel type)
- Leak Rate (0%, TIAX Estimate[4])

To recover the LFG, a hermetically sealed electric blower is utilized. The assumed energy required to recover 1 mmBtu of LFG is **4,621.25 Btu**. Because the blower is hermetically sealed and the landfill cap is under negative pressure, it is assumed that no LFG leaks during the recovery process.

The figure of **4,621.25 Btu/mmBtu** is the direct energy consumption for the LFG recovery step (mainly electricity for the blower). This is not the total energy required however, since GREET accounts for the "upstream" energy associated with each of the fuels utilized. The total energy associated with the electricity includes the energy used to produce the electricity and the energy used to recover and deliver the fuels to the power plants.

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[2] Regulation to reduce methane emissions from municipal solid waste (MSW) landfills - ISOR by California ARB May 2009

[3] Based on data provided by Prometheus-Energy for the Bowerman landfill in Orange County, California. 37.5 hp are required to recover 770 scfm LFG with an LHV of 446 Btu/scf.

[4] Standard practice for many years is to use hermetically sealed blowers to transfer landfill and digester gases. Verbal information from Bruce at Spencer Turbine Company (1-800-232-4321) 7/08.

Once the LFG has been recovered, it is transferred a short distance by pipeline to the processing plant. For this pathway, it has been assumed that the processing plant is 1 mile from the landfill. For landfill gas transport, hermetically sealed blowers are utilized, so the leak rate is assumed to be zero. The pipeline energy consumption is the energy associated with moving the landfill gas through the pipeline. The main assumptions are:

- Fuel Shares (100% electricity)
- Energy Intensity (203 Btu/ton-mile, calculated from CA-GREET defaults and LFG density)
- Distance (1 mile)
- Lower Heating Value (446 Btu/scf[5])
- Density (34.54 g/scf)

The transport pipeline direct energy consumption is calculated as follows:

Pipeline Energy (Btu/mmBtu) =

$$\frac{34.54 g/scf}{446 Btu/scf} \times 1 mile \times 203 Btu/ton-mile \times \frac{1 lb}{454 g} \times \frac{1 ton}{2,000 lbs} \times 10^6 \, Btu/mmBtu$$

= **17.31** Btu/mmBtu

The total direct energy consumption for LFG recovery and transport of one mile to processing is (4,621.25 + 17.31) = **4,638.56** Btu/mmBtu. The relationship between figure and the combined recovery and transport efficiency is shown in Table 1.01.

Table 1.01. Calculation of Direct Energy Consumption (Btu/mmBtu) to LFG Collection from Assumed Values for Efficiency and Fuel Shares

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

The feed loss (leak) share of 11.4% is back calculated from an assumed leak fraction of 0.35% (0.0035 g methane leaks per g natural gas). This is converted to g/mmBtu using the natural gas density and heating value as shown below:

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

$$\left[(72.166g/mmBtu)\times\frac{930Btu/ft^3}{20.4g/ft^3\times10^6}\right]\div(\frac{1}{97.2\%}-1)=\mathbf{11.4\%}$$

Where:
72.166 g/mmBtu CH_4 leakage = 0.35% x (20.4 g/ft^3/930 Btu/ft^3) x 10^6 – 4.6 g/mmBtu of CH_4 from combustion (calculated in table 1.02 below)
930 Btu/ft^3: LHV of NG
20.4 g/ft^3: density of NG

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

Total Energy for LFG Recovery (Btu/mmBtu)	**4,621.25 + 4,638.56**	**9,262**

1.2 GHG Emissions from Landfill Gas Collection and Transport to Processing

The emission calculation methodology is analogous to the energy calculations. First the direct emissions are calculated and then the upstream emissions (due to recovery and processing of each direct fuel used) are added. To calculate the direct emissions, direct energy by fuel type (provided in detail above) is multiplied by the technology share (% fired in turbine, boiler, engine etc) and then multiplied by the appropriate emission factor. Emissions of CO_2, N_2O and methane due to combustion are quantified. In addition, emissions of VOC and CO are quantified and assumed to convert to CO_2 in the atmosphere. The conversions are calculated as follows:

CO (g/mmBtu) * 44 gCO_2/gmole / 28 gCO/gmole

VOC (g/mmBtu) * 44 gCO_2/gmole / 12 gC/gmole * 0.85 gC/ gVOC

For LFG recovery and transport, only electric blowers are utilized. Therefore, there are no direct emissions, only upstream emissions from electricity production. The emissions are calculated as follows:

Emissions = Miles * Energy Intensity * Fuel Density / Lower Heating Value * Upstream Emission Factor

Table 1.03 provides all of the emission factors for electricity production utilized to calculate LFG recovery and transport GHG emissions.

