Johnstown Regional Energy

Method 2A/2B application

Landfill Gas to Liquefued Natural Gas

Submitted on behalf of JRE by Element Markets LLC
Dated: 7/3/2013

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1 Summary

Johnstown Regional Energy Pathway Description

A Well-To-Tank (WTT) life cycle analysis of the Johnstown Regional Energy's (JRE) Landfill Gas (LFG) to Liquefied Natural Gas (LNG) pathway considers all fuel production steps from feedstock recovery to finished fuel. Tank-to-Wheel (TTW) analysis includes actual combustion of LNG as a transportation fuel in a motor vehicle. Together, WTT and TTW analysis are combined to provide a total Well-to-Wheel (WTW) analysis.

A Life Cycle Analysis Model called the **G**reenhouse gases, **R**egulated **E**missions, and **E**nergy use in **T**ransportation (GREET) developed by Argonne National Laboratory forms the core basis of the method used in this document. Changes specific to our pathway were restricted mostly to input factors with no substantial changes in methodology inherent in the original CA-GREET model.

The three JRE Landfill gas processing facilities namely, Southern Alleghenies Landfill, Shade Landfill and Raeger Mtn Landfill, all located in Pennsylvania, use landfill gas coming in from attached landfills and filter the gas to pipeline quality gas. This purified landfill gas is then transported to California refueling stations via a pipeline.

The pathway described here combines recovery of landfill gas, filtration of inlet gas to pipeline quality gas and final compression to pipeline pressures for all the three processing facilities. The "natural gas" obtained from the 3 facilities is then transported by pipeline to LNG processing plants in California, the LNG is transported to refueling stations and finally used in a heavy duty vehicles.

The pathway LCA calculations for liquefaction of landfill gas, transportation, distribution and storage of LNG, as well as vehicular emission from combusting LNG are mostly unchanged from those described in ARB's internal LFG to LNG pathway documentation published in the ARB Method 1 lookup table on Sep 23, 2009 under pathway identifier "LNG006". Pathway steps up to LNG liquefaction (LFG collection, processing and transportation to California) are identical to those described in pathway "CNG007", published by ARB on 04/10/2013.

