California Environmental Protection Agency

Air Resources Board

California-Modified GREET Pathways: North American Landfill Gas to Compressed Natural Gas, Liquefied Natural Gas, and Liquefied-Compressed Natural Gas

Industrial Strategies Division

Transportation Fuels Branch

Fuels Evaluation Section

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California-Modified GREET Pathways: North American Landfill Gas to Compressed Natural Gas, Liquefied Natural Gas, and Liquefied-Compressed Natural Gas

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I. Overview

On January 28, 2013, staff released a landfill-gas-to-compressed-natural-gas (LFG-to-CNG) pathway document covering biomethane originating from any landfill in North America (California Air Resources Board, 2013). This pathway is available to any supplier of CNG produced from LFG extracted from any landfill in North America, if that LFG was processed into pipeline quality biomethane, injected into the interstate natural gas pipeline system, extracted in California, compressed, and dispensed as motor vehicle fuel. This document amends that original pathway document to cover liquefied natural gas (LNG) and liquefied-compressed natural gas (L-CNG)[1] produced from the same biomethane stream described in the original pathway document.

This pathway document, therefore, describes three North American biomethane fuel pathways:

- LFG-to-CNG
- LFG-to-LNG
- LFG-to-L-CNG

The existing North American LFG-to-CNG pathway was based on a previously approved pathway for LFG- to-CNG (California Air Resources Board, 2009a). The inputs were selected in order to make the North American pathway available to as many North American LFG-to-biomethane producers as possible. The North American pathway was developed by assuming that the biomethane is transported 3,600 miles by pipeline to California. The LFG facilities were assumed to use older, less efficient equipment, and to use grid electricity generated only with steam from coal-fired boilers. Table 1 summarizes these assumptions.

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[1] When CNG is produced from LNG, it is referred to L-CNG. L-CNG is produced by vaporizing LNG and compressing the resulting gas into CNG.

Table 1. CA-GREET Inputs used for the North American LFG-to-CNG Pathway

Model Parameters	Modified Input Values Used	CA-GREET1.8b Model Cell References
Electricity Mix at LFG processing facility	100% from coal	Regional LT!C83:C88
Coal Fuel Properties	Set to “U.S. Average” values	Regional LT!C192:C195
Crude Recovery Fuel Shares	Set to “U.S. Average” values	Regional LT!C13:C22
Methane Membrane Efficiency	84%	N/A
Total Processing Efficiency	77.2%	NG!AI66
LFG process share (due to membrane)	76.2%	NG!AI76
Electricity process share (due to membrane)	23.8%	NG!!AI80
Pipeline Leakage	0.15%	NG!X120
Pipeline Distance	3,600 miles	T&D_Flowcharts! AE478

The new LNG and L-CNG pathways use the same LFG processing and pipeline transport distance inputs used in the LFG-CNG pathway. Once the biomethane is extracted in California, it is either liquefied and used in LNG-powered vehicles, or liquefied, regasified, and compressed for use in CNG-powered vehicles. The LNG pathway inputs were taken from an existing LCFS LNG pathway (California Air Resources Board, 2009b).