Table 1.03. Emission Factors for California Marginal Stationary Electricity Use, g/mmBtu

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

The upstream emissions are those associated with electricity production and electricity feedstock recovery and transport. This pathway utilizes marginal electricity (natural gas and renewables).

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

Table 1.04. Calculation of Upstream CO_2 Emissions from Direct Energy Consumption for LFG Recovery and Transport

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

Table 1.05. Values Used to Calculate Upstream CO_2 Emissions for LFG Recovery

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

Table 1.06. Total GHG Emissions from Landfill Gas Recovery, g/mmBtu

	VOC	CO	CH_4	N_2O	CO_2	CO_2*	Total GHG gCO_2e/ mmBtu	Total GHG gCO_2e/ MJ
Electricity	0.074	0.270	1.018	0.012	484.8	485.5	514.5	0.488
Total	**0.074**	**0.270**	**1.018**	**0.012**	**484.8**	**485.5**	**514.5**	**0.49**

* Includes contributions from VOC and CO.

SECTION 2. LANDFILL GAS PROCESSING

2.1 Energy Use for Landfill Gas Processing

The next step in the LFG to CNG pathway is cleaning the LFG to pipeline quality and compressing it to natural gas distribution pipeline pressures. The LFG processing data are based on an LFG to pipeline facility in Canada[6]. The facility draws 2,570 mmBtu/day of LFG from the landfill (~3,500 scfm) and requires 1.8 MW of grid electricity to run the compressors before the membrane to clean the gas. Currently, the facility uses UOP membranes which can achieve 84% methane removal, but the new standard is the Air Liquide MEDAL membrane that can achieve 90% removal efficiency. The Air Liquide MEDAL membrane's 90% removal efficiency[1] is used in this calculation. The remaining 10% is combusted in a thermal oxidizer to minimize emissions. The thermal oxidizer uses pre-membrane LFG as the fuel at a rate of 3 mmBtu/hr (72 mmBtu/day).

With 2,570 mmBtu/day drawn from the landfill, and 72 mmBtu/day being used as fuel in the thermal oxidizer, 2,498 mmBtu/day is fed to the membrane where 90% (2,248 MMBtu/day) is sent to the pipeline. The remaining 10% (250 mmBtu/day) is sent to the thermal oxidizer, 1.8 MW (147.41 mmBtu/day) is used as the process energy. Therefore, the overall efficiency of the LFG gas cleaning process is 2,248/(2570+147.41) = 82.7%. The breakdown of the process energy used is 322 mmBtu/day total in the thermal oxidizer and 147.41 mmBtu/day from electricity, which is 68.6% and 31.4% respectively

The methodology to calculate direct and total energy for landfill gas processing is the same as that to calculate direct and total energy for LFG recovery. Table 2.01 provides details of direct energy consumption to process landfill gas. Note that this pathway includes a credit for the energy associated with all of the LFG that would have otherwise been flared.

Table 2.01. Calculation of Direct Energy Consumption for LFG Processing

Process Fuel Type	Fuel Shares	Relationship of Process Efficiency (0.827) and Fuel Shares	Direct Energy Consumption, Btu/mmBtu
Landfill Gas	68.6%	$(10^6)(1/0.827 - 1)(0.686)$	143,504
Electricity	31.4%	$(10^6)(1/0.827 - 1)(0.314)$	65,686
Flaring Credit		– (1,000,000 + 143,504)	– 1,143,504
Direct Energy Consumption for LFG Processing			**– 934,314**

The values provided in Table 2.01 are direct energy consumption per Btu for the LFG processing step. This is not the total energy required however, since GREET accounts

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

for the “upstream” energy associated with each of the fuels utilized to process the LFG. Table 2.02 demonstrates how the direct energy consumption values shown in Table 2.01 and values in Table 2.03 are utilized to calculate total energy required.