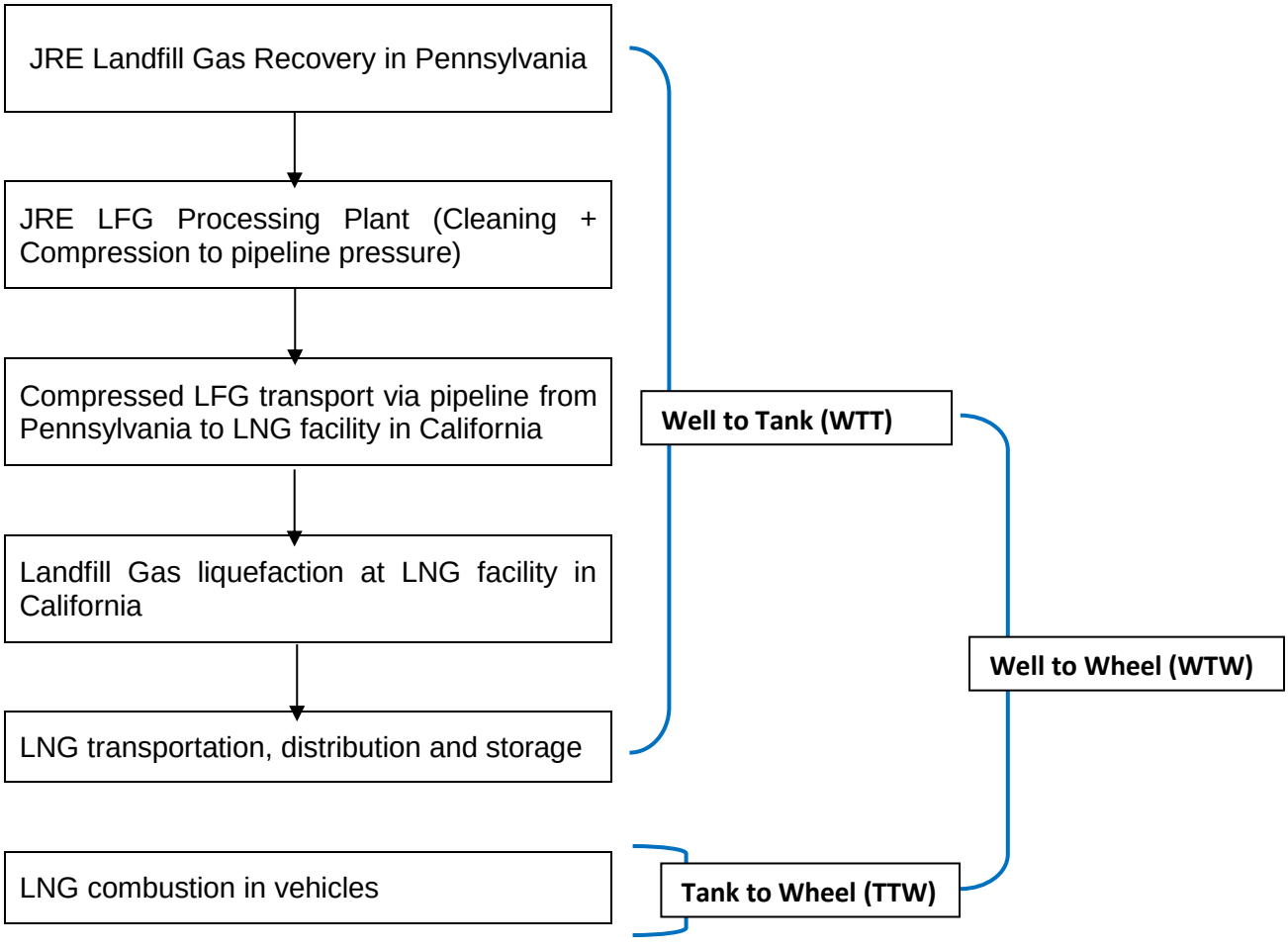

Figure 1. Discrete Components of the Landfill gas to LNG Pathway

Table A below provides a summary of the results for this LFG to LNG pathway. The WTW analysis shows that **456,561** Btu of energy is required to produce 1 (one) mmBtu of available fuel energy. From a GHG perspective, **32.53** g CO_2 e/MJ of GHG emissions are generated during the production and use of LNG in heavy duty trucks.

Table A. Summary of Energy Consumption and GHG Emissions per mmBtu of LNG produced from LFG

	Energy Required (Btu/mmBtu)	GHG Emissions (g CO_2e/MJ)
Landfill Gas Recovery	REDACTED	
Landfill Gas Processing		
Transport to LNG facility		
NG Liquefaction		
LNG Transport & Distribution & Storage		
Total WTT		
Carbon in Fuel		
Vehicle CH_4 and N_2O		
Total TTW		
Total WTW	**456,561**	**32.53**

*Credit for landfill gas processing

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.

Landfill Gas Recovery

Tables B and C provide a summary of the energy consumption and associated GHG emissions from LFG recovery. Calculation details are provided in Appendix A.

Table B. Total Energy Consumption by Fuel Type for LFG Recovery

Fuel Type	**Btu/mmBtu**	
Electricity		
Total		

Table C. Total GHG Emissions from LFG Recovery

	Total GHG g CO_2e/MJ	
LFG Recovery		
Total GHG Emissions		

Landfill Gas Processing

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

Table D. Total Energy Consumption for the LFG Processing Step

Fuel Type	**Btu/mmBtu**	
Landfill Gas		
Electricity		
Avoided Flaring Credit		
Total Energy		

Table E. Total GHG Emissions from LFG Processing

	Total GHG g CO_2e/MJ
Landfill Gas	
Electricity	
Avoided Flaring Credit	
Total	

Natural Gas Transport

Tables F and G summarize energy consumption and GHG emissions from natural gas transport. Calculation details are provided in Appendix A.