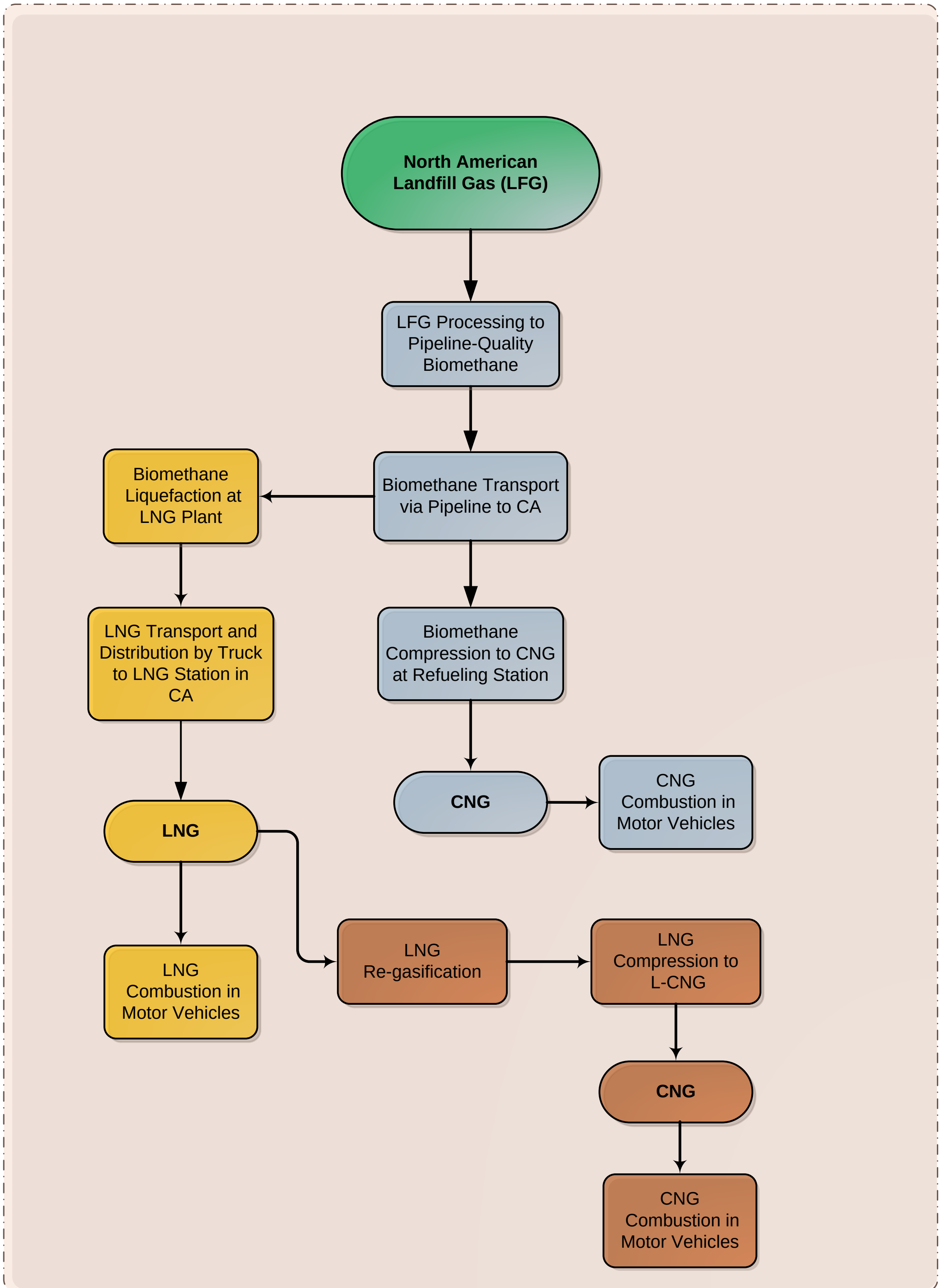
The Well-to-Tank (WTT) portion of this Life Cycle Analysis includes all steps from the North American landfill-gas feedstock recovery to the dispensing of finished biomethane (in the form of CNG, LNG, or L-CNG) into motor vehicle fuel tanks. The Tank-to-Wheels (TTW) portion includes the actual combustion of the resulting fuel in a motor vehicle for motive power. Taken together, the WTT and the TTW analyses comprise a total Well-to-Wheels (WTW) analysis.

A version of the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model (Argonne National Laboratory and Life Cycle Associates LLC, 2009) was used to calculate the energy consumed and the greenhouse gases (GHGs) emitted during the WTW fuel life cycle. Life Cycle Associates LLC modified the original GREET model to create a California-specific version known as the CA-GREET model. Changes were restricted mostly to adding California-specific input factors (emission factors, electrical energy generation mixes, transportation distances, etc.); no substantial changes were made to the methodology inherent in the original GREET model on which CA-GREET is based.

The results obtained from the CA-GREET model (v1.8b, released December 2009) are reported in this document. General terms and conventions used in CA-GREET analyses are discussed in Appendix A. This document presents the energy consumed and the GHGs emitted during the process of producing and using CNG, LNG, and L-CNG from landfill gas in a heavy-duty vehicle.

These pathways cover pipeline-quality biomethane produced from landfill gas extracted from any North American landfill. If that biomethane is injected into the interstate pipeline system, withdrawn in California, and compressed for use in CNG-powered motor vehicles, it is covered under the LFG-to-CNG pathway. If the biomethane is withdrawn in California, liquefied, and transported to a LNG dispensing facility for use in LNG-powered motor vehicles, it is covered under the LFG-to LNG pathway. If the LNG produced as described in the LFG-to-LNG pathway is vaporized and compressed for use in CNG-powered motor vehicles, it is covered under the LFG-to-L-CNG pathway. Much of the calculation methodology and many of the basic inputs and assumptions used in all three pathways are discussed in this document. A schematic of all three pathways is presented in Figure 1.