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

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

Table 2.03. Values Used in Table 2.02

Fuel Type	Description
A	143,504 Btu of direct LFG fuel used per mmBtu LFG processed.
B	Total energy to recover LFG is 9,262 Btu/mmBtu.
C	65,686 Btu of direct electricity used to process 1 mmBtu LFG.
D	111,649 Btu of energy used to recover and transport sufficient feedstock to generate 1 mmBtu electricity.
E	1,884,989 Btu used to produce 1 mmBtu electricity.
L1	Loss factor for LFG transport to processing, 1.000 calculated based on assumption of no leakage.

2.2 GHG Emissions from Landfill Gas Processing

As mentioned above, the only fuel directly combusted is LFG in a thermal oxidizer. A large industrial boiler has been used as a surrogate for the thermal oxidizer in GREET when calculating emissions. The exception is the CO_2 emission factor – LFG fuel properties were utilized for this emission factor. Because the LFG would otherwise have been flared, a credit is applied for the flare emissions. The emission factors are provided in Table 2.04. Note that LFG contains approximately 42% CO_2. Two emission factors are shown: the total CO_2 emitted and the CO_2 emitted due to the LFG methane. The emission factor utilized in the calculations is the one that only considers the methane content, since the CO_2 would have been emitted regardless.

Table 2.04. Direct LFG Emission Factors, g/mmBtu

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

These emission factors are combined with direct energy consumption to yield direct emissions,. Similar to total energy, the total emissions include direct emissions plus the emissions associated with recovery and processing/refining the fuels used to process landfill gas. Table 2.05 provides the total emissions associated with LFG processing.

Table 2.05. Total Direct and Upstream GHG Emissions for LFG Processing, g/mmBtu

	VOC	**CO**	**CH_4**	**N_2O**	**CO_2**	**CO_2***	**Total GHG gCO_2e/ mmBtu**	**Total GHG gCO_2e/ MJ**
Landfill Gas	0.154	3.483	16.257	0.217	8,418	8,424	8,896	8.431
Electricity	1.042	3.820	4.033	0.170	6,866	6,875	7,027	6.878
Flare Credit	-2.859	-29.731	-56.032	-1.258	-66,378	-66,434	-68,209	-64.650
Total	**-1.662**	**-22.43**	**-35.74**	**-0.87**	**-51,093**	**-51,134**	**-52,287**	**-49.56**

* Includes contribution from VOC and CO.

SECTION 3. NATURAL GAS TRANSPORTATION AND DISTRIBUTION

3.1 Energy Use for NG Transport and Distribution

The third step in the LNG from LFG pathway is transport and distribution of the cleaned natural gas by pipeline (assumed 50 miles distance) from the processing plant to the LNG plants. Detail calculation of the value is shown in the LFG to CNG pathway document published in February 2009. It consists of:

- T&D Feedstock Loss
- T&D Pipeline Transport Energy Consumption

Table 3.01 presents the total T&D energy is the sum of the feedstock loss (800 Btu/mmBtu) and pipeline energy consumption (550 Btu/mmBtu).

Table 3.01. Energy Use for NG Transport to LNG Plants

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

3.2 GHG Emissions from Natural Gas Transport to LNG Plants in California

The pipeline transport emissions are composed of methane leaks and emissions associated with transporting the natural gas through the pipeline. Similar to the discussion in the LFG to CNG document, GHG emissions consist of electricity and natural gas use in the pipeline and methane leakage[7].

Table 3.02. Direct and Upstream Emissions for NG Transport to Refueling, g/mmBtu

	VOC	**CO**	**CH_4**	**N_2O**	**CO_2**	**CO_2***	**Total GHG gCO_2e/ mmBtu**	**Total GHG gCO_2e/ MJ**
Natural Gas	0.044	0.101	0.131	0.001	28.635	28.931	32.501	0.0308
Electricity	0.000	0.002	0.006	0.000	3.069	3.073	3.257	0.0031
Leakage	0.000	0.000	17.548	0.000	0.000	0.000	438.71	0.4158
Total	**0.04**	**0.10**	**17.69**	**0.001**	**31.70**	**32.00**	**474.47**	**0.45**

* Includes contribution from VOC and CO

[7] See LFG to CNG pathway document published in February 2009 by ARB http://www.arb.ca.gov/fuels/lcfs/022709lcfs_lfg.pdf