Table F. Energy Use for NG Transport

Total T&D Energy Use =

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

	Total GHG g CO_2e/MJ
Total	

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, Btu/mmBtu

Total energy use for Liquefaction is

Table I. Total GHG Emissions Associated with Natural Gas Liquefaction

	CO_2* g/mmBtu	**CH_4 g/mmBtu**	**N_2O g/mmBtu**	**Total GHG gCO_2e/mmBtu**	**Total GHG gCO_2e/MJ**
Total					

* CO_2 includes VOC and CO values

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, Btu/mmBtu

Total Energy Use for LNG T&D

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

	CO_2* g/mmBtu	**CH_4 g/mmBtu**	**N_2O g/mmBtu**	**Total GHG gCO_2e/mmBtu**	**Total GHG gCO_2e/MJ**
Total					

* CO_2 includes VOC and CO values

LNG Tank to Wheel

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

Table L. Tank to Wheel GHG Emissions for NG

TTW = Vehicle = O_2e/MJ

APPENDIX A

SECTION 1. LANDFILL GAS RECOVERY

1.1 Energy Use for Landfill Gas Recovery and Transport to Processing

The first step in the LNG from LFG pathway is LFG recovery and transport to the point of processing. Because the location of our processing facility is practically attached to the landfill, the energy consumed in this transport is assumed to be negligible. Hence for this stage, we only calculate the energy required to recover the landfill gas.

1.1.1 Energy Use for Landfill Gas Recovery

There are three key assumptions made to calculate direct energy consumption for landfill gas recovery:

Direct Energy Required ([redacted]Btu/mmBtu, see Table 1.01 below for calculation of total energy required to extract landfill gas at all facilities. Data for individual facilities were obtained using JRE's process flow diagrams and nameplate capacities of blowers in all three facilities)

Table 1.01 Calculation for individual facilities and total power consumption for LFG recovery

Facility	Electricity usage (hp)	Electricity usage (Btu/min)	LFG in rate (mcfd)	LFG in rate (scfm)	LFG LHV (Btu/scf)	LFG in rate (Btu/min)	Electricity used per LFG (Btu /mmBtu LFG)
Raeger Mtn	[redacted]						
Shade							
Southern Alleghenies							

Electricity Generation Mix (The electricity generation mix for JRE facilities was assumed to be same as that provided on EPA's eGRID database for state of Pennsylvania which falls under RFC East region. See Appendix C. The RFC East mix was further converted to RFC East Marginal and used for our LCFS pathway calculation. Table 1.02 provides detailed electricity mix calculation)

Table 1.02 Calculation for electricity mix using data from e-GRID website

Generation Resource Mix (%)	eGRID data (RFC East)	Data used in pathway (RFC East marginal)
Coal	[redacted]	
Residual Oil		
Natural Gas		
Other fossil		
Biomass		
Hydro		
Nuclear		
Renewable(Wind + Solar + Geothermal)		

Leak Rate (0%, Standard industry practice since many years is to use hermetically sealed blowers to transfer landfill and digester gases - Verbal information from JRE engineers)

To recover the LFG, a hermetically sealed electric blower is utilized. The direct energy, in the form of electricity, required to recover 1 mmBtu of LFG [redacted] 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.

Since GREET accounts for the "upstream" energy associated with each of the fuels utilized. The total energy associated with the [redacted] electricity includes the energy used to produce the electricity and the energy used to recover and deliver the fuels to the power plants.

The total Table 1.03 details how total energy is calculated from direct energy.

Table 1.03 Total Energy Consumption from Direct Energy Consumption for LFG Recovery

Fuel Type	**Formula**	**Btu/mmBtu**
Electricity	A (B+C) / 10^6	[redacted]
Total energy for LFG recovery		

Table 1.04 Values Used in Table 1.03

Fuel type	**Description**
A	[redacted] direct electricity used to recover 1 mmBtu of LFG
B	[redacted] of energy used to recover and transport sufficient feedstock to generate 1 mmBtu electricity
C	[redacted] Btu used to produce 1 mmBtu electricity

1.2 GHG Emissions from Landfill Gas Recovery

First the direct emissions are calculated and then the upstream emissions (due to recovery and processing of each direct fuel used) are added. 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 g CO_2/gmole / 28 gCO/gmole

VOC (g/MMBtu) * 44 g CO_2/gmole / 12 gC/gmole * 0.85 gC/ gVOC

For LFG recovery, only electric blowers are utilized. Therefore, there are no direct emissions, only upstream emissions from electricity production.

Table 1.05 provides all of the emission factors for electricity production utilized to calculate LFG recovery GHG emissions.