Figure 1. North American Landfill Gas to CNG, LNG, and L-CNG Fuel Pathways Process System Boundary



II. North American Landfill Gas to CNG Pathway Description

The North American LFG-to-CNG pathway is based on an existing Low Carbon Fuel Standard (LCFS) pathway for landfill gas to CNG (California Air Resources Board, 2009a). The inputs used in that pathway were modified in order to create a pathway that would cover biomethane produced from landfill gas originating anywhere in North America. To achieve this goal, the following inputs parameters were used:

- A pipeline distance of 3,600 miles.
- The LFG processing equipment used is capable of extracting 84 percent of the methane in the LFG.
- LFG processing is assumed to be 77.2 percent efficient and to utilize fuel shares consisting of 76.2 percent LFG and 23.8 percent electricity.
- The electricity used to process the LFG was assumed to be generated entirely from coal.
- The transportation and distribution leakage rate assumed for this pathway was the CA-GREET default of 0.15 percent for the North American pipeline grid.

Unless otherwise noted, no other inputs from the precursor LCFS LFG-to-CNG pathway were modified in this pathway.

1. Landfill Gas Recovery and Transport to Processing

The North American LFG-to-CNG pathway begins with the collection of raw landfill gas from wells drilled into the landfill. Gas is collected and then transported approximately one mile to an on-site processing facility via a negative pressure pipeline system, powered by a hermetically sealed electric blower. According to the CA-GREET model, the energy necessary for these steps is approximately 15,104 Btu for every one million Btu collected. The blower is powered by electricity from the local grid. Because electricity generates no emissions at its point of use, the only emissions associated with the operation of the electric blower are 1.59 gCO_2e/MJ from the upstream sources of that electricity (coal-powered steam turbines).

2. Landfill Gas Processing

Once at the processing facility, the LFG is fed via a compressor to a membrane separation unit designed to recover most of the methane in the input stream. In order to ensure that the North American pathway can be used by most LFG processing facilities in operation today, a membrane efficiency of 84 percent is assumed. The LFG gas stream is assumed to contain about 95 percent methane. The tail gas stream containing 16 percent methane (in addition to moisture and impurities) is combusted in a thermal oxidizer to minimize emissions.

In the existing ARB pathway, 2,570 MMBtu/day of the extracted LFG is processed (only the methane in the LFG contributes to this Btu total). Of this total, 72 MMBtu/day bypasses the membrane separation unit and is used as fuel in the thermal oxidizer. The remaining 2,498 MMBtu/day is fed to the membrane separation unit, which recovers 84 percent, or 2,098 MMBtu/day as pipeline-quality methane. The 16 percent (400 MMBtu/day) that remains in the LFG stream is sent to the thermal oxidizer for destruction. Diverted LFG rather than fossil natural gas is assumed to serve as thermal oxidizer fuel.

LFG processing consumes 147.41 MMBtu/day. Therefore, the overall efficiency of the LFG gas-cleaning process is 2,098/(2,570+147.41) = 77.2 percent. Because this relatively low overall process efficiency removes less methane from the gas stream, this North American pathway uses more LFG and less electricity than does the precursor LFG-CNG pathway: the process energy shares for the North American pathway are 76.2 percent LFG and 23.8 percent electricity.

Like the existing LFG-CNG pathway, this North American pathway benefits from a credit for avoided flaring emissions. In both cases, LFG that would have been flared to the atmosphere is captured and used to perform productive work. The relatively low efficiency assumed for the North American pathway leaves more methane in the LFG tail gas stream. Since this tail gas is used for process energy (thermal oxidizer fuel), an increase in the methane content of the tail gas results in a corresponding increase in the flare credit. A higher flare credit reduces the pathway CI. The credit for flaring emissions avoided under the North American pathway is -1,226,886 Btu/MMBtu. Combining this credit with the LFG processing energy use value yields a net energy expenditure of -769,371 Btu/MMBtu. The corresponding CI value is -32.82 gCO_2e/MJ.