SECTION 4. NATURAL GAS LIQUEFACTION TO LNG

4.1 LNG Liquefaction Energy Use

For this document, small scale systems (about 5,000 tonne/year) have been considered based on the systems likely to be used in California. Small scale LNG facilities operate with typical efficiencies between 76 and 92% using a simple cascade cycle (Kunert 2008[8]). Liquefaction energy inputs were calculated for small scale liquefiers based on electric power consumption of 0.6 kWh/kg of LNG (Jakobsen 2008[8]; Kunert 2008[7]). This analysis assumes 80% liquefaction efficiency, due to the smaller scale of liquefiers likely in California. Complete details for liquefaction are provided in the pathway document for LNG from NA NG and RNG sources

North American NG is liquefied at a central facility and distributed by heavy duty LNG trucks. NG liquefaction in California is done by pressure let down or electromagnetic liquefaction and is all electric. Liquefaction in California is assumed to be 100% natural gas-based, with an 80% average efficiency. This efficiency is somewhat lower than the efficiency assumed for larger scale remote liquefaction and is consistent with current industry liquefaction curves[7,8]. The main parameters for NA liquefaction modeling are:

- Region: CA Marginal (CA petroleum and CA marginal electricity)
- NG efficiency (80%)
- Process fuel shares (100% NG)
- LNG storage leakage rate (0.05% day, IPCC value)
- LNG storage duration (5 days, CA-GREET default)
- Recovery rate of LNG boil-off (100%)

The liquefaction efficiency for North American NG means that 250,000 Btu of direct NG is required to liquefy 1 mmBtu of NG fuel. A natural gas turbine is used for liquefaction energy. Unlike NG extraction and processing, GREET models feed loss (Btu/mmBtu) based directly on the methane boil-off rather than using a fuel share for feed loss. However, zero percent feed loss is assumed because typically LNG facilities recapture boil off and re-liquefy the NG or use it as fuel.

Total energy for liquefaction is based on the direct energy input plus the upstream energy for that fuel and is calculated in the same way as total energy for extraction and processing. Total energy is shown in Table 4.01. The total energy is based on a California marginal electricity mix.

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[8] Kunert (2008). "Small is Beautiful - MiniLNG Concept: A Very Small LNG Production Plant for the Potential Use of Bio-Energy for Future Energy Supply". "The Potential of Bioenergy for Future Energy Supply" Conference, Leipzig, Germany

[8] Jakobsen, A. (2008). "Energy Efficient LNG Technology for Recovery of Flare Gas". Presentation at the "Global Forum on Flaring and Venting Reduction and Natural Gas Utilisation".

Table 4.01. Total Energy Use by Process Fuel for NA NG 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 LFG to LNG.

Table 4.02. Total Emissions (Direct + Upstream) 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**

Note: See detailed calculation in the LNG from NA NG published by ARB

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 LNG Truck Transport Summary

Complete details for energy from liquefaction are provided in the LNG from NA NG and Remote NG sources document.

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)

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

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

5.2 GHG Emissions from Truck Transport of LNG

Complete details for GHG emissions from liquefaction are provided in the LNG from NA NG and Remote NG sources document and are 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:

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

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

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

= **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** g CO_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 VEHICLE

6.1 LNG Composition

LNG composition affects the inputs to its life cycle analysis in two ways. First, the composition determines the product fuel's carbon content which can range from 74.7 to 76.1% with corresponding to 55.4 to about 56.8 g/MJ (as CO2) when calculated from the individual LNG composition. The range in carbon content for LNG is relatively small as it contains low levels of nitrogen and no CO_2. A carbon content of 75.7% was selected as the CA-GREET input based on the average of a range of LNG compositions. The CA-GREET inputs for heating value and density were also changed to reflect LNG compositional data that was consistent with data and the carbon content in g/MJ.

6.2 GHG Emissions from Vehicles

Vehicle GHG emissions consist of:

- Tailpipe CO_2 (combusted CH_4)
- Tailpipe N_2O (combustion product)
- Tailpipe CH_4 (product of incomplete combustion, evaporative losses)

In this analysis, heavy duty trucks use LNG. The CO_2 is calculated from the carbon content of the fuel, minus the tailpipe methane emissions. CO_2 emissions therefore depend on the fuel heating value (LHV), density (g/gal) and carbon content (% C by weight), and differ for NA NG and remote NG. Methane and nitrous oxide emissions are calculated based on the g/mi emission factors from the California Climate Action Registry.