Table 1.05 Emission Factors for Pennsylvania (RFC East Marginal) Stationary Electricity Use, g/mmBtu

	VOC	**CO**	**CH_4**	**N_2O**	**CO_2**
Feedstock	[redacted]				
Electricity Generation					
Total					

The upstream emissions are those associated with electricity production and electricity feedstock recovery and transport. This pathway utilizes RFC East Marginal electricity mix.

Table 1.06 provides the upstream CO_2 emissions for landfill gas recovery and transport.
Table 1.07 details the values used in Table 1.06.
The total emissions are presented in Table 1.08 along with the other GHGs; the CO and VOC values are converted to CO_2.

Table 1.06 Calculation of Upstream CO_2 Emissions from Direct Energy Consumption for LFG Recovery

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

Table 1.07 Values Used to Calculate Upstream CO_2 Emissions for LFG Recovery

Fuel type	**Description**	
A		Btu of direct electricity used to recover 1 mmBtu of LFG
B		g CO_2/mmBtu Electricity to produce & transport feedstock
C		g CO_2 to produce 1 mmBtu electricity

Table 1.08 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 gCO2e/MJ
Electricity								
Total								

*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 LNG pathway is cleaning the LFG to pipeline quality and compressing it to natural gas distribution pipeline pressures. The three JRE facilities together draw [redacted]u/day of LFG from the landfill ([redacted] and require [redacted] of grid electricity (See Table 2.01 for details on individual facilities). The compressors are needed to compress the gas before the membrane filters as well as to compress the gas to pipeline pressures after it has been filtered. All the facilities use the Air Liquide MEDAL membrane that can achieve >90% removal efficiency. The remaining gas is combusted in a thermal oxidizer (TOX) to minimize emissions. The thermal oxidizers at all the three facilities use post-membrane LFG (i.e. sales gas) as the fuel.

Table 2.01 Calculation for individual facilities and total power consumption for LFG processing

Facility	LFG in rate (mcfd)	Inlet LFG heat content (Btu/scf)	LFG in rate (mmBtu/day)	Compressor Power (hp)	Compressor Power* (mmBtu/day)	LFG out rate (mcfd)	Outlet LFG heat content (Btu/scf)	LFG out rate (mmBtu/day)	TOX Inlet (mcfd)	TOX Inlet (mmBtu/day)
Raeger Mtn	[redacted]									
Shade										
Southern Alleghenies										
Total										

*1 hp = 42.32 Btu/min

Figure 2 below depicts the process flow diagram where all the facilities are combined into single flow diagram

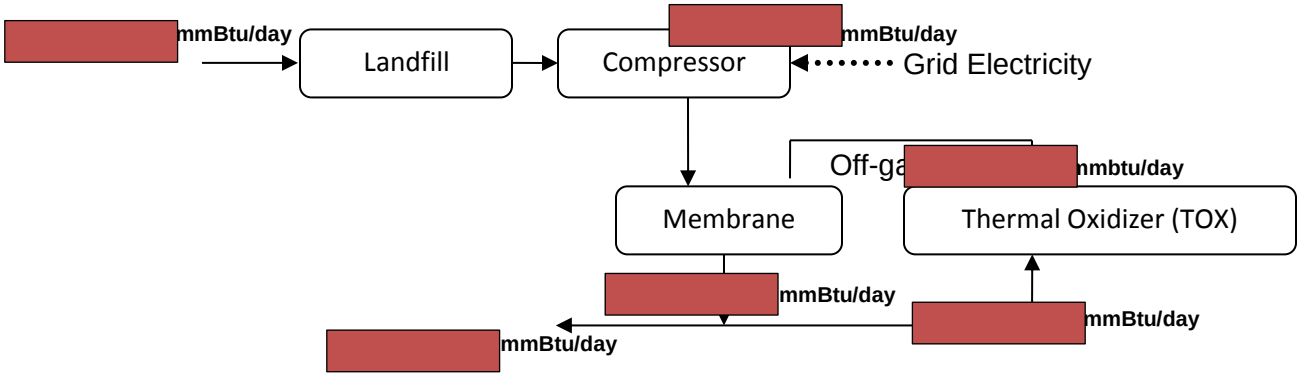

Figure 2. Process (Energy) Flow Diagram (combined description of all three facilities)