3. Biomethane Transport and Distribution

The third step in the LFG-CNG pathway is transport and distribution (T&D) of the biomethane by pipeline from the processing plant to the CNG refueling station in California. This pathway assumes that the refueling station is located 3,600 miles from the LFG processing plant. The resulting energy consumption for T&D consists of:

- T&D feedstock loss
- T&D pipeline transport energy consumption

T&D feedstock loss consists of leakage from the pipeline system. This analysis uses the CA-GREET value of 0.15 percent.

Based on the relevant values in the CA-GREET model, and the pipeline distance and leakage rate assumptions made above, the T&D stage of the North American pathway consumes 43,826 Btu/MMBtu and produces 3.73 gCO_2e/MJ in GHG emissions.

4. CNG Compression at the Fueling Station

Once the biomethane reaches California, the remaining steps in the North American pathway are identical to the existing ARB LFG-to-CNG pathway.

At the CNG fueling station, the gas is withdrawn from the pipeline and compressed to approximately 3,000 psi for dispensing into natural gas vehicles. Fueling station compressors are assumed to be 98 percent efficient and powered by California marginal grid electricity. This results in the consumption of 40,746 Btu/MMBtu of process energy, and 2.15 gCO_2e/MJ of GHG emissions.

5. Pathway Carbon Intensity

When the inputs described in Table 1 above are entered into the CA-GREET model, the final result is a pathway carbon intensity (CI) of 33.02 gCO_2e/MJ, as summarized in Table 2 below.

Table 2. Energy Consumption and GHG Emissions: North American LFG-to-CNG Pathway

Pathway Stage	Energy Use Btu/MMBtu[a]	GHG Emissions gCO_2e/MJ
Well-to-Tank (WTT)		
Landfill Gas Recovery and Transport	15,104[b]	1.59
Landfill Gas Processing & Flaring Credit	-769,371[b]	-32.19
Transport & Distribution	43,826	3.73
Compression at Station in California	40,746	2.15
Total WTT	**-669,722**	**-24.71**
Carbon in Fuel	1,000,000	55.20
Vehicle CH_4 and N_2O		2.53
Total TTW	**1,000,000**	**57.73**
Total Well-to-Wheel (WTW)	**330,278**	**33.02[c]**

[a]The electrical energy generation mix used for the LFG recovery, transport, processing, and biomethane T&D portions of this pathway consists of 100 percent coal-generated electricity. The corresponding mix for the remaining stages in the pathway is the California marginal mix.
[b]This value differs between the CNG and LNG pathways because CA-GREET applies a higher loss factor to LNG pathways.
[c]Numbers do not add up exactly due to rounding. No rounding was performed when calculating the WTW CI.

III. North American Landfill Gas to LNG Pathway Description

The biomethane produced from North American LFG, as described in the previous sections, can also be liquefied and used in LNG-powered vehicles. This section describes an LFG-to-LNG pathway in which biomethane from any North American landfill is injected into the interstate pipeline system, extracted at a liquefaction plant in

California, transported by heavy-duty truck to bulk terminal storage and fueling stations in California, and dispensed to LNG-powered vehicles. The upstream phases of this pathway (up to and including pipeline transport) are identical to the corresponding phases of the LFG-to-CNG pathway described above, and the downstream phases (liquefaction through combustion in a LNG-powered vehicle) are based on an existing LFG-to-LNG pathway (California Air Resources Board, 2009b). The following sections describe the energy consumption and GHG emissions associated with the liquefaction, transport, storage, and dispensing of biomethane from North American landfills.

1. Biomethane Liquefaction to LNG

LFG-based biomethane is withdrawn from the pipeline in California, liquefied, and distributed by heavy-duty LNG trucks to fueling stations. Liquefaction is accomplished by pressure let-down or electromagnetic liquefaction operating at an average efficiency of 80 percent. This efficiency is somewhat lower than the efficiency achieved by larger-scale, remote liquefaction plants, but is consistent with existing industry liquefaction curves (Kunert et al., 2008; Jakobsen, 2008). The liquefaction process consumes 100 percent natural gas.

Based on differences in liquefaction efficiencies, two separate pathways have been modeled in this document. The main inputs for modeling North American natural gas liquefaction emissions are:

- Electrical energy generation mix: CA-Marginal electricity
- NG liquefaction efficiencies: 80% and 90%
- Process fuel shares: 100% NG
- LNG storage boil-off rate: 0.05% per day (IPCC value included in CA-GREET1.8b)
- Recovery rate of boiled-off LNG at liquefaction plant: 100%

The total energy of liquefaction used in the 80% liquefaction efficiency pathway consists of the 250,000 Btu of direct natural gas consumption, the energy consumed upstream for the production of that natural gas, and a loss factor to account for downstream feed loss. The total energy requirement is 266,335 Btu/MMBtu, resulting in greenhouse gas emissions totaling 15.91 gCO_2e/MJ.
The 90% liquefaction efficiency pathway requires 111,111 Btu of direct natural gas to liquefy one MMBtu to natural gas fuel. The total energy requirement for liquefaction is 118,371 Btu/MMBtu, resulting in emissions of 7.07 gCO_2e/MJ.