(1,724 g-LNG/gal)*(0.757 g-C/g-NG)*(1/80,968 Btu/gal)*(44 g-CO_2/12 g-C)*(Btu/1.055 kJ)*(1,000 kJ/MJ) = **56.0** g CO_2/MJ

In the above equations 1,724 is the density of NG (CA-GREET default), 0.757 is the Carbon in NG (Ca-GREET default) and the LHV of NG is 80,968 Btu/gal.

The same vehicle CH_4 and N_2O emissions are assumed for LNG vehicles as CNG vehicles[9], (See CNG from NA NG document).

Table 6.01. LNG Tailpipe Emissions.

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

[9] See CNG pathway document published in by ARB in Feb 2009

APPENDIX B

LIQUEFIED NATURAL GAS (LNG) FROM CALIFORNIA LANFFILL GAS 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
Natural Gas Recovery			
Process Efficiency		97.2%	CA-GREET Default
Natural Gas Leak Rate		0.35%	CA-GREET Default
Fuel Shares			
Residual Oil		0.9%	CA-GREET Default
Conventional Diesel		9.8%	CA-GREET Default
Conventional Gasoline		0.9%	CA-GREET Default
Natural Gas		76.2%	CA-GREET Default
Electricity		0.9%	CA-GREET Default
Feed Loss (Leak)		11.4%	CA-GREET Default
Equipment Shares			
Small Boiler - Residual Oil		100%	CA-GREET Default
CO_2 Emission Factor	gCO_2/mmBtu	85,049	CA-GREET Default
Commercial Boiler - Diesel		25%	CA-GREET Default
CO_2 Emission Factor	gCO_2/mmBtu	78,167	CA-GREET Default
Stationary Reciprocating Eng. - Diesel		50%	CA-GREET Default
CO_2 Emission Factor	gCO_2/mmBtu	77,349	CA-GREET Default
Turbine - Diesel		25%	CA-GREET Default
CO_2 Emission Factor	gCO_2/mmBtu	78,179	CA-GREET Default
Stationary Reciprocating Eng. - Gasoline			
CO_2 Emission Factor	gCO_2/mmBtu	50,480	CA-GREET Default
Small Boiler - NG		50%	CA-GREET Default
CO_2 Emission Factor	gCO_2/mmBtu	58,215	CA-GREET Default
Stationary Reciprocating Eng. - NG		50%	CA-GREET Default
CO_2 Emission Factor	gCO_2/mmBtu	56,388	CA-GREET Default
Natural Gas Processing			
Process Efficiency		97.2%	CA-GREET Default
Natural Gas Leak Rate		0.15%	CA-GREET Default
Fuel Shares			
Conventional Diesel		0.9%	CA-GREET Default
Natural Gas		91.1%	CA-GREET Default
Electricity		2.8%	CA-GREET Default
Feed Loss (Leak)		5.1%	CA-GREET Default
Equipment Shares			
Commercial Boiler - Diesel		33%	CA-GREET Default
CO_2 Emission Factor	gCO_2/mmBtu	78,167	CA-GREET Default
Stationary Reciprocating Eng. - Diesel		33%	CA-GREET Default
CO_2 Emission Factor	gCO_2/mmBtu	77,349	CA-GREET Default
Turbine - Diesel		34%	CA-GREET Default
CO_2 Emission Factor	gCO_2/mmBtu	78,179	CA-GREET Default
Large Boiler - NG		50%	CA-GREET Default
CO_2 Emission Factor	gCO_2/mmBtu	58,215	CA-GREET Default

Parameters	Units	Values	Note
Large Turbine - NG		50%	CA-GREET Default
CO_2 Emission Factor	gCO_2/mmBtu	58,196	CA-GREET Default
Feed Loss		1.001	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 NA NG
Natural Gas Pipeline Transmission			
Natural Gas Use		94%	CA-GREET Default
Electricity Use		6%	CA-GREET Default
Distance travel	Miles	1,400	For NA NG to California
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
Vehicle Emissions			
Carbon in NG	grams C/gram NG	72.4	
Fuels Properties	**LHV (Btu/gal)**	**Density (g/gal)**	
Crude	129,670	3,205	CA-GREET Default
Residual Oil	140,353	3,752	CA-GREET Default
Conventional Diesel	128,450	3,167	CA-GREET Default
Conventional Gasoline	116,090	2,819	CA-GREET Default
CaRFG	111,289	2,828	CA-GREET Default
CARBOB	113,300	2,767	CA-GREET Default
Natural Gas	83,686	2,651	NG Liquids
Natural Gas			NG gaseous: 930 Btu/scf