[redacted] mmBtu/day LFG is drawn from the landfill and everything is fed to the membrane via compressors, of which [redacted] MMBtu/day) is recovered as sales quality gas. Of the total sales gas recovered [redacted] mBtu/day is sent to the sales pipeline and the remaining [redacted] is sent to the thermal oxidizer as fuel. [redacted] mmBtu/day) is used as the process energy to run the compressors. Therefore, the overall efficiency of the LFG gas cleaning process is [redacted]

The breakdown of the process energy used is [redacted] ay in the thermal oxidizers and [redacted] in the compressors, which is [redacted] % respectively.

The direct and total energy for landfill gas processing is calculated the same way as for LFG recovery. Table 2.02 provides details of direct energy consumption to process landfill gas.

The calculation includes a credit for the energy associated with all of the LFG that would have otherwise been flared.

Table 2.02 Calculation of Direct Energy Consumption for LFG Processing

Process Fuel Type	**Fuel Shares**	**Relationship of Process Efficiency (0.719) and Fuel Shares**	**Direct Energy Consumption, Btu/mmBtu**
Landfill Gas	[redacted]		
Electricity			
Flaring Credit			
Direct Energy Consur			

Since GREET accounts for the "upstream" energy associated with each of the fuels utilized to process the LFG, the direct energy consumption values and upstream energy consumption values in Table 2.04 are utilized to calculate total energy required. The calculation is shown in Table 2.03

Table 2.03 Total Energy Consumption from Direct Energy Consumption for LFG Processing

Fuel Type	**Formula**	**g/mmBtu**
Landfill Gas	$A(1+ B/10^6)*L1$	[redacted]
Electricity	$C(D+E)/10^6$	
Flaring credit	G	
Total energy consumption for NG Processing		

Table 2.04 Values Used in Table 2.03

Fuel type	**Description**
A	[redacted] Btu of direct LFG fuel used per mmBtu of LFG processed
B	Total energy needed to recover 1 mmBtu LFG is [redacted]
C	[redacted] Btu of direct electricity used to process 1 mmBtu LFG
D	[redacted] Btu of energy used to recover and transport sufficient feedstock to generate 1 mmBtu electricity
E	[redacted] Btu used to produce 1 mmBtu electricity
L1	Loss factor for LFG transport to processing. 1.00 calculated based on assumption of no leakage.

2.2 GHG Emissions from LFG Processing

As mentioned above, the only fuel directly combusted is LFG in the TOX. Input to TOX is [redacted]m Figure 2 above) = [redacted], which is [redacted] Therefore [redacted] boiler has been used as a surrogate for the thermal oxidizer in GREET when calculating emissions. Because the LFG would otherwise have been flared, a credit is applied for the flare emissions. The emission factors are provided in Table 2.05. Two emission factors are shown: those for a small boiler and those for flaring landfill gas.
The emission factor that is utilized for calculating CO_2 emissions is the one that only considers the methane content, since the CO_2 would have been emitted regardless.

Table 2.05 Direct LFG Emission Factors, g/mmBtu

	Small Boiler	**Flare**
VOC	[redacted]	
CO		
CH_4		
N_2O		
CO_2 (Only LFG Methane)		

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 2.06 provides the total emissions associated with LFG processing.

Table 2.06 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	[redacted]							
Electricity								
Flaring credit								
Total								

* Includes contribution from VOC and CO.

SECTION 3. NATURAL GAS TRANSPORT & DISTRIBUTION

3.1 Energy Use for NG Transport and Distribution

The fourth step in the LNG from LFG pathway is transport and distribution of the natural gas by pipeline from the processing plant to the LNG production facility. Since processed landfill gas is to be transported to a liquefaction plant in California, it is assumed that the distance covered by gas in the pip[redacted]miles. 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 feedstock loss factor value is assumed to be 0.08%, same as that used for LFG to CNG pathway published by ARB.
Because almost all of this loss occurs in the distribution system, the leak rate does not vary with distance.
The leak rate is calculated as follows:

CH_4 Leak Rate = 0.0008 g CH_4/gNG[redacted]