Rather than using a fuel share, as in most natural gas pathways, LNG feed losses are measured in terms of boil-off from LNG storage vessels. Boil-off is a process for maintaining a constant pressure within LNG storage vessels: as the vessel absorbs heat from its surroundings, pressure begins to build within the tank, forcing gas to be vented in order to maintain a constant internal pressure. Modern LNG facilities generally capture and re-liquefy (or otherwise utilize) the boiled-off gas, therefore this pathway assumes 100% recovery of LNG feed loss at the liquefaction facility; however, boil-off losses do occur during transport, bulk terminal storage and distribution to refueling stations.

2. LNG Transport, Storage, and Dispensing

LNG is assumed to be transported 50 miles by heavy-duty diesel truck to fueling stations in California. CA-GREET 1.8b calculates the energy use and emissions from LNG transport and dispensing feed loss from boil-off during transportation to be 4,902 Btu/MMBtu, and 0.42 gCO_2e/MJ, respectively. The model also calculates 1,103 Btu/MMBtu of feed loss from boil-off during terminal storage,resulting in emissions of 1.32 gCO_2e/MJ. The CA-GREET inputs used in this analysis are:

- 50 miles by heavy-duty diesel truck
- LNG terminal storage duration: 5 days (CA-GREET1.8b default)
- Transportation boil-off loss rate: 0.1% per day (CA-GREET1.8b default).
- Recovery rate of boiled-off LNG at terminal storage, transportation and distribution: 0%

3. Pathway Carbon Intensity

Table 3 summarizes the energy consumption and emissions associated with each phase of the LFG-to-LNG pathway. As shown, the final carbon intensity of LNG is 49.10 gCO_2e/MJ. The tank-to-wheels emissions vary slightly between the CNG and LNG pathways, as can be observed by comparison of Tables 2 and 3; this is due to differences in the heating values and carbon contents of CNG and LNG.

Table 3. Energy Consumption and GHG Emissions: North American LFG-to-LNG Pathway

Pathway Stage	80% Liquefaction Efficiency		90% Liquefaction Efficiency	
	Energy Btu/MMBtu[a]	GHG Emissions gCO_2e/MJ	Energy Btu/MMBtu[a]	GHG Emissions gCO_2e/MJ
Well-to-Tank (WTT)				
Landfill Gas Recovery and Transport	15,104[b]	1.60	15,104[b]	1.60
Landfill Gas Processing & Flaring Credit	-771,454[b]	-32.37	-771,454 [b]	-32.37
Biomethane Transport & Distribution	43,826	3.73	43,826	3.73
Biomethane Liquefaction	266,335	15.91	118,371	7.07
LNG Transport & Distribution	4,902	0.42	4,902	0.42
LNG Storage	1,103	1.32	1,103	1.32
Total WTT	**-440,171**	**-9.40**	**-588,135**	**-18.23**
Tank-to-Well (TTW)				
Carbon in Fuel	1,000,000	56.00	1,000,000	56.00
Vehicle CH_4 and N_2O		2.50		2.50
Total TTW	**1,000,000**	**58.50**	**1,000,000**	**58.50**
Total Well-to-Wheel (WTW)	**559,829**	**49.10**[c]	**293,500**	**40.27**

[a]The electrical energy generation mix used for the LFG recovery, transport, processing, and biomethane T&D portions of this pathway consists of 100-percent coal-generated electricity. The corresponding mix for the remaining stages in the pathway is the California marginal mix.
[b]This value differs between the CNG and LNG pathways because CA-GREET applies a higher loss factor to LNG pathways.
[c]Numbers do not add up exactly due to rounding. No rounding was performed when calculation the WTW CI.

IV. North American Landfill Gas to L-CNG Pathway Description

LNG produced from LFG-based biomethane, as described in the previous section, can also be re-gasified and compressed into CNG for use in CNG-powered vehicles. Re-gasification and compression both consume energy and produce GHG emissions, but compression contributes the largest share to overall emissions.

1. LNG Re-gasification

After delivery to the fueling station, LNG is heated and re-gasified by being pumped through heat exchangers. Heat is supplied to the heat exchangers by various means, including sea water and the combustion of the vaporized gas. In some cases, the latent heat from the LNG is captured and used to perform useful work. The energy required for re-gasification ranges from 0.5 percent to 3 percent (Heede, 2006 & Rahal, 2006). An average re-gasification energy requirement of 1 percent (10,000 Btu of LNG) was assumed for this pathway (California Air Resources Board, 2009c). The resulting re-gasification energy expenditure, as calculated using CA-GREET, is 13,760 Btu/MMBtu.

2. LNG Compression to L-CNG

The final step in the LFG-L-CNG pathway is compression of the re-gasified biomethane into CNG at the refueling station. This process requires the standard natural gas compression stage energy of 40,746 Btu/MMBtu.

3. Pathway Carbon Intensity

In this analysis, the CI of liquefied-compressed natural gas is calculated as incremental emissions that occur from the additional expenditure of energy necessary to re-gasify and then compress the LFG-based LNG. The additional energy requirement is 54,506 Btu/MMBtu, resulting in greenhouse gas emissions totaling 2.97 gCO_2e/MJ. Adding these stages to the LFG-LNG pathway with 80% liquefaction efficiency produces a full WTW L-CNG pathway CI of 51.30 gCO_2e/MJ. The LFG to L-CNG pathway with 90% liquefaction efficiency produces 42.46 gCO_2e/MJ. These results are summarized in Table 4.

Table 4. Energy Consumption and GHG Emissions: North American LFG-to-L-CNG Pathway

Pathway Stage	80% Liquefaction Efficiency		90% Liquefaction Efficiency	
	Energy Btu/MMBtu[a]	GHG Emissions gCO_2e/MJ	Energy Btu/MMBtu[a]	GHG Emissions gCO_2e/MJ
Well-to-Tank (WTT)				
Landfill Gas Recovery and Transport	15,104[b]	1.60	15,104[b]	1.60
Landfill Gas Processing & Flaring Credit	-771,454[b]	-32.37	-771,454[b]	-32.37
Biomethane Transport & Distribution	43,826	3.73	43,826	3.73
Biomethane Liquefaction	266,335	15.91	118,371	7.07
LNG Transport & Distribution	4,902	0.42	4,902	0.42
LNG Storage	1,103	1.32	1,103	1.32
LNG Re-gasification	13,760	0.82	13,760	0.82
LNG Compression	40,746	2.15	40,746	2.15
Total WTT	**-385,666**	**-6.43**	**-385,666**	**-6.43**
Tank-to-Well (TTW)				
Carbon in Fuel	1,000,000	55.20	1,000,000	55.20
Vehicle CH_4 and N_2O		2.53		2.53
Total TTW	**1,000,000**	**57.73**	**1,000,000**	**57.73**
Total Well-to-Wheel (WTW)	**614,334**	**51.30**[c]	**466,370**	**42.46**

[a]The electrical energy generation mix used for the LFG recovery, transport, processing, and biomethane T&D portions of this pathway consists of 100-percent coal-generated electricity. The corresponding mix for the remaining stages in the pathway is the California marginal mix.
[b]This value differs between the CNG and LNG pathways because CA-GREET applies a higher loss factor to LNG pathways.
[c]Numbers do not add up exactly due to rounding. No rounding was performed when calculation the WTW CI.

V. Operating Conditions

- Actual energy consumption values shall remain at or below the levels specified in this document for CNG, LNG, and L-CNG pathways. The recovery and processing efficiency levels shall remain at or above the ones specified in the pathway document. In addition, the liquefaction efficiency at the LNG plant and the compression efficiency level at the L-CNG stations in California shall remain at or above the levels specified in this document.

- Because the biomethane supplied under these pathways is commingled with fossil natural gas, both when it enters into the interstate pipeline system and when it enters into the LNG plants in California, applicants must maintain an accounting system that will enable it to demonstrate unequivocally at any time that every unit of biomethane-based transportation fuel reported under the LCFS can be associated with an equal unit of biomethane purchased from a landfill in North America.

- Volumes of biomethane reported under the LCFS pathways described in this document cannot be used by the LCFS regulated party or any other entity to obtain credits of any type under any other GHG reduction program except for the U.S. Environmental Protection Agency's Renewable Fuels Standard (RFS2).

- The LNG pathway described in this document applies to, and may only be used for, LNG used in LNG-powered vehicles. It would not apply, for example, to LNG that is vaporized, compressed into CNG, and used in CNG vehicles.

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APPENDIX A

CA-GREET Terminology and Conventions

The analysis appearing in this fuel pathway document uses conventions and technical terms with specific meanings that are defined here:

- Emissions from the generation of electricity depend upon the mix of energy sources used to generate that electricity. Electrical energy generation mixes are determined in CA-GREET using the U.S. Environmental Protection Agency's Emissions & Generation Resource Integrated Database (eGRID) (U.S. Environmental Protection Agency, 2014). CA-GREET uses eGRID subregional energy mixes. The average energy mixes reported in the eGRID database must be converted to marginal mixes for purposes of CI calculation under the LCFS. Average mixes are typically converted to marginal mixes by reallocating nuclear and large hydroelectric generation to natural gas generation. Marginal mixes include energy sources most likely to be used to meet the new electrical demand.

- Some emission values in CA-GREET are calculated recursively. This happens when a fuel is used in the process that produces that same fuel. Diesel fuel, for example, is used to extract and transport crude oil. This means that the CI of diesel contributes to the CI of crude oil. Since diesel is refined from crude, the CI of diesel plays a role in its own CI. The CIs of crude oil and diesel fuel are recursively calculated in CA-GREET. If a new CI for diesel is entered into the model, that CI will be used to calculate a new CI for crude oil. The result of that calculation will be used to calculate a new CI for diesel. This iterative recalculation process will continue 100 times.

- The British thermal unit (Btu) per million Btu (Btu/MMBtu) is the energy input necessary in Btus to produce one million Btus of a finished (or intermediate) product. This description is used consistently in CA-GREET for all energy calculations.

- In order to calculate a single aggregate carbon intensity value for all greenhouse gas emissions occurring throughout the well-to-wheels life cycle, the atmospheric heat-trapping potential of all greenhouse gases must be expressed in standardized additive units. Under the LCFS, all greenhouse gas species other than CO_2 are converted to CO_2-equivalent (CO_2e) values. These conversions are accomplished by using the Intergovernmental Panel on Climate Change (IPCC) global warming potential indices. Methane (CH_4) and nitrous oxide (N_2O) are converted to a CO_2-equivalent basis using (IPCC) global warming potential values for inclusion in the total pathway carbon intensity (Solomon et al., 2007).[2] The IPCC Global Warming Potential (GWP) indices function as multipliers: CH_4 emissions, for example, are multiplied by 25.

- CA-GREET assumes that volatile organic compounds and carbon monoxide are converted to CO_2 in the atmosphere. It therefore, includes these pollutants in the total CO_2 value using ratios of the appropriate molecular weights.[3]

- The input values extracted from reference materials may have been in units that differ from the units used in this document. For example, if a fertilizer value was in kilograms per hectare (kg/ha), ARB staff would apply the standard conversion factors to convert this value to grams per acre (g/ac).

- Process efficiency for any step in CA-GREET is defined as the ratio of energy output to the sum of the energy output and energy consumed. (Efficiency = energy output/(energy output + energy consumed)).

- As used in this document, the term "upstream" refers to the energy use and emissions associated with the inputs supplied to the fuel production process. Upstream energy is produced from natural gas, nuclear power, renewables, etc. to generate the electrical and thermal energy consumed by the feedstock and fuel production processes. In the case of most fuels, including corn oil biodiesel, the two upstream processes considered in the well-to-tank analysis are the production of natural gas and the generation of electricity. In the case of natural gas, the energy used to extract, process, and transport the gas is quantified. In the case of electrical generation, the energy needed to produce and transport the fuels used to generate the electrical energy is considered. In both cases, the consumption of this energy results in GHG emissions.

[2] The 2007 IPCC GHG CO_2-equivalence (CO_2e) values are 1 for CO_2, 25 for CH_4, and 298 for N_2O.

[3] For other GHGs, CA-GREET uses molecular weight ratios to calculate the amount of carbon present relative to the carbon in CO_2. The ratio of the molecular weight of carbon to the molecular weight of CO_2, for example is 12/44 = 0.273. The CO_2e values of VOCs and CO are, therefore, 0.85/0.273 = 3.12, and 0.43/0.273 = 1.57, respectively.