The leak rate is then used to calculate the Loss Factor as follows:
Loss Factor = [redacted]

Finally, the feedstock loss can be calculated:
T&D Feedstock Loss = [redacted]

The pipeline energy consumption is the energy associated with moving the natural gas through the pipeline. The main assumptions are:

- Fuel Shares: [redacted] natural gas, [redacted] electricity (Pennsylvania Electricity)
- Energy Intensity [redacted] Btu/ton-mile (calculated by GREET for [redacted] miles distance)
- Distance: [redacted] miles (approximate distance between Pennsylvania and California)
- Heating value [redacted] Btu/scf (based on ARB's recommendation and sales gas meter data)
- Density: [redacted] g/scf (assumed for average pipeline gas quality gas)

The T&D pipeline energy consumption is calculated as follows:
Pipeline Energy (Btu/mmBtu)
[redacted]

The values [redacted] and [redacted] 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 = [redacted]

3.2 GHG Emissions from Natural Gas Transport to the LNG Facility

The pipeline transport emissions are composed of methane leaks and emissions associated with moving the natural gas through the pipeline. As discussed in the energy section, an assumed leak fraction dictates CH_4 leakage emissions of [redacted] g/mmBtu.

The pipeline combustion emissions are calculated using the energy intensity of [redacted] Btu/ton-mile and the assumed transport distance of [redacted] miles. The direct energy use is [redacted] u/mmBtu. The fuel split is [redacted] natural gas, [redacted] 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) and Equipment Shares

	Natural Gas
Direct Energy	[redacted]
Equipment Shares	[redacted]
Turbine	[redacted]
Engine	[redacted]
Advanced Engine	[redacted]

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

	CO_2	**VOC**	**CO**	**CH_4 (comb.)**	**N_2O**
Turbine	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Engine	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Adv Engine	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Table 3.04 Direct and Upstream Emissions for NG Transport to Refueling, g/mmBtu

	VOC	**CO**	**CH_4**	**N_2O**	**CO_2**	**CO_2***	**Total GHG g CO_2e/ mmBtu**	**Total GHG g CO_2e/ MJ**
Natural Gas	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Electricity	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Leakage	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Total	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

* Includes contribution from VOC and CO

SECTION 4. NATURAL GAS LIQUEFACTION TO LNG

4.1 LNG Liquefaction Energy Use

In our LCA we assume 80% liquefaction efficiency, as described in the LNG from Landfill Gas pathway description published by ARB on Sep 23, 2009.

Landfill Gas 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.

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.

Table 1.03 Total Energy Consumption from Direct Energy Consumption for LFG Recovery

Fuel Type	**Direct Energy**	**Upstream Energy**	**Total Energy**
Natural Gas	$A(1/B-1)*10^6$	$250{,}000*(C+D)/10^6$	
Total [Btu/mmBtu]	250,000	15,616	**265,616**

Table 1.04 Values Used in Table 1.03

Fuel type	**Description**
A	100% process fuel share of NG in liquefaction
B	80% liquefaction efficiency
C	31,144 Btu/mmBtu total energy consumption for NA NG recovery
D	31,321 Btu/mmBtu total energy consumption for NA NG processing

4.2 GHG Emissions from Natural Gas Liquefaction to LNG

For this document, liquefaction energy for the 80% efficient case comes from cogenerated 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.

	VOC g/mmBtu	CO g/mmBtu	CH_4 g/mmBtu	N_2O g/mmBtu	CO_2 g/mmBtu	Total GHG gCO_2e/mmBtu	Total GHG gCO_2e/MJ
Natural Gas	1.707	8.590	32.906	0.389	15717.957	16674.522	15.80
Total	**1.707**	**8.590**	**32.906**	**0.389**	**15717.957**	**16674.522**	**15.80**

SECTION 5. LNG TRANSPORT, DISTRIBUTION AND STORAGE

5.1 LNG Truck Transport Summary

LNG is distributed by heavy duty truck (HDT) from the bulk terminal in California to end user. The 80,000 lb GVW limit for tanker trucks carrying liquid fuels sets the theoretical upper weight limit for LNG (or any liquid fuel) cargo. The cargo capacity for gasoline tanker trucks is 54,000 lbs, or 9,000 gallons of gasoline. Since the density of LNG is slightly more than half of the density of gasoline, the practical LNG cargo capacity is limited by volume rather than weight. The 9,000 gallon capacity of a tanker truck translates into approximately 32,000 lbs (16 tons) LNG cargo capacity, or ~60% of the cargo weight limit. The Argonne GREET model default of 15 tons is close to this and used in this analysis.

Heavy duty tanker trucks transfer LNG by passing a small amount of LNG into a heat exchanger to increase the pressure in the tanker truck and force the liquid into the receiver tank. After transferring the vapors, the LNG tank on the truck is purged. Life cycle energy includes the direct and upstream diesel energy used to operate the truck and the fuel lost to boil off methane emissions (which contributes to the loss factor). Emissions include direct and upstream emissions for diesel fuel in a HDT and the fugitive methane boil-off emissions.

5.2 LNG Truck Transport Energy Consumption

Heavy duty trucks distribute the LNG from the liquefaction facility to the LNG station.
The energy results are calculated using a 50 mile transport distance from a LNG plant in California. The main transport inputs are shown below. All inputs except for distances are CA-GREET default values.

- Region: CA (CA marginal electricity, CA average crude)
- 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)

The calculations for heavy duty truck energy consumption are based on truck energy intensity in Btu/ton-mi. The energy intensity is calculated as follows:

Btu/ton-mi = ((128,450 Btu/gal Diesel LHV)/(5 mi/gal))/capacity in tons. The upstream and total energy results are presented in Table 5.02.

Table 5.01. Energy Intensity for Trip to Destination and Return Trip

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

Table 5.02. Direct, Upstream and Total Energy Use for Heavy-Duty Diesel Truck Delivering LNG from LNG Plants to Refueling Stations in California

Fuel	**Trip Energy Intensity**	**Direct Energy Usage**	**Upstream Energy Usage**	**Total Energy Usage**
US Diesel	1713 Btu/ton-mi	4016 Btu/mmBtu	663 Btu/mmBtu	**4679 Btu/mmBtu**

5.3 GHG Emissions from Truck Transport of LNG

Upstream and direct emissions from LNG transport by truck from the LNG plants are summarized in Table 5.03, inclusive of methane losses.

Fugitive emissions from truck transport are modeled based on 0.1% boil-off/day and 80% recovery. These are CA-GREET default parameters.

Table 5.03 Upstream and Direct Emissions for Heavy-Duty Diesel Truck Transport of LNG from LNG Plants to Refueling Stations in California

	VOC g/mmBtu	CO g/mmBtu	CH_4 g/mmBtu	N_2O g/mmBtu	CO_2 g/mmBtu	Total GHG gCO_2e/mmBtu	Total GHG gCO2e/MJ
US Diesel	0.159	0.717	0.460	0,009	373.691	389.567	0.37
Fugitive Emissions			2.129			10.647	0.01
Total							**0.38**

5.4 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 in Table 5.04.

Table 5.04. Assumptions of LNG Storage Emissions calculations

Description	**Bulk Terminal**	**Distribution**
Daily Boil-Off Rate	0.05%	0.10%
Duration [Days]	5	0.1
Boil-Off Recovery Rate	80%	80%

Total fugitive emission calculations for the storage of LNG are shown in Table 5.05.

Table 5.05. LNG Storage Emissions calculations

	Bulk Terminal [gCH_4/mmBtu]	**Distribution [gCH_4/mmBtu]**	**Total [gCH_4/mmBtu]**	**Total GHG Emissions [gCO_2e/mmBtu]**
Fugitive Emissions	10.67	0.43	11.10	0.26
Total	**10.67**	**0.43**	**11.10**	**0.26**

SECTION 6. GHG EMISSIONS FROM VEHICLES

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% corresponding to a range of 55.4 to 56.8 g/MJ (as CO_2) 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 used in this calculation.

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)

(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 (See LCA report of pathway "CNG007" published by ARB on 04/10/2013).

Table 6.01. LNG Tailpipe Emissions

	CO_2 [g CO_2/MJ]	**CH_4 + N_2O [g CO_2e/MJ]**	**Total [g CO_2e/MJ]**
Tailpipe Emissions	56.02	[redacted]	**58.